



Samuel Labi

Foreword by Richard de Neufville

INTRODUCTION TO **CIVIL ENGINEERING SYSTEMS**

*A Systems Perspective to the Development of
Civil Engineering Facilities*

WILEY

Introduction to Civil Engineering Systems

A Systems Perspective to the Development of Civil Engineering Facilities

Samuel Labi

WILEY

Cover image: © MichaelRutkowskiPhotography
Cover design: Michael Rutkowski

This book is printed on acid-free paper. (∞)

Copyright © 2014 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey

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, 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 646-8600, or on the web at 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 www.wiley.com/go/permissions.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with the 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 the author shall be liable for damages arising herefrom.

For general information about our other products and services, 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 publishes in a variety of print and electronic formats and by print-on-demand. Some material included with standard print versions of this book may not be included in e-books or in print-on-demand. If this book refers to media such as a CD or DVD that is not included in the version you purchased, you may download this material at <http://booksupport.wiley.com>. For more information about Wiley products, visit www.wiley.com.

Library of Congress Cataloging-in-Publication Data

Labi, Samuel, 1962-

Introduction to civil engineering systems : a systems perspective to the development of civil engineering facilities / Samuel Labi.

pages cm

Includes index.

ISBN 978-0-470-53063-4 (hardback); ISBN 978-1-118-41530-6 (ebk); ISBN 978-1-118-41817-8 (ebk)

1. Civil engineering. 2. Systems engineering. I. Title.

TA145.L38 2014

624—dc23

2013038048

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

FOREWORD

The book in your hands is a most welcome addition to the range of textbooks in civil and environmental engineering. There is no other up-to-date text that covers the important elements of civil engineering systems. This book provides a significant and needed resource for majors in the field.

Labi's *Introduction to Civil Engineering Systems* fills an important gap. The previous lack of a current text on the subject has been most unfortunate. It is clear that the proper development of our infrastructure requires a holistic, coherent understanding of all the important elements that will make our products successful. Civil engineers have a responsibility for the entire life cycle of what we build: from planning, through design, to the management of the facility over its useful life. A civil engineering curriculum should thus provide its students with the opportunity to learn how to consider carefully the range of issues in civil engineering systems. This text now provides a basis for such a capstone course.

This text has the great merit of being thoughtful, innovative, comprehensive, and forward-looking.

- Beyond procedures and methods, Labi thoughtfully presents issues and discusses their whys and hows.
- He has innovatively structured the material as a coherent cycle of eight phases through the life cycle of a project in a way that makes it much easier to make sense of systems thinking.
- He comprehensively defines the tasks that should be done at each phase in the life cycle and describes the tools for each task.
- Aside from being the most forward-looking work in the field, the text recognizes the great uncertainty about future demands on our systems, and the consequent need for a flexible approach to systems design.

Readers will appreciate that this treatment of engineering systems focuses on civil engineering. Its extensive excellent illustrations display a most interesting array of infrastructure projects. This is a book for us. I hope you will like it!

Richard de Neufville
Professor of Engineering Systems and of Civil
and Environmental Engineering
Massachusetts Institute of Technology
Life Member, American Society of Civil Engineers

PREFACE

GENERAL BACKGROUND

The civil engineering discipline involves the development of structural, hydraulic, geotechnical, construction, environmental, transportation, architectural, and other civil systems that address societies' infrastructure needs. The planning and design of these systems are well covered in traditional courses and texts at most universities. In recent years, however, universities have increasingly sought to infuse a "systems" perspective to their traditional civil engineering curricula. This development arose out of the recognition that the developers of civil engineering systems need a solid set of skills in other disciplines. These skills are needed to equip them further for their traditional tasks at the design and construction phases and also to burnish their analytical skills for other less-obvious or emerging tasks at all phases of system development.

