# 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: *S*tate the Problem, *I*nvestigate Alternatives, *M*odel the System, *I*ntegrate the System, *L*aunch the System, *A*ssess Performance, and *R*e-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 multi-faceted, 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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John Brooks Slaughter

# 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.

Tucson, AZ — A. Terry Bahill
Los Angeles, CA — Azad M. Madni

# Acknowledgments

We thank Edwin Ordoukhanian for writing the scoring function toolbox program and for managing the references for this textbook and providing feedback from a student's perspective. Edwin is pursuing his doctorate in astronautical engineering under Professor Madni's direction at the University of Southern California. We thank Ken Cureton at the University of Southern California for reviewing the book.

# Contents

# Abbreviations and Acronyms

| | |
|---|---|
| $S_\alpha^F = \frac{\partial F}{\partial \alpha}\big\vert_{\text{NOP}}$ | Absolute-sensitivity function |
| $\overline{S}_\alpha^F = \frac{\partial F}{\partial \alpha}\big\vert_{\text{NOP}} \frac{\alpha_0}{F_0}$ | Relative-sensitivity function |
| $\widetilde{S}_\alpha^F = \frac{\partial F}{\partial \alpha}\big\vert_{\text{NOP}} \alpha_0$ | 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 |
| DeriveReqt | 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 | Systeme International d'Unites |
| 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, the systems engineering honor society. He received the Sandia National Laboratories Gold President's Quality Award. He is an elected fellow of the Institute of Electrical and Electronics Engineers (IEEE), of Raytheon Missile Systems, of the International Council on Systems Engineering (INCOSE), and of the American Association for the Advancement of Science (AAAS). He is the founding chair emeritus of the INCOSE Fellows Committee. His picture is in the Baseball Hall of Fame's exhibition "Baseball as America." You can view this picture at http://www.sie.arizona.edu/sysengr/. His research interests are in the fields of system design, modeling physiological systems, eye-hand-head coordination, human decision-making, and systems engineering application and theory. He has tried to make the public appreciate engineering research by applying his scientific findings to the sport of baseball.

**Azad M. Madni** is a Professor of Astronautical Engineering and the Technical Director of the Systems Architecting and Engineering Program in the University of Southern California's Viterbi School of Engineering. He is also a Professor (by courtesy) in USC's Schools of Medicine and Education. He is the founder and Chairman of Intelligent Systems Technology, Inc., a high tech R&D company specializing in game-based educational simulations, and methods, processes and tools for complex systems engineering. He received his B.S., M.S. and Ph.D. degrees from the University of California, Los Angeles. His research has been sponsored by both government research organizations such as DARPA, OSD, ARL, RDECOM, ONR, AFOSR, DHS S&T, DTRA, NIST, DOE and NASA, and aerospace and automotive companies such as Boeing, Northrop Grumman, Raytheon and General Motors. He is an elected Fellow of the American Association for Advancement of Science (AAAS), the American Institute for Aeronautics and Astronautics (AIAA), the Institute for Electrical and Electronics Engineers (IEEE), the Institution for Electronics and Telecommunications Engineers (IETE), the International Council on Systems Engineering (INCOSE) and the Society for Design and Process Science (SDPS). His recent awards include *2016 Boeing Lifetime Accomplishment Award* and *2016 Boeing Visionary Systems Engineering Leadership Award* for contributions to industry and academia (awards received in Boeing's 100th anniversary); the 2016 INCOSE RMC Special Award for pioneering, industry-relevant contributions to Transdisciplinary Systems Engineering; the *2016 Distinguished Engineering Educator Award* from the Engineers' Council; the *2016 Outstanding Educator Award* from the Orange County Engineering Council; the 2014 *Lifetime Achievement Award* from the International Council on Systems Engineering; the 2013 *Innovation in Curriculum Award* from the Institute of Industrial Engineers; the 2012 *Exceptional Achievement Award* from INCOSE and the 2011 *Pioneer Award* from the International Council on Systems Engineering. He serves on the USC's Council of the Center of Cyber-Physical Systems and Internet of Things (CCI), and Steering Committee of USC Provost's STEM Consortium. His research interests include formal and probabilistic methods in systems engineering, model-based architecting and engineering, engineered resilient systems, cyber-physical systems, and exploiting disciplinary and technology convergence in systems engineering. He is listed in Who's Who in Science and Engineering, Who's Who in Industry and Finance and Who's Who in America.