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FOREWORD

Though many may not recognize it as such, we live in the systems age. Those engaged with systems engineering understand the challenges and opportunities of today and tomorrow are truly systems challenges. On the grand scale, we must address clean energy, clean water, food, resource allocation, health care, and more. None would argue that these are systems engineering challenges, but they are systems challenges indeed. On a somewhat smaller scale, we see unprecedented opportunities fueled by the ever-increasing rate of technology infusion and the opportunity to connect existing systems in new and novel ways. Our stakeholders demand more from us, and technology allows us to deliver: end-to-end connected transportation enabled by autonomous vehicles; new efficiencies in energy generation, storage, and distribution unlocked by new sensor technologies and insights from big data; innovations in personal health care through wearables and other technologies.

Scientists, architects, specialists, and engineers of all types collaborate in a wide range of complicated and often complex situations to address issues and deliver against stakeholder demands with upgraded and innovative systems. As Randy Pausch reminded us in *The Last Lecture*, "engineering is not about perfect solutions, it's about doing the best you can with limited resources." In this quest to serve our customers and stakeholders, the fundamental purpose of systems engineering is neither process, enabler, specification, nor any other tool or artifact. Systems engineering is charged with delivering the required value in an effective and efficient manner, making the best possible use of the resources available. In doing so, making the inevitable trade-offs should not be treated as a necessary evil. Informed trade-offs based on appropriate analysis properly performed are a critical enabler delivering the required value efficiently and effectively. They are a key tool in our systems engineering toolbox – one that we must embrace and improve.

Systems engineering and all those who practice it are connectors, and connecting diverse approaches across multiple perspectives requires these trade-offs, both large and small. In connecting processes and analytics to properly understand the true problem and architect the right solution, what processes do we select and what level of fidelity do we pursue to balance investment made with value delivered? In assessing both the problem space and the possible solution space, how do we prioritize the "right" blend of desires, constraints, approaches, technologies, and specialties necessary to solve the problem within the bounds of capability, schedule, and budget? Looking to the evolution of the environment and our solution, what resilience and adaptability must we account for and what range of sensitivity can we accept?

As we continue to embrace and expand systems practices across diverse communities, our problems move from the complicated to the complex. We engage an even broader range of subject matter experts with their particular perspectives, tools, and techniques. We have greater technical, economic, and social considerations as we address both bounded problems with defined requirements and fuzzy problems characterized by market behaviors and stakeholder concerns. As the scope continues to expand, these questions become more challenging. Properly performing trade-off analysis from problem definition through ultimate solution delivery becomes even more critical.

In this text, Parnell et al. bring together in a systems engineering context the fundamental foundations, the processes and principles, the techniques and examples necessary to help us perform better trade-off analyses. They recognize the broad scope including cost, value, schedule, and risk drivers and provide tools to deal with the inherent uncertainty within which systems engineers operate. Put simply, Parnell and his colleagues provide a complete and cohesive treatment of this critical enabler for systems engineering, moving us from sometimes disjoint, ad hoc approaches to an informed, disciplined approach to explicitly define our decision opportunities and alternatives in the journey to making better decisions.

As we connect teams and technologies to better meet stakeholder needs in an ever-evolving environment, it is not a question of whether or not we perform trade-off analysis. It is a question of how well we do so: whether we make errors of omission and commission, whether we are implicit or explicit, whether we rely on unsound approaches or informed practices. All those who practice systems engineering serve as the "guardians of why," balancing multiple options and considerations as we collaborate with others to match the right solution to the real problem. Through informed trade-off analysis, we better leverage the talents, techniques, insights, and perspectives of those around us, ultimately driving better decisions and enabling the delivery of systems to meet the diverse and complex challenges of today and tomorrow.

David Long
President, Vitech Corporation
INCOSE President (2014 & 2015)

PREFACE

NEED FOR MORE EFFECTIVE TRADE STUDIES

Today's complex systems are multidisciplinary systems involving challenging missions, advanced technologies, significant uncertainties, and multiple stakeholders with conflicting objectives. Decision-making is central to generating creative alternatives, creating value, managing risks, and meeting affordability goals. Systems engineering trade-offs are needed throughout the system life cycle to inform these system decisions. In the absence of a formal framework, trade-off studies are sometimes performed in an ad hoc manner. Also, some systems engineers may not have an in-depth understanding of trade-off analysis techniques. As a result, some use unsound techniques.

This project began with a need identified by a professional society. The International Council on Systems Engineering (INCOSE) (www.incose.org) has nearly 10,000 members and about 95 members of its Corporate Advisory Board. The INCOSE Corporate Advisory Board documented the need for more effective trade studies. They believed there was a lack of best practices information that crossed the life cycle and aligned with ISO standard (ISO/IEC/IEEE 15288, 2015), the Systems Engineering Handbook (INCOSE, 2015), and the Systems Engineering Body of Knowledge (SEBok, Systems Engineering Body of Knowledge (SEBoK), 2015).

This textbook presents a Decision Management process based on decision theory and cost analysis best practices and is aligned with ISO/IEC 15288, the Systems Engineering Handbook, and the Systems Engineering Body of Knowledge. We introduce key concepts and demonstrate these trade-off analysis concepts in the different life cycle stages using illustrative examples from defense and commercial domains.

AUDIENCE

The audience for this book are graduate students (systems engineering, industrial engineering, engineering management, other engineering disciplines); professional systems engineers, operations analysts, project managers, and engineering managers; and undergraduate students (systems engineering, industrial engineering, engineering management, other engineering disciplines). We assume that the reader has had an introduction to systems engineering, an undergraduate knowledge in probability and statistics, a course in systems modeling, and a course in engineering economy and/or life cycle cost. However, Chapter 3 reviews probability and Chapter 4 presents important resource analysis techniques required for cost analysis and affordability analysis.

THEMES

We had several major themes that provided the foundation for this book.