The development of civil engineering systems over the centuries and millennia has been characterized by continual improvements that were achieved mostly through series of trial-and-error as systems were constructed and reconstructed by learning from past mistakes. At the current time, the use of trial-and-error methods on real-life systems is infeasible because it may take not only several decades but also involve excessive costs in resources and, possibly, human lives before the best system can be finally realized. Also in the past, systems have been developed in ways that were not always effective or cost-effective. For these and other reasons, the current era, which has inherited the civil engineering systems built decades ago, poses a unique set of challenges for today's civil engineers. A large number of these systems, dams, bridges, roads, ports, and so on are functionally obsolescent or are approaching the end of their design lives and are in need of expansion, rehabilitation, or replacement. The issue of inadequate or aging civil infrastructure has deservedly gained national attention due to a series of publicized engineering system failures in the United States, such as the New Orleans levees, the Minnesota and Seattle interstate highway bridges, and the New York and Dallas sewers, and in other countries. The current problem of aging infrastructure is further exacerbated by increased demand and loading fueled by population growth, rising user expectations of system performance, increased desire for stakeholder participation in decision-making processes, terrorism threats, the looming specter of tort liability, and above all, inadequate funding for sustained preservation and renewal of these systems.

As such, civil engineers of today need not only to develop skills in the traditional design areas but also to continually seek and implement traditional and emerging tools in other related areas such as operations research, economics, law, finance, statistics, and other areas. These efforts can facilitate a more comprehensive yet holistic approach to problem solving at any phase of the civil engineering system development cycle. This way, these systems can be constructed, maintained, and operated in the most cost-effective way with minimal damage to the environment, maximum system longevity, reduced exposure to torts, optimal use of the taxpayers' dollar, and other benefits. Unfortunately, at the current time, graduating engineers enter the workforce with few or no skills in systems engineering and learn these skills informally only after several decades. With limited skill in how to integrate specific knowledge from external disciplines into their work, practicing engineers will be potentially handicapped unless their organizations provide formal training in the concepts of systems engineering. This text addresses these issues.

THE TEXT

The first part of this text discusses the historical evolution of the various engineering disciplines and general concepts of systems engineering. This includes formal definitions, systems classifications, systems attributes, and general and specific examples of systems in everyday life and in civil engineering. The part also identifies the phases of development of civil systems over their life cycle and discusses the tasks faced by civil systems engineers at each phase. Most working engineers are typically involved in only one or two of these phases, but it is important for all engineers to acquire an overall bird's eye view of all phases so that decisions they make at any phase are holistic and within the context of the entire life cycle of their systems. The next two parts discuss the tasks that civil engineers encounter at each phase and the tools they need to address these tasks. For example, at the needs assessment phase, one possible task is to predict the level of expected usage of the system, and the tool for this task could be statistical modeling or simulation. Certain tools are useful in more than one phase. Given this background, Part IV provides a detailed discussion of each phase of civil systems development and presents specific examples of tasks and tools used to address questions at these phases. Part V presents topics that may seem peripheral but are critical to civil systems development, such as legal issues, ethics, sustainability, and resilience, and discusses their relevance at each phase.

Clearly, this text differs from other texts in the manner in which it presents the material. The systems tasks and tools are presented not in a scattered fashion but rather in the organized context of a phasal framework of system development. Why is it so important to view the entire life cycle of civil engineering systems within a phasal framework? And why do we need to acquire those skills that are needed for the tasks at each phase? One reason is the typically large expense involved in the provision of such facilities. Every year, several trillion dollars are invested worldwide in civil engineering systems, to build new facilities or to operate and maintain existing ones. The beneficial impacts of these investments permeate every sphere of our lives including safety, mobility, security, and the economy and thus need to be identified and measured systematically. Also, adverse impacts such as environmental degradation, community disruption, and inequities are often evident and need to be assessed and mitigated. In summation, given the large expanse and value of civil engineering assets, the massive volume of national and state investments annually to build and operate these systems, and the multiplicity of stakeholders, there is need for a comprehensive yet integrated approach to the planning, design, implementation, operations, and preservation of these systems. A second reason for advocating an organized systems approach is the nature of recent and ongoing trends in the socioeconomic environment: at the current time of tight budgets, increasing loadings and demand, aging infrastructure, global economic changes, and increased need for security and safety, civil engineering systems are facing scrutiny more than ever before and the biggest

