

Tradeoff Decisions in System Design

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Foreword

Tradeoff Decisions in System Design is an easy-to-read, user-oriented book that offers readers a comprehensive treatment of the fundamental processes of system design and development. The volume covers in a thorough but readily understood manner the principles of requirements and specifications discovery, tradeoff studies and the analysis of system risks. Terry A. Bahill and my colleague at the Viterbi School of Engineering of the University of Southern California, Azad Madni, have done an excellent job of capturing the essential elements of system design and presenting them using illustrative examples that aid the reader in understanding the evolution of the conception and creation of complex systems. The authors are especially qualified to write about this subject because of their collective experiences in military systems, space systems, commercial sector systems, sociotechnical systems and fields as varied as education and baseball.

Although the book will be of value to those readers involved in the design of systems that fall outside the realm of what is normally considered engineering, such as business processes, health care, education and other organizational structures, it will be of particular interest to those engaged in systems engineering, the interdisciplinary field of engineering that embraces the design, development and management of complex systems. Originating in the days before WWII, the discipline of systems engineering offers a holistic view of engineering principles and practices, transcending and, yet, incorporating the traditional fields of civil, chemical, electrical, industrial and mechanical engineering as well as the more recent entries of software engineering, information and communication technologies, biotechnology and robotics. Importantly, Bahill and Madni point out to the reader the importance of the user community in the generation of the system requirements, performance measures, the user interfaces to the system operation, the possible human biases and errors in the decision making leading to the planning, design, development and deployment of the system, among other social influences.

The authors describe SIMILAR, an approach to the design and development of system products and processes. SIMILAR is composed of a number of steps that are essential to achieving a higher probability of success in the system development and

implementation. These steps are: *State the Problem*, *Investigate Alternatives*, *Model the System*, *Integrate the System*, *Launch the System*, *Assess Performance*, and *Re-evaluate*. Their successful completion ensures the achievement of the system's requirements throughout its useful life.

As the nations of our global society become more interdependent and more beset with complex and threatening environmental, security and social challenges, among others, the systems needed to confront those challenges will become more difficult to define, create, operate and maintain. Their design, development and deployment will require cooperation and commitment from a broad and diverse set of participants who are characterized by a myriad of cultures, nationalities, languages, religions and backgrounds. System designers will have to know more than science and engineering to develop the organizational structures, processes and arrangements that will be needed to serve the needs of this disparate world population and meet the difficult and demanding requirements of the future. It is to these women and men to whom I commend this book for it offers more than a set of rules and equations to solve a range of system problems. It provides an insight into decision making, tradeoff and risk analysis strategies for those system designers who recognize that we are all part of a pluralistic but fractious society—a multifaceted, global system of people and nations—that is facing daunting issues whose solutions will require talented individuals with the advanced systems thinking abilities and tools put forth in this important book.

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Preface

This book is primarily for seniors and graduate students in engineering and business and professionals interested in acquiring knowledge of three fundamental processes associated with system development—requirements discovery, trade-off studies, and risk analysis. These three important technical areas are covered in a unified manner in this single, easy-to-read volume. This book is organized into seven parts, with each part comprising multiple independent, self-contained chapters. This structure allows both instructors and students to read the chapters in the order of their need, preference, or interest. It can be used as a textbook for a single course covering the three main topic areas or as a reference text for three separate courses, each covering a topic area. This flexibility should appeal to faculty members, students, professional development instructors, and consultants.

This is a learner-centric book. It allows students to access a relevant body of knowledge from a single source rather than scouring multiple volumes to find the needed information. The examples employed to illustrate the use of different methods also discuss potential pitfalls to avoid when using them. The examples are small enough to be cognitively manageable and rich enough to convey key concepts and highlight key aspects of the methods. A strategy that we employed in scoping the illustrative problems was to ensure that each one spanned the process being discussed, rather than resort to multiple, disconnected examples. The continuity provided by having a few illustrative examples that serve as a common thread across the process being discussed is a distinguishing feature of this book that should make it an easy read.

We cover requirements discovery, trade-off studies, and risk analysis—three core processes in system development, product reengineering, and service design and implementation. We specifically address human cognitive biases and heuristics and their implications while executing these processes. We draw attention to the fact that while on the surface these processes appear to be distinctly different, employ different vocabularies, and require different inputs, they have the same underlying structure and process pattern. We exploited this recognition to identify a

general process and thereby reduced the cognitive load on the readers. In other words, learning how to perform one process facilitates the learning of the others.

Requirements discovery, trade-off studies, and risk analysis are critical and recurrent processes that come into play when developing, redesigning, and deploying systems. These processes require human judgment and frequent assessments. And we know that human judgment can be fallible and humans tend to exhibit significant variability arising from cognitive biases and occasional misapplication of heuristics that can throw off carefully planned trade-off studies and risk analyses. To circumvent these outcomes, we offer recommendations on how to exploit heuristics to cope with problem and system complexity and mitigate the effects of cognitive biases when conducting trade-off studies and performing risk analyses. This is another key discriminator of this book.

The requirements for deriving maximum value from this book are quite modest. You need to be conversant in using calculators and Microsoft Excel[®] spreadsheets. Knowledge of modeling languages such as UML and SysML is desirable, but not necessary. Knowledge of basic mathematics is also desirable but not necessary to appreciate the full impact of sensitivity analyses and scoring functions—two key functions employed in trade-off studies. Learners unfamiliar with the underlying mathematics can skip the mathematical material without experiencing lack of continuity. This book invites the reader to explore the richness of requirements discovery, trade-off studies, and risk analyses. The illustrative examples provide a continuous thread through each core process. On rare occasions, the illustrative examples can appear to be somewhat long. However, in those instances that length is necessary to illuminate the different aspects of the methods. Such is the case when making multiple iterations through a process in light of new evidence.