1. **Use standard SE terminology.** We have attempted to use terminology from the ISO standard (ISO/IEC/IEEE 15288, 2015), the Systems Engineering Handbook (INCOSE, 2015), and the Systems Engineering Body of Knowledge (SEBok, Systems Engineering Body of Knowledge (SEBoK) wiki page, 2015).
2. **Avoid trade-off analysis mistakes of omission and commission.** The mistakes of omission are errors made by not doing the right things. The mistakes of commission are errors made by doing the right things the wrong way.
3. **Use a decision management process.** Systems decisions are made throughout the life cycle. Many of these systems decisions are difficult decisions that include multiple competing objectives, numerous stakeholders, substantial uncertainty, significant consequences, and high accountability. These decisions can benefit from a structured decision management process.
4. **Use decision analysis as the mathematical foundation for trade-off analyses.** A credible trade-off analysis should be based on a sound mathematical foundation. Ad hoc methods and unsound mathematics provide a base of sand for a trade-off study and, therefore, a base of sand for the decision-makers. Since trade-off studies involve complex alternatives, multiple objectives, and major uncertainties, we believe that decision analysis is the operations research technique that provides this sound mathematical foundation for trade-off analyses.
5. **Explicitly define the decision opportunity.** Every trade-off study begins with an implicit understanding of the problem or opportunity. The initial problem is never the final problem. It is important to clearly define the decision problem as a broader decision opportunity.
6. **Identify and structure decision objectives and measures.** Once the opportunity is explicitly identified, the next step is to identify and structure the decision objectives of the decision-makers and stakeholders. The decision

opportunity and stakeholder values determine the objectives. Measures that align with the objectives are required to perform the trade-off analysis.

7. **Develop creative, doable alternatives.** The key to trade-off analysis is developing good alternatives that span the tradespace. The generation of the tradespace is a critical trade-off analysis task that requires participation of the entire trade-off analysis team and support from decision-makers, stakeholders, and subject matter experts.
8. **Include resource analysis in the trade-off analysis.** Organizations do not have unlimited resources. Therefore, affordability analysis is almost always a critical part of the trade-off analysis.
9. **Explicitly consider uncertainty.** Systems development, deployment, operation, and retirement involve many uncertainties. The systems life cycle may be years to decades. The major uncertainties include technology performance, integration with other systems, markets/missions, environments, and the actions of competitors/ adversaries.
10. **Identify the cost, value, schedule, and risk drivers**. The purpose of a trade-off analysis is to provide insights for system decision-making. Decision-makers need to understand the cost, value, schedule, and risk drivers of the system.
11. **Provide an integrated for cost, value, and risk analysis.** Unfortunately, most of the current systems engineering practice develops and performs separate cost, value, and risk analyses. We recommend an integrated framework for cost, value, and risk analysis.

BOOK ORGANIZATION

The book is organized into three sections and a summary (Figure 1). The first section discusses the trade-off analysis foundations. Chapter 1 provides an introduction to trade-off analysis and includes common mistakes of commission and omission made in trade studies. Chapter 2 provides a conceptual framework for trade-off analysis and presents key decision theory concepts required for a sound mathematical foundation. As mentioned earlier, Chapter 3 reviews probability and Chapter 4 presents resource analysis techniques and affordability analysis.

The Decision Management process is presented in the second section of the book. Chapter 5 introduces the INCOSE Decision Management process and provides a detailed illustrative example of the process. Chapter 6 provides the principles and techniques for identifying the decision opportunity that the trade-off analysis supports. Chapter 7 provides principles and techniques for identifying objectives and value measures that assess how well the alternatives meet the objectives. These measures are the foundation for assessing the trade-offs. Chapter 8 reviews and evaluates the techniques for generating and evaluating alternatives. Many of these techniques are illustrated in the third section of the book. Chapter 9 illustrates a model for trade-off analysis that integrates value and cost analysis.

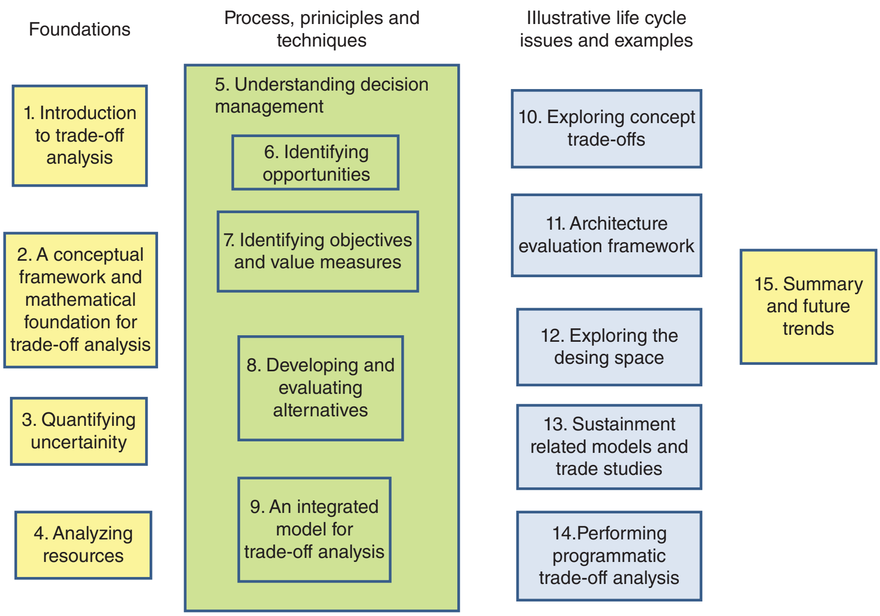

Figure 1 Organization of the book

The third section provides trade-off analysis issues and illustrative examples in the life cycle stages. The scope and information available for trade-off analysis are different in each life cycle stage. Chapter 10 presents trade-off analysis methods to explore the trade-offs in the early life cycle stages when many system concepts and architectures need to be evaluated to determine the most affordable concept for further development. Chapter 11 presents processes and techniques for evaluating system architectures. Chapter 12 presents illustrative examples for system design trade-off analysis. Chapter 13 presents an illustrative sustainment model with deterministic and probabilistic analysis. Chapter 14 provides several illustrative examples of programmatic trade-offs that focus on system acceptance and termination.

Chapter 15 summarizes the major themes of the book and identifies some potential trends that may impact trade-off analyses in the future.

COURSE OUTLINES USING THE TEXTBOOK

In this section, we offer some possible course outlines that could be developed using this textbook. Of course, the content presented in the course should be selected based on the academic/professional education program objectives and the course objectives.

We present a notional set of course objectives and offer some potential course outlines.

NOTIONAL COURSE OBJECTIVES

1. Understand the role of trade-off analyses to support system decisions in each stage in the system life cycle.
2. Identify and avoid the mistakes of omission and commission in trade-off analysis.
3. Understand and use decision analysis as the mathematical foundation for trade-off analysis.
4. Understand the sources of uncertainty in the system life cycle and be able to identify, assess, and model uncertainty using probability.
5. Understand the advantages and disadvantages of common systems engineering approaches used to generate and evaluate system alternatives.
6. Identify and structure stakeholder objectives and develop single objective and multiobjective decision analysis models to evaluate alternatives.
7. Identify and define a system decision opportunity that requires a trade-off analysis.
8. Understand the advantages and disadvantages of tradespace exploration techniques for trade-off analysis of concepts, architectures, designs, operations, and retirement.
9. Understand the need for an integrated decision model that incorporates design features, value, cost, and risk.
10. Perform a trade-off analysis using the INCOSE Decision Management Process using both deterministic and probabilistic techniques.
11. Communicate the insights of a trade study and the important trade-offs to senior stakeholders and decision-makers.

ILLUSTRATIVE ACADEMIC COURSE OUTLINES

In addition to the course objectives, the coverage of course topics will depend on the role of the course in the curriculum (required or elective), the prerequisites, the location of the course (early or late in program), and the type of course (lecture, project, or combined). The textbook could be used to prepare for a capstone design course. The textbook presents more material that can probably be covered in a one semester course. I would recommend covering all of Chapters 1, 2, 5–7. The instructor would select the sections to read for other chapters. Depending on the academic curriculum, Chapters 3 and 4 could be reviewed or covered in more detail.

Week	Systems Analysis Project Course	System Design Project Course	Systems Analysis Lecture Course
Pre-reqs	Undergrad probability and statistics	Undergrad probability and statistics	None
1	Introduction (Chapter 1)	Introduction (Chapter 1)	Introduction (Chapter 1)
2	Framework and Mathematical Foundations (Chapter 2)	Framework and Mathematical Foundations (Chapter 2)	Framework and Mathematical Foundations (Chapter 2)
3	Uncertainty (Chapter 3)	Uncertainty (Chapter 3)	Uncertainty (Chapter 3)
4	Resource Analysis (Chapter 4)	Resource Analysis (Chapter 4)	Uncertainty (Chapter 3)
5	Decision Management Process I (Chapter 5)	Decision Management Process I (Chapter 5)	Resource Analysis (Chapter 4)
6	Decision Management Process II (Chapter 5)	Opportunity Definition (Chapter 6)	Resource Analysis (Chapter 4)
7	Opportunity Definition (Chapter 6)	Objectives and Measures (Chapter 7)	Decision Management Process II (Chapter 5)
8	Objectives and Measures (Chapter 7)	Class Project – Opportunity Presentations	Opportunity Definition (Chapter 6)
9	Class Project – Opportunity Presentations	Generation and Evaluation of Alternatives (Chapter 8)	Objectives and Measures (Chapter 7)
10	Generation and Evaluation of Alternatives (Chapter 8)	Integrated Value, Cost, and Risk Analysis (Chapter 9)	Generation and Evaluation of Alternatives (Chapter 8)
11	Integrated Value, Cost, and Risk Analysis (Chapter 9)	Concept Evaluation (Chapter 10)	Integrated Value, Cost, and Risk Analysis (Chapter 9)
12	Concept and Architecture Evaluation (Chapters 10 & 11)	Architecture Evaluation (Chapter 11)	Concept Evaluation (Chapter 10)
13	Design Evaluation (Chapter 12)	Design Evaluation (Chapter 12)	Architecture Evaluation (Chapter 11)
14	Sustainment Trade-Offs (Chapter 13)	Design Evaluation (Chapter 12)	Design Evaluation (Chapter 12)
15	Programmatic Trade-Offs (Chapter 14)	Sustainment Trade-Offs (Chapter 13) Programmatic Trade-Offs (Chapter 14)	Sustainment Trade-Offs (Chapter 13)
16	Class Project – Trade-off Analysis Presentations (Chapter 15)	Class Project – Trade-off Analysis Presentations (Chapter 15)	Programmatic Trade-Offs (Chapter 14) Summary (Chapter 15)

ILLUSTRATIVE PROFESSIONAL SHORT COURSE OUTLINE

The textbook can also be used as a textbook/reference for professional short courses. The topics presented in the course would depend on the needs of the organization and the students' academic and professional backgrounds. The course could be taught as a seminar to present new material or as a project course with student's applying the material they learn in the course on a notional trade-off analysis or trade-off analyses they are working or will work in the future. The following outline is for a 1-week project course with trade-off analysis modeling using notional data (provided to students or developed by students).

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning	Introduction (Chapter 1) Framework and Mathematical foundations (Chapter 2)	Decision Management Process I (Chapter 5)	Resource Analysis (Chapter 4)	Concept and Architecture Evaluation (Chapters 10 & 11)	Sustainment Trade-Offs (Chapter 13)
	Opportunity Definition (Chapter 6)	Decision Management Process II (Chapter 5)	Uncertainty (Chapter 3) Monte Carlo Simulation	Design Evaluation (Chapter 12)	Programmatic Trade-Offs (Chapter 14)
Afternoon	Objectives and Measures (Chapter 7)	Generation and Evaluation of Alternatives (Chapter 8)	Integrated Value, Cost, and Risk Analysis (Chapter 9)	Class Project – Development of Notational Life Cycle Cost Model	Class Project – Monte Carlo Simulation of Value and Cost Models
	Class Project – Opportunity Presentation	Class Project – Generation of Alternatives	Class Project – Development of Notional tradespace Exploration Model	Class Project – Integration of Cost and Value Model	Class Project – Trade-Off Analysis Presentations (Chapter 15)

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Editor
University of Arkansas
Fayetteville, AR
September 2016

REFERENCE

ISO/IEC/IEEE 15288 (2015). *Systems and Software Engineering – System Life Cycle Processes*, International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC)/Institute of Electrical and Electronics Engineers (IEEE), Geneva, Switzerland.

SEBoK (2015). Systems Engineering Body of Knowledge (SEBoK) wiki page. SEBoK: http://www.sebokwiki.org (accessed 06 June 2016).

ACKNOWLEDGMENTS

The development and writing of this book was an intense 1-year team effort by 18 contributors. As the editor, I would like to acknowledge some special contributions.

INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE) CORPORATE ADVISORY BOARD (CAB)

The INCOSE CAB identified the need for more effective trade studies as one of their top five needs. **Garry Roedler** (one of the contributors) was CAB Chair when the need was identified. **Max Berthold,** the next CAB Chair, has continued the support. This book is one of the INCOSE activities to help meet this need. The INCOSE CAB has reviewed our plan for the book, and three INCOSE CAB representatives have become chapter authors, including **Azad Madni**, **Cliff Whitcomb**, and myself.

INCOSE TECHNICAL DIRECTORS

The Technical Director is a voting member of the INCOSE Board of Directors and has functional responsibility for Technical Operations. As the Technical Director at the time, **Bill Miller** (later one of our contributors) assigned this need to the INCOSE Decision Analysis Working Group. **Paul Schreinemakers**, the next Technical Director, has continued to support our effort.

INCOSE DECISION ANALYSIS WORKING GROUP

The INCOSE Decision Analysis Working Group, led by **Frank Salvatore**, has played a central role. Frank has supported our entire effort including the Decision

Management input to the Systems Engineering Handbook, the Decision Management input to the Systems Engineering Body of Knowledge (SEBoK), and using working group meetings to recruit chapter authors, provide feedback on the book plan, and recruit chapter reviewers. **Matt Cilli** (chapter author) developed the Decision Management framework for the SE Handbook and SEBoK and provided more useful information on the framework in Chapter 5. **Clifford Marini** spearheaded all the computer code development efforts needed to generate many of the visualizations used in the examples of Chapter 5.

CHAPTER AUTHORS

\looseness=-1{}The chapter authors are systems engineering thought leaders and fully employed with senior academic, corporate, or government positions (see About the Authors). The role of the chapter authors was much more than writing their chapters. The authors provided recommendations on the content of the book, and each author has peer-reviewed one or two chapters, revised their chapters based on my reviews, and the reviews of two internal reviewers (authors of other chapters) and two external reviewers. Several authors contributed to more than one chapter. Based on when I received emails, most of their work on the book was done at night and on the weekends.

CHAPTER REVIEWERS

Our goal was to have every chapter reviewed by an academic and a practitioner who had not been participating in the book project. We asked for and received very helpful reviews. Many times, these reviews caused the authors to add material or reorganize the chapter to be clearer. The following individuals provided valuable chapter reviews that improved the quality of the book: Tyson Browning, Roger Burk, Chuck Ebeling, Tony Farina, Paul Garvey, Melissa Garber, Daniel McCarthy, Kim Needy, George Rebovich, Frank Salvatore, James “Jed” Richards, Valarie Sitterle, Gerardo Siva, Michael Vinarcik, and Adam Whitlock.

DEPARTMENT OF INDUSTRIAL ENGINEERING AT THE UNIVERSITY OF ARKANSAS

I would like to acknowledge the support of my department head, **Ed Pohl** (also a chapter author), who supported my participation in this project and provided a research assistant to help with the effort.

RESEARCH ASSISTANT

This book would not have been possible in 1 year without the dedicated help of **Andres Vargas**, my research assistant for the past year. Andres performed

an excellent literature search that provided references for all chapter authors. In addition, he performed many of the tasks required to align each chapter to the final format in the book. He is also preparing the solutions manual and the Excel files that will be provided on the Wiley book site.

FINAL NOTE

Any remaining errors of omission or commission are of course my responsibility.

Gregory S. Parnell, PhD, INCOSE Fellow
Editor
University of Arkansas
September 2016

ABOUT THE COMPANION WEBSITE

This book is accompanied by a companion website:
www.wiley.com/go/Parnell/Trade-off_Analytics

The website includes:

- An instructor website with a solutions manual
- A student website with Excel files

1

INTRODUCTION TO TRADE-OFF ANALYSIS

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> The complexity of man-made systems has increased to an unprecedented level. This has led to new opportunities, but also to increased challenges for the organizations that create and utilize systems.
>
> (ISO/IEC/IEEE 15288, 2015)

Trade-off Analytics: Creating and Exploring the System Tradespace, First Edition. Edited by Gregory S. Parnell.

Companion website: www.wiley.com/go/Parnell/Trade-off_Analytics

1.1 INTRODUCTION

This book is about trade-off analyses in the life cycle of a system. It is written from the perspective of engineers, systems engineers, and other decision-makers involved in the life cycle of a system. In this book, we present the best practices for performing systems engineering trade-off analyses in a step-by-step, structured manner. Our intent is to make it an easy-to-understand and useful reference for students, practitioners, and researchers.

Systems are developed to create value for stakeholders by providing desired capabilities. Stakeholders include investors, government agencies, customers/acquirers, end users/operators, system developers/integrators, trainers, and system maintainers, among others. Decisions are ubiquitous across the system life cycle. System decision-makers (DMs) are those individuals who make important decisions pertaining to the technical and management compromises that shape the concept definition, system definition, system realization, deployment and use, and product and service life management (including maintenance, enhancement, and disposal).

When there are multiple stakeholders, there are often competing objectives and requirements. To achieve a certain attainment level on one objective, a sacrifice or trade-off may be required in the attainment level of other objectives. Similarly, complex system designs may offer multiple alternatives to achieve the system's objectives, and this, too, requires analysis to achieve the best balance among the trade-offs. The process that leads to a reasoned compromise in these situations is commonly referred to as a "trade-off analysis" or a "trade study."

This book project began with a request by the International Council on Systems Engineering (INCOSE) (INCOSE Home Page, 2015) Corporate Advisory Board (CAB) to the INCOSE Decision Analysis Working Group. The CAB identified the lack of effective trade-off analysis methods as a key concern and requested help in documenting best practices. This book project was also motivated by the need to formalize systems engineering trade-off analysis to help make it an integral part of the systems engineering life cycle. It provides essential elaboration of the decision management process in ISO/IEC/IEEE 15288, Systems and Software Engineering – System Life Cycle Processes, the INCOSE Systems Engineering Handbook Version 4, and the Systems Engineering Body of Knowledge (SEBoK, 2015).

Decision-makers (DM), especially program managers and systems engineers, stand to benefit from a collaborative decision management process that engages all stakeholders (SH) who have a say in system design decisions. In particular, systems engineers can exploit trade-off studies to help define the problem/opportunity, characterize the solution space, identify sources of value, identify and evaluate alternatives, identify risks, acquire insights, and provide recommendations to system SHs and other DMs.

This book focuses on engineering trade-off analysis techniques for both systems and systems of systems (Madni and Sievers, 2014a,b; Ordoukhanian and

Madni, 2015). We recommend that trade-off studies be consistent with SE standards (ISO/IEC/IEEE 15288:2015), based on a formal lexicon, have a sound mathematical foundation, and provide credible and timely data to DMs and other SHs. We provide such a lexicon and a formal foundation (Chapter 2) based on decision analysis for effective and efficient trade-off studies. Our approach supplements decision analysis, a central part of decision-based design (Hazelrigg, 1998), with Value-Focused Thinking (Keeney, 1992) within a model-based engineering framework (Madni & Sievers, 2015).

1.2 TRADE-OFF ANALYSES THROUGHOUT THE LIFE CYCLE

New system development entails a number of interrelated decisions. Table 1.1 provides a partial list of decisions opportunities to improve the system value that are commonly encountered throughout a system's life cycle. Many of these decisions stand to benefit from a holistic perspective that combines the systems engineering discipline with a composite decision model that aggregates the data produced by engineering, performance, and cost models and translates them into terms that are relevant and meaningful to the various stakeholders, especially DMs. This holistic perspective is especially valuable in gate (go/no-go funding) decisions to ensure that affordable alternatives are available for the next life cycle stage.

1.3 TRADE-OFF ANALYSIS TO IDENTIFY SYSTEM VALUE

Systems provide value through the capabilities they provide or the products and services they enable (Madni, 2012). Decision analysis is an operations research technique that provides models to define value and a sound data-driven, objective, defensible, mathematical foundation for trade-off analyses. The graphic shown in Figure 1.1 helps visualize the importance of opportunity definition (Chapter 6) to value creation. For example, Chevron uses the "Eagle's Beak ", as shown in this figure, to convey the importance of project definition and project execution. The five phases shown in Figure 1.1 constitute the project life cycle used by Chevron (Lavingia, 2014). The process leads to value identification and value realization. At Chevron, decision analysis plays an important role in the three phases of value identification: identify opportunity; generate and select alternatives; and develop the preferred opportunity. The Chevron process employs stages and gates similar to those found in most system life cycles. Each phase consists of activities that produce information; clearly defined deliverables; and an explicit decision to proceed, exit, or recycle. Chevron employs project management in all five phases of the Chevron Project Development and Execution Process (Decision-Making in an Uncertain World: A Chevron Case Study, 2014). Similarly, for the system life cycle, value

Table 1.1 Partial List of Decision Opportunities throughout the Life Cycle

Life Cycle Stage	Decision Opportunity
Exploratory research	Assess technology opportunity/initial business case • Of all the potential system concepts or capabilities that could incorporate the emerging technology of interest, do any offer a potentially compelling and achievable market opportunity? • Of those that do, which should be pursued, when, and in what order?
Concept	Inform, generate, and refine a capability • What requirements should be included? What are the desired parameters? • What really needs to be accomplished and what is able to be traded away to achieve it within anticipated cost and schedule constraints? • How should requirements be expressed such that they are focused yet flexible? • How can the set of requirements be demonstrated to be sufficiently compelling while at the same time achievable within anticipated cost and schedule constraints? • Which concepts are affordable?
	Create solution class alternatives and select preferred alternative • After considering the system-level consequences of the sum of solution class alternatives across the full set of stakeholder values (to include cost and schedule), which solution class alternative should be pursued? • Is the solution class still affordable?
Development	Select/define system elements • After considering the system-level consequences of the sum of system element design choices across the full set of stakeholder values (to include cost and schedule), which system element alternatives should be pursued? (Repeated for each recursive level of the system structure.)
	Select/design verification and validation methods • Is prototyping warranted? • What verification and validation methods should be performed (test, demonstration, analysis/simulation, inspection)? • What are the verification and validation plans?

(*continued overleaf*)

Table 1.1 ***(Continued)***

Life Cycle Stage	Decision Opportunity
Production	Craft production plans • What is the target production rate? • To what extent will low-rate initial production be utilized? • What is the ramp-up plan? • What production process will be used? • Who will produce the system? • Where will the system be produced? • Is the system still affordable?
Operation, support	Generate maintenance approach • What is the maintenance strategy? • What is the logistics concept? • What is the preventive-maintenance plan? • What is the corrective-maintenance plan? • What is the spare-parts plan? • Is the system still affordable?
Retirement	Retirement plan • When is it time to retire the system? • How will disposal of materials be accomplished?

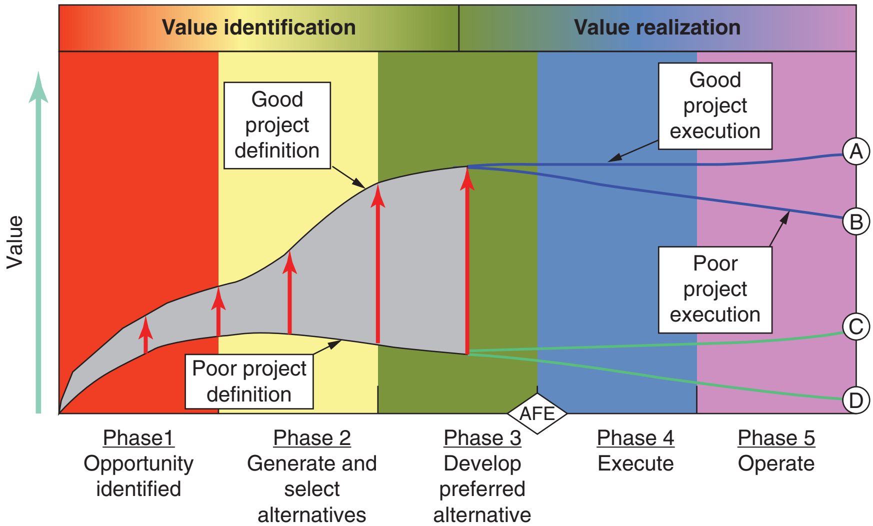

Figure 1.1 Eagle's beak chart

identification occurs during the concept definition and system definition phases, and decision analysis plays the same important role.

Figure 1.1 highlights five important points. First, the problem or opportunity definition (see Chapter 6) is an important first step in value identification. Second, the generation of good alternatives (see Chapter 8) is critical to identifying higher value. Third, the development, evaluation, and selection of preferred alternatives can significantly increase value. Fourth, good project execution is required to realize potential value. Fifth, project execution is performed in the face of uncertainties (see Chapter 3). In this book, we focus on the value of using trade-off studies to help in the identification of both value and risk, as the timely identification of risk can help implementers mitigate potential barriers to value realization.

1.4 TRADE-OFF ANALYSIS TO IDENTIFY SYSTEM UNCERTAINTIES AND RISKS

System risks can affect performance, schedule, and cost. Building on several frameworks, Table 1.2 provides a list of the sources of systems risk (Parnell, 2009). The first column in Table 1.2 lists the potential source of risk. The second column lists the major questions defining the risk. The third column lists some of the major potential uncertainties for this risk source. The major questions and the uncertainties are meant to be illustrative and not all inclusive. Many of these risks create uncertainties, which should be considered in trade-off analyses. Chapter 3 provides techniques for using probability to model these uncertainties in trade-off analyses. Later chapters explicitly consider these uncertainties in illustrative trade-off analyses.

1.5 TRADE-OFF ANALYSES CAN INTEGRATE VALUE AND RISK ANALYSIS

Program managers for the development of a new system must consider performance, cost, and schedule, as they are all interrelated. We know that performance problems can cause cost increases and schedule delays. Similarly, schedule changes can increase costs. Finally, cost estimate increases can result in reduced performance targets or schedule delays to make the system more affordable. Trade-off analysis, cost analysis, and risk analysis are frequently separate analyses performed by different analysts. Cost analysts typically perform a cost-risk analysis using Monte Carlo simulation. Many trade-off studies ignore uncertainty and risk.

A major theme of this book is that trade-off analyses should be used to identify both system value and system risks and that the analysis needs to be performed in a more integrated manner. In Chapter 9, we discuss and provide examples of how system value, system costs, and system risks can be integrated by identifying the system features that impact value, cost, and risk.

Table 1.2 Sources of Systems Risk

Sources of Risk	Major Questions	Potential Uncertainties
Business	Will political, economic, labor, social, technological, environmental, legal, or other factors adversely affect the business environment?	Changes in political viewpoint (e.g., elections) Economic disruptions (e.g., recession) Global disruptions (e.g., supply chain) Changes to law Disruptive technologies Adverse publicity
Market	Will there be a market if the product or service works?	Consumer demand Threats from competitors (quality and price) and adversaries (e.g., hackers and terrorists) Continuing stakeholder support
Performance (technical)	Will the product or service meet the required/desired performance?	Defining future requirements in dynamic environments Understanding technical baseline Technology maturity to meet performance. Adequate modeling, simulation, test, and evaluation capabilities to predict and evaluate performance Impact to performance from external factors (e.g., interoperating systems) Availability of enabling systems needed to support use
Schedule	Can the system that provides the product or service be delivered on time?	Concurrency in development Impact of uncertain events on schedule Time and budget to resolve technical and cost risks
Development and production cost	Can the system be delivered within the budget? Will the cost be affordable?	Changes in concept definition (mission or needs) Technology maturity Stability of the system definition Hardware and software development processes Industrial/supply chain capabilities Production/facilities capabilities Manufacturing processes
Management	Does the organization have the people, processes, and culture to manage a major system?	Organization culture SE and management experience and expertise Mature baselining (technical, cost, schedule) processes Reliable cost-estimating processes

(*continued overleaf*)

Table 1.2 (*Continued*)

Sources of Risk	Major Questions	Potential Uncertainties
Operations and support cost	Can the owner afford to operate and support the system?	Increasing operations and support (e.g., resource or environmental) costs Trades of performance versus ease/cost of operations and support Adaptability of the design Changes in maintenance or logistics strategy/needs
Sustainability	Will the system provide sustainable future value?	Availability of future resources and impact on the natural environment

1.6 TRADE-OFF ANALYSIS IN THE SYSTEMS ENGINEERING DECISION MANAGEMENT PROCESS

Successful systems engineering requires sound decision making. Many systems engineering decisions are difficult because they include multiple competing objectives, numerous stakeholders, substantial uncertainty, significant consequences, and high accountability. In these cases, sound decision making requires a formal decision management process. The purpose of the decision management process, as defined by ISO/IEC/IEEE 15288:2015, is " … to provide a structured, analytical framework for objectively identifying, characterizing and evaluating a set of alternatives for a decision at any point in the life cycle and select the most beneficial course of action." The process presented in this book aligns with the structure and principles of the decision management process of ISO/IEC/IEEE 15288, the INCOSE Systems Engineering Handbook v4.0 (INCOSE, 2015), the Systems Engineering Body of Knowledge (SEBoK), and an INCOSE proceedings paper that elaborated this process (Cilli & Parnell, 2014). This process was designed to use best practices and to avoid the trade-off analysis mistakes discussed in the next section.

The INCOSE decision management process, introduced in Figure 1.2, is presented in more detail in Chapter 5. The purpose of the process is to "provide a structured, analytical framework for objectively identifying, characterizing, and evaluating a set of alternatives for a decision at any point in the life cycle and select the most beneficial course of action." The white text within the outer green ring identifies elements of a systems engineering process while the 10 blue arrows represent the 10 steps of the decision management process. Interactions between the systems engineering process and the decision management process are represented by the small, dotted green (outer ring to inner ring) or blue arrows (inner ring to outer ring). (*The reader is referred to the online version of this book for color indication.*)

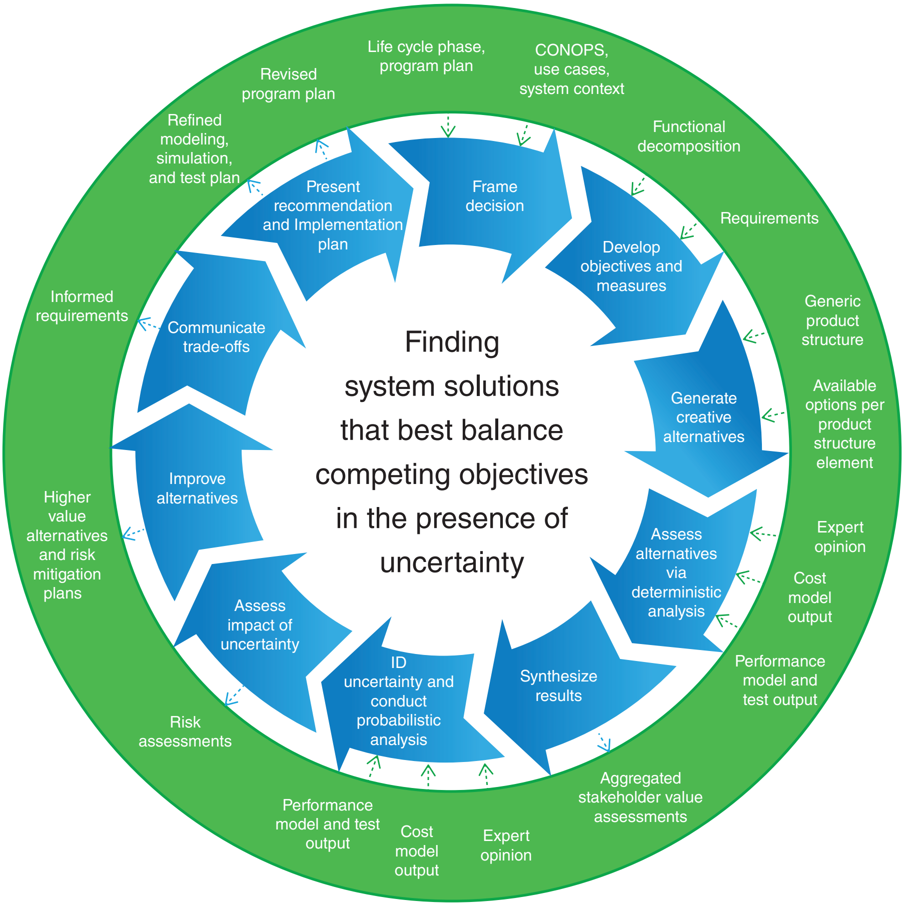

Figure 1.2 INCOSE decision management process

The steps in the decision management process are briefly described in Table 1.3, with references to the primary chapters that provide additional details about each step. Chapter 5 describes and illustrates the INCOSE decision management process.

1.7 TRADE-OFF ANALYSIS MISTAKES OF OMISSION AND COMMISSION

Using the INCOSE decision management process, we identify and discuss the most common trade-off study mistakes of omission and commission (Parnell et al., 2014).

Table 1.3 Decision Management Process

Process Step	Description	Primary Chapters
Frame decision	Describe the decision problem or opportunity that is the focus of the trade-off analysis in a particular system life cycle stage	Chapter 6
Develop objectives and measures	Use mission and stakeholder analysis and the system artifacts in the life cycle stage (e.g., function, requirements) to define the objectives and value measures for each objective alternative needed to satisfy	Chapter 7
Generate creative alternatives	Use a divergent–convergent process to develop creative, feasible alternatives	Chapter 8
Assess alternatives via deterministic analysis	Use a value model to perform deterministic analysis for trade-off analyses	Chapters 9–14
Synthesize results	Provide an assessment of the value of each alternative and the cost versus value to identify the dominated alternatives	Chapters 9–14
Identify uncertainty and conduct probabilistic analysis	Identify the major scenarios and system features that are uncertain and conduct probability analysis	Chapters 9, 12–14
Assess impact of uncertainty	Assess the impact of the uncertainties on value and cost	Chapters 9, 12–14
Improve alternatives	Improve the alternatives by increasing their system value and/or reducing their associated system risk	Chapters 9–14
Communicate trade-offs	Communicate the trade-off analysis results to decision-makers and other stakeholders	Chapters 9–14
Present recommendations and implementation plan	Provide decision recommendations and an implementation plan to describe the next steps to implement the decision	Chapter 5

Mistakes of omission are errors made by not doing the right things, while mistakes of commission are errors made by doing the right things the wrong way. For each step in the decision process, Table 1.4 provides a list of trade-off mistakes, the type of mistake (omission or commission), and the potential impacts.

Table 1.4 Trade-Off Mistakes

Step	Mistakes	Omission/ Commission	Impacts
Overall process	Not having a decision management process	Omission	No trade-off studies or variable trade-off study quality of those conducted Poor decisions; potential selection of a poor design Increased cost and schedule; inadequate performance Loss of SE credibility
Frame decision	Not obtaining access to key DM and SH	Omission	No trade-off studies or trade-off studies on the wrong issues
		Omission	Incorrect selection criteria
	Decision frame not defined		Loss of trade-off study and SE credibility
Develop objectives and measures	Objectives and/or measures not credible	Commission	Loss of trade-off study and SE credibility Potential selection of a poor design
Generate creative alternatives	Decision space not defined	Omission	Potential selection of poor design
	Doing an advocacy study	Commission	Potential increased cost and schedule Loss of trade-off study and SE credibility
Assess alternatives via deterministic analysis	Using non-normalized value functions	Commission	Potential selection of poor designs
	Not using swing weights	Commission	Loss of trade-off study and SE credibility
	No sensitivity analysis	Omission	
Synthesize results	Lack of a sound mathematical foundation	Omission	Potential selection of poor designs Loss of trade-off study and SE credibility

(*continued overleaf*)

Table 1.4 (*Continued*)

Step	Mistakes	Omission/ Commission	Impacts
Identify uncertainty and conduct probabilistic analysis	Not identifying uncertainties	Omission	Loss of trade-off study and SE credibility
	Improper assessment of uncertainty	Commission	Potential selection of poor designs
Assess impact of uncertainty	Not integrating with system/program risk assessments	Omission	Potential selection of poor designs Loss of SE credibility
Improve alternatives	Not improving alternatives	Omission	Loss of trade-off study and SE credibility Potential selection of poor designs
Communicate trade-offs	Results not timely or understood	Commission	Recommendations not implemented Loss of SE credibility
Present recommendations and implementation plan	Recommendations not implemented	Commission	Loss of trade-off study and SE credibility
Overall process	Not using trade-off study models on subsequent trade-off studies	Omission	Loss of trade-off study and SE credibility

1.7.1 Mistakes of Omission

There are 10 common mistakes of omission.

1.7.1.1 Not Having a Decision Management Process One of the most fundamental trade-off analysis mistakes is not having a decision management process that provides a foundation for all studies. The decision management process should have the acceptance and participation of the decision-makers and other stakeholders. To achieve stakeholder acceptance, the process should be tailorable to the needs of each specific trade-off analysis. Having a sound decision management process can save time while allowing for organizational learning and development of best practices. The INCOSE decision management process, shown in Figure 1.2, is an example of this kind of process. Without such a process, engineers in an organization are essentially free to use their own, invariably unsound process, and unsound processes can have a long lifetime! Since systems engineers are the ones who frequently perform trade-off analysis for critical system decisions, a natural home for the decision management process is the systems engineering organization.

1.7.1.2 Not Obtaining Access to Key DM, SH, and Subject Matter Experts (SMEs) Framing any system decision can be a challenge, especially without the right stakeholders involved. Therefore, it is critically important to have access to key decision makers, stakeholders, and SMEs to ensure that the opportunity is adequately defined and the important objectives have been identified. Challenges include gaining access to leaders and senior decision makers despite their busy schedules, including stakeholders who are critical to the system or its impact on them, and assuring access to SMEs in all steps of the trade-off study. To achieve this end, experiential opportunities that allow all stakeholders to readily understand the context and situation without having to understand SE notations are an imperative (Madni, 2016).

1.7.1.3 Decision Frame Not Defined The first step in the decision management process is to identify and describe the decision opportunity in the context of the problem space. In decision analysis, we call this framing the decision. Experience has taught us that the initial problem is never the final problem (Madni, 2013; Madni et al., 1985). The frame describes how we look at the problem. A good decision frame begins with thorough research and mission/stakeholder analysis (Parnell et al., 2011). A decision hierarchy (Parnell et al., 2013), which lists the past decisions, the current decisions, and the subsequent decisions, can also be useful. A short paragraph, written in clear terms that define the problem, can be quite helpful to decision-makers, other stakeholders, and study participants.

1.7.1.4 Lack of a Sound Mathematical Foundation To be credible and have defensible results, a trade-off study should be based on a sound mathematical foundation comprising both deterministic and probabilistic analyses. Several operations research and engineering analysis techniques (e.g., optimization, simulation, decision analysis) are potentially appropriate for trade-off studies. If all the objectives can be converted into dollars, then a net present value model would serve as a sound foundation. If not, then the mathematics of multiple objective decision analysis (MODA) offers a sound foundation for trade-off studies. Chapter 2 discusses this further.

1.7.1.5 Undefined Decision Space Some trade-off studies list alternatives that are not explicitly connected to the decision space. In many studies, alternatives are listed as bullets on a PowerPoint chart. In these cases, there is no explicit understanding of the decision space. The best techniques to help develop good alternatives are those that explicitly define the decision space (see Chapter 8). One best practice technique is called Zwicky's Morphological Box or Alternative Generation Table

(Parnell et al., 2011). In decision analysis, the technique is called the Strategy Table (Parnell et al., 2013), and it seeks to design alternatives that span the decision space. When the decision space is explicitly defined, it becomes possible to explore the decision space, identify more decision options, and come up with a better set of alternatives (Madni, 2012; Madni et al., 1985). The impact of not defining the decision space is the loss of the opportunity to create better alternatives to achieve the desired system value and/or reduce risk.

1.7.1.6 Absence of Sensitivity Analysis Any deterministic