bang is now sought for every dollar spent on these systems. As such, civil system engineers are increasingly being called upon to render account of their fiduciary stewardship of the public infrastructure and assets. This is best done when the development of such systems is viewed within a phasal framework, when civil engineering system managers acquire the requisite tools needed to address the tasks at each phase, and when these managers provide evidence of organized planning for long-term life-cycle development of their systems.

DIDACTIC STYLE AND RESOURCES

There is a wealth of engineering knowledge that is well documented in textbooks that address specific branches and domain areas in civil engineering and also in other system engineering related disciplines including economics, operations research, and statistics. The author's purpose in writing this text is not to duplicate what already exists but to link the systems concepts from the different disciplines and traditional roles of the civil engineer, and to do this within the context of each system phase, tasks at each phase, and tools for the tasks.

The reader is afforded a clear and understandable text that presents well-explained methodologies and procedures useful for addressing tasks at each phase. Throughout its chapters, the text emphasizes practical applications of the concepts. Theoretical backgrounds are provided only to enable the reader to enhance their understanding of the concepts and to recognize the merits and demerits of alternative theories in solving a particular problem. The chapters and concepts are presented in a sequence and style that are expected to encourage the student to define and solve problems with requisite tools in a manner consistent with engineering and professional excellence. As such, each chapter is an integrated blend of theory and practice, and numerous conceptual and computational illustrations are provided.

As educational experts have acknowledged, students' didactic experience is more fruitful when they are asked to apply the concepts to a real-world problem. As such, a term project, to be carried out by multiperson teams, is recommended as part of any course for which this book is used. A list of possible topics for the term project can be found at the website purposely established for this book. Additional information on each of the 30 chapters, such as updated tools and news items relating to civil systems development at various countries worldwide, Facebook discussions, and YouTube presentations can be found at the book's website.

The subject of civil engineering systems is indeed a broad subject that could fill several texts. As such, there is a limitation to the scope and depth that can be provided in a single text as this. The text therefore provides only a basic fundamental understanding of what civil systems are, the various phases of their development, and the tools needed to address the tasks at each phase. The text serves as a central repository of references for persons interested in further inquiry. Also, recognizing that only a limited number of numerical examples can be included within the covers of this book, the author has provided a set of useful resources at the end of most chapters for the reader who wishes to acquire further knowledge on the subject.

ABET REQUIREMENTS AND AUDIENCE

This text satisfies a significant section of Accreditation Board for Engineering and Technology, Inc. (ABET) requirements for undergraduate civil engineering education such as problem solving, experiments and simulations, data analysis, optimization and financial analysis tools, and use of systems approaches in design of facility components and processes. Also, the text addresses other ABET requirements of socially and environmentally responsible design, engineering practice issues, ethics, licensure requirements, and managerial skills. The text's online resources addresses the requirement of student participation in multidisciplinary project teams.

This book is useful for college instructors and students for courses related to civil engineering systems. Most of the material could be covered in one semester if at least three credit hours per week are used for the course. The book is written primarily for midsenior undergraduate and beginning graduate students. The book should be useful not only in academia but also to practicing civil engineers, civil systems managers and policymakers in general. This includes private and nongovernmental organizations, consultants, international development agencies and lending institutions, public policy makers, government (state, county, provincial, or city) departments, municipal authorities, public works departments, regional planning agencies, metropolitan planning organizations, and other institutions involved in at least one of the phases of civil systems development. These persons will find that the text provides useful fundamentals for understanding and implementing systems perspectives at any of their system development phases of need assessment, planning, design, construction, operations, monitoring, maintenance, or end of life.

ACKNOWLEDGMENTS

The development of a textbook is very much like the development of a civil engineering system—it goes through the initial phases of needs assessment, planning and design of the chapters, feedback from readers, and improvement of subsequent editions. This is particularly true for *Introduction to Civil Engineering Systems*.

First, I recognize the contribution of the pioneers of civil engineering systems: Robert Stark, Robert Nichols, Jeff Wright, Charles Revelle, Earl Whitlach, Lester Hoel, Nicholas Garber, Richard de Neufville, C. Jotin Khisty, Jashmid Mohammadi, Dale Meredith, Kam Wong, Ronald Woodhead, Robert Wortman, Richard Larson, Joseph Stafford, Gerard Volland, and Graeme Dandy. They deserve tremendous credit for blazing the trail, navigating the difficult waters, and thus making it possible for civil engineers to recognize the usefulness of systems concepts to their field.

My appreciation goes to all those who created the materials that served as sources for this text. A large number of books, technical papers, and reports were reviewed during the writing of this text. The work of those who developed these materials served as a valuable knowledge base for developing this book. Without their work, this book would not be the valuable learning resource that it currently is and hopefully will continue to be.

I gratefully acknowledge the support of my colleagues in academia as well as the industry. These include the following professors: Kumares Sinha of Purdue University; Richard de Neufville, Fred Moavenzadeh, and Joe Sussman of MIT; Neville Parker of the City College of New York; Sue McNeil and Nii Attah-Okine of the University of Delaware; and Adjo Amekudji of Georgia Tech. They also include Dr. Chuanxin Fang of Microsoft Corporation; Mr. Gilbert Kporku of Conterra Limited; and Mr. Arun Shirole, former chief bridge engineer of the New York State Department of Transportation; and Dr. Jung Eun Oh of the World Bank.

I would also like to give credit to my friends, colleagues, and graduate students for enhancing the manuscript in various ways, including Qiang Bai, Zhibo Zhang, Nathee Athigakunagorn and Arash Roshandeh, Charles Atisso, and Rita Adom. No words can describe my appreciation for the support of my family, Grace, Valerie, Rachel, and Chelsea.

The staff at John Wiley & Sons has been extremely supportive, and I am thankful to editors Bob Argentieri and Margaret Cummins for their continual support and understanding.

Finally, for all the good aspects of this book, I duly reserve credit to my helpers, contributors and supporters; for any flaw, the full responsibility is mine.

AUTHOR BIOGRAPHY

Dr. Samuel Labi is an Associate Professor at Purdue University's School of Civil Engineering. He has seven years experience in consulting at Conterra Limited, where his work traversed different civil engineering disciplines and included economic and technical feasibility studies, facilities planning and design, geotechnical investigations, contract administration, and construction and maintenance supervision. Dr. Labi has worked on projects such as the World Bank–sponsored Transportation Rehabilitation Projects in Ghana, in the late 1980s. His national academic awards include the 2002 Milton Pikarski Award for outstanding doctoral dissertation in transportation engineering, the 2007 Bryant Mather Award for best paper in concrete materials awarded by the American Society of Testing and Materials (ASTM), the 2008 K.B. Woods prize awarded by the Transportation Research Board for the best journal paper in design and construction, and the 2014 Frank Masters Award from the American Society of Civil Engineers (ASCE) for innovative or noteworthy contributions to the planning, design and construction of transportation facilities. He is a member of Sigma Xi (Scientific Research Society) and Chi Epsilon (National Civil Engineering Honors Society) and several professional organizations including the American Society of Civil Engineers (ASCE), International Association for Life-Cycle Civil Engineering (IALCCE), Institute for Operations Research and the Management Sciences (INFORMS), and the American Association for the Advancement of Sciences (AAAS). Dr. Labi has taught a number of undergraduate and graduate-level courses at Purdue University and the Massachusetts Institute of Technology, and he has served as a major thesis advisor for several doctoral students. He is an associate editor of the ASCE Journal of Risk and Uncertainty and member of the editorial board of the ASCE Journal of Infrastructure Systems. He is a reviewer for several major international technical journals, conferences, and textbook publishers and a co-author of *Transportation Decision Making—Principles of Project Evaluation and Programming* published by John Wiley & Sons in 2007.

CONTENTS

Foreword	xvii
Preface	xix
Author Biography	xxiii

I	Introduction	1
1	Civil Engineering Systems and Their Evolution	3
1.0	Introduction	3
1.1	Civil Engineering Systems and Historical Developments	3
1.2	Civil Engineering System—The Branches	8
1.3	Final Comments on the Historical Evolution and Future of Civil Engineering Systems	44
	Summary	45
	Exercises	45
	References	46
	Useful Resources	49
2	Fundamental Concepts in Systems Engineering	50
2.0	Introduction	50
2.1	What Is a System?	50
2.2	Systems Considerations in Civil Engineering	60
2.3	Development of Civil Engineering Systems	63
2.4	Some Terms and Concepts Related to Systems Thinking	66
2.5	Global Initiatives in the Study of Systems	68
	Summary	70
	Exercises	70
	References	71
	Useful Resources	72

3	Goals and Objectives of Civil Engineering Systems	74
3.0	Introduction	74
3.1	Hierarchy of Desired Outcomes: Values, Goals, and Objectives	75
3.2	Common MOEs Used in Decision Making at Any Phase of System Development	82
3.3	Goals and MOEs at Each Phase of Civil Engineering Systems Development	91
3.4	Desired Properties of a Set of MOEs for a Given Analysis	95
3.5	Overall Discussion of Engineering Systems Goals and Objectives	95
	Summary	96
	Exercises	97
	References	98
	Useful Resources	98
II	The Tasks at Each Phase of Systems Development	99
4	Tasks within the Phases of Systems Development	101
4.0	Introduction	101
4.1	The Task of Description	103
4.2	Traditional Tasks of Analyzing Systems in Civil Engineering	111
4.3	The Task of System Evaluation	113
4.4	The Task of Feedback between Phases	117
4.5	Examples of Tasks at Each Phase of Systems Development	118
	Summary	123
	Exercises	123
	References	124
III	Tools Needed to Carry Out the Tasks	125
5	Probability	127
5.0	Introduction	127
5.1	Set Theory	129
5.2	Some Basic Concepts in Probability	132
5.3	Random Variables	140
5.4	Probability Functions	142
5.5	Discrete Probability Distributions	149
5.6	Continuous Probability Distributions	157
5.7	Common Terminology in Probabilistic Analysis	159
	Summary	161
	Exercises	162
	References	164
	Useful Resources	164
6	Statistics	165
6.0	Introduction	165
6.1	Population and Sampling	168
6.2	Descriptive Statistics	171

6.3	Inferential Statistics	177	
6.4	Hypothesis Testing	189	
6.5	Some Common Terminology and Concepts in Engineering Statistics	197	
	Summary	197	
	Exercises	198	
	References	200	
	Useful Resources	200	
7	Modeling		201
7.0	Introduction	201	
7.1	Steps for Developing Statistical Models	201	
7.2	Model Specifications in Statistical Modeling	215	
7.3	Some Important Issues in Statistical Modeling	228	
7.4	Glossary of Modeling Terms	234	
	Exercises	235	
	References	238	
	Useful Resources	239	
8	Simulation		240
8.0	Introduction	240	
8.1	Simulation Terminology	243	
8.2	Categories of Simulation	244	
8.3	Random Number Generation	247	
8.4	Monte Carlo Simulation	255	
	Summary	263	
	Exercises	264	
	References	265	
	Useful Resources	266	
9	Optimization		267
9.0	Introduction	267	
9.1	Unconstrained Optimization Using Calculus	276	
9.2	Constrained Optimization Using Calculus	281	
9.3	Constrained Optimization Using Mathematical Programming Techniques	283	
9.4	Constrained Optimization Involving Binary Decision Variables	300	
9.5	Search for the Optimal Solution—Quicker and Efficient Techniques	307	
9.6	Discussions and Final Comments	313	
	Summary	316	
	Exercises	316	
	References	320	
10	Cost Analysis		321
10.0	Introduction	321	
10.1	System Cost Classifications	321	
10.2	Costs Incurred by System Owner/Operator	327	
10.3	Costs Incurred by the System User	328	
10.4	Costs Incurred by the Community	335	
10.5	System Costs Categorized by Phase of System Development	338	

10.6	Average and Marginal Cost Concepts	341
10.7	Cost Estimation at the Construction Phase	343
10.8	Issues in Systems Costing	353
	Summary	362
	Exercises	363
	References	365
	Useful Resources	367
11	Economic Analysis	368
11.0	Introduction	368
11.1	Basic Concepts in Economic Analysis	369
11.2	Interest Formulas (or Equivalence Equations)	375
11.3	Criteria for Economic Analysis	380
11.4	Discussion of Relative Merits of the Economic Efficiency Criteria	385
11.5	Effect of Evaluation Parameters on the Evaluation Outcome	390
11.6	Effect of Analysis Period on Systems Evaluation	395
11.7	Perpetuity Considerations	397
11.8	Some Key Considerations in Monetary LCCA	398
11.9	Economic Efficiency Analysis—Issues and Limitations	399
	Summary	403
	Exercises	403
	References	405
	Useful Resources	406
12	Multiple-Criteria Analysis	407
12.0	Introduction	407
12.1	Framework for MCDM Analysis Using Multiattribute Utility Theory	410
12.2	Establishing the Weights of Decision Criteria	416
12.3	Scaling of the Decision Criteria	420
12.4	Amalgamation	428
12.5	Preference versus Nonpreference Approaches for Weighting, Scaling, or Amalgamation (WSA)	443
	Summary	445
	Exercises	445
	References and Resources	447
	Useful Resources	448
	Appendix 12.1	449
13	Risk and Reliability	450
13.0	Introduction	450
13.1	Certainty, Risk, and Uncertainty	451
13.2	Uncertainties in System Development	452
13.3	The Management of Risks and Uncertainties	454
13.4	The Basics of Reliability	459
13.5	Common Contexts of Reliability Analysis in Civil Engineering	462
13.6	Laboratory and Field Testing of System Reliability	482

13.7	Reliability-Based Design of Civil Engineering Systems	483
13.8	System Reliability and System Resilience	484
	Summary	486
	Exercises	487
	References	488
	Useful Resources	490
14	System Dynamics	491
14.0	Introduction	491
14.1	Some Basic Concepts In System Dynamics	492
14.2	Variable versus Time (VVT) Patterns in System Dynamics Modeling	494
14.3	Causal Loop Diagrams (the Concept of Feedback)	496
14.4	Stocks and Flows	498
14.5	Framework for Systems Dynamics Analysis	501
14.6	Some Past Applications of Systems Dynamics at Civil System Development Phases	502
14.7	Chaos Theory	503
	Summary	504
	Exercises	504
	References	505
	Useful Resources	505
15	Real Options Analysis	507
15.0	Introduction	507
15.1	Real Options Taxonomy	511
15.2	Categories of Real Options	512
15.3	Valuing Flexibility in Real Options Analysis	517
15.4	Real Options Case Examples in Civil Engineering	522
15.5	Numerical Example	524
	Summary	526
	Exercises	526
	References	527
	Useful Resources	528
16	Decision Analysis	529
16.0	Introduction	529
16.1	General Contexts of Decision Making	529
16.2	Basic Process of Decision Making and Relevant Tools	530
16.3	Classification of Decision Models	531
16.4	Decision Making Associated with Uncertainty	533
16.5	Inputs for Uncertainty-Based Decision Making	535
16.6	Decisions under Risk	536
16.7	Decisions under Uncertainty	541
16.8	Other Techniques for Modeling Decisions	546
16.9	Impact of Decision-Maker's Risk Preferences on Decision Making	547
	Summary	548
	Exercises	548
	References	549

17	Network Analysis Tools	550
17.0	Introduction	550
17.1	Fundamentals of Graph Theory	551
17.2	Trees, Spanning Trees, and Minimum Spanning Trees	554
17.3	Shortest Path through a Network	557
17.4	Maximum Flow Problem	560
17.5	Locating Facilities on Civil Engineering Networks	561
17.6	Network Connectivity	564
17.7	Optimal Coverage of Networks	568
17.8	Optimal Shipping across Origin–Destination (O–D) Pairs in a Network	573
17.9	Network Applications in Project Management	582
	Summary	587
	Exercises	587
	References	592
	Useful Resources	594
18	Queuing Analysis	595
18.0	Introduction	595
18.1	Attributes of a Queuing Process	596
18.2	Performance of Queuing Processes	600
18.3	Role of Markov Chains in Queuing Analysis	601
18.4	Notations for Describing Queuing Processes	602
18.5	Analysis of Selected Queuing Process Configurations	603
18.6	Concluding Remarks on Queuing Analysis	609
	Summary	611
	Exercises	611
	References	613
	Useful Resources	613
IV	The Phases of Systems Development	615
19	The Needs Assessment Phase	617
19.0	Introduction	617
19.1	Assessment of System Needs	619
19.2	Mechanisms for Assessing System Needs	627
19.3	Assessing System Needs Using User-Targeted Mechanisms	628
19.4	Assessing Long-Term System Needs via Demand and Supply Trends	629
19.5	Optimal Scheduling of Supply—Mathematical Derivations	635
19.6	Some Issues and Considerations in Needs Assessment	642
	Summary	648
	Exercises	648
	References	649
	Useful Resources	650
20	Systems Planning	651
20.0	Introduction	651
20.1	Brief History of Civil Systems Planning	652
20.2	Dimensions (Perspectives) of Civil System Planning	652

20.3	Rationale and Impetus for System Planning	656
20.4	Evolving and Emerging Contexts of Systems Planning	657
20.5	Principles of Civil Systems Planning	659
20.6	System Planning Process	662
20.7	Barriers to Effective Planning	669
20.8	Computations in Civil Systems Planning	670
	Summary	675
	Exercises	675
	References	677
	Useful Resources	678
21	System Design	679
21.0	Introduction	679
21.1	Classifications of Engineering Design	680
21.2	Engineering Design Process	682
21.3	Applications of Systems Design in Selected Areas of Civil Engineering	694
21.4	Considerations in Civil Engineering Systems Design	697
21.5	Design Failures in Civil Engineering	701
21.6	Some Design Computations	703
	Summary	706
	Exercises	707
	References	709
	Useful Resources	711
22	Systems Construction	712
22.0	Introduction	712
22.1	Stages of the System Construction Phase	714
22.2	Project Delivery Options and Contracting Approaches	717
22.3	Construction Cost Analysis	722
22.4	General Decision Contexts in Construction That Merit Application of Systems Concepts	726
22.5	Managing Risks at the Construction Phase	739
22.6	Emerging and Evolving Issues in Civil Systems Construction	748
	Summary	750
	Exercises	751
	References	752
	Useful Resources	756
23	System Operations	757
23.0	Introduction	757
23.1	Definition	757
23.2	General Duties at the Operations Phase	760
23.3	Some Problem Contexts at the Operations Phase of Selected Types of Civil Engineering (CE) Systems	761
23.4	Numerical Examples of Application of Tools in CE System Operations	763
	Summary	778
	Exercises	778
	References	781
	Useful Resources	781