This book reflects our real-world experiences in academia and industry. We have had the rare opportunity to be involved in the early and late stages of development of systems ranging from smart portable devices to missiles, satellite networks, spacecraft, commercial aircraft, and electrical power grids, to command and control of complex system-of-systems. The opportunity to participate in the development of systems of such vastly different scales has given us valuable perspectives that we have shared with you in this volume.

We enjoyed writing and assembling the various chapters of this book with you, the intended audience, in mind. We hope you will find the illustrative examples and homework problems to be informative, *fun*, and insightful. We expect to refine and add to the content based on the feedback we receive from you.

You are about to embark on the journey of unraveling the mysteries and understanding the nuances of requirements discovery, trade-off studies, and risk analysis. We hope that you will find the journey rewarding in understanding and applying the methods. And we hope that the methods will prove to be of value when you are engineering new systems or redesigning existing systems and services.

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Abbreviations and Acronyms

$S_{\alpha}^F = \left. \frac{\partial F}{\partial \alpha} \right _{\text{NOP}}$	Absolute-sensitivity function
$\bar{S}_{\alpha}^F = \left. \frac{\partial F}{\partial \alpha} \right _{\text{NOP}} \frac{\alpha_0}{F_0}$	Relative-sensitivity function
$\tilde{S}_{\alpha}^F = \left. \frac{\partial F}{\partial \alpha} \right _{\text{NOP}} \alpha_0$	Semirelative-sensitivity function
1B	Single
2B	Double
3B	Triple
AC	Alternating current
act	Activity diagram
AHP	Analytic hierarchy process
ATM	Automated teller machine
B	Baseline value
BA	Batting average
BB	Base on balls
bdd	Block definition diagram
BICS	Bahill Intelligent Computer Systems
BIMS	BICS Illuminance Management System
BiST	Built-in self-test
BSA	Boy Scouts of America
CCB	Change control board
CDR	Critical design review
CDRL	Contract deliverable requirements list
CF	Certainty factor
CFL	Compact fluorescent light bulb
CMMI	Capability Maturity Model Integration
ConOps	Concept of operations
CoR	Cost requirement
COTS	Commercial off the shelf
CS	Caught stealing
CuR	Customer requirement

DAR	Decision analysis and resolution
dB	Decibel
DC	Direct current
DD	Difficulty of detection
DeriveReq	Derive requirement
DM	Decision-maker
DoE	Design of experiments
EV	Expected value
F	Frequency of occurrence
FEMA	Failure modes and effects analysis
FoM	Figure of merit
FR	Functional requirement
GDP	Grounded into a double play
GIS	Geographic information system
GNC	Guidance, navigation, and control
GUI	Graphical user interface
HOA	Homeowner association
HR	Homerun
HVAC	Heating, ventilation, and air conditioning
Hz	Frequency in Hertz
ibd	Internal block diagram
IC	Illuminance controller
Id	Identification
IJS	Integers
INCOSE	International Council on Systems Engineering
IR	Infrared
IZ	Inputs to a system
L	Lower threshold
LED	Light-emitting diode
LIMPET	Land Installed Marine Power Energy Transmitter
LP	Launch platform
MAUT	Multi-attribute utility technique
MCAS	Marine Corps Air Station
MCR	Mission concept review
MG	Motor generator
MLB	Major League Baseball
NBA	National Basketball Association
NCAA	National Collegiate Athletic Association
NFL	National Football League
NFPR	Nonfunctional performance requirement
NOAO	National Optical Astronomy Observatory
NOP	Nominal operating point
NZ	Next state function for a system
OCD	Operational concept description

OMG	Object Modeling Group
OZ	Outputs from a system
PAL	Process assets library
par	Parametric diagram
PCB	Printed circuit board
PDR	Preliminary design review
PI	Performance index
PIN	Personal identification number
PRR	Production readiness review
PV	Photovoltaic
QFD	Quality function deployment
R	Risk
R	Runs scored
RA	Risk analyst
RAM	Random access memory
RAM	Rolling airframe missile
RBI	Run batted in
req	Requirements diagram
ReqF	Functional requirement
RF	Radio frequency
RLS	Real numbers
RMS	Royal mail ship
ROE	Reached base on error
RR	Risk requirement
RZ	Readout function for a system
S	Severity of consequences
S	Slope of tangent to the curve at B
SB	Stolen base
sc	Score
sd	Sequence diagram
SEMP	Systems engineering management plan
SEU	Subjective expected utility
SH	Successful bunt
SI	Système International d'Unités
SO	Strikeout
SR	Schedule requirement
SRR	System requirements review
SSF	Standard scoring function
stm	State machine diagram
SysML	Systems Modeling Language
SZ	States of a system
TBD	To be determined
TEP	Tucson Electric Power
TPM	Technical performance measure

TRR	Test readiness review
TST	Total system test
uc	Use case diagram
UML	Unified Modeling Language
UofA	University of Arizona
v	Value of the input
V&V	Verification and validation
VLS	Vertical launch system
w	Weight
Z	System

About the Authors



A. Terry Bahill is professor emeritus of systems and industrial engineering at the University of Arizona in Tucson. He received his Ph.D. in electrical engineering and computer science from the University of California, Berkeley, in 1975. He is the author of six engineering books and 250 papers; over 100 of these are in peer-reviewed scientific journals. Bahill has worked with dozens of technical companies presenting seminars on systems engineering, working on system development teams, and helping them to describe their systems engineering processes. He holds a US patent for the Bat Chooser™, a system that computes the Ideal Bat Weight™ for individual baseball and softball batters. He was elected to the Omega Alpha Association,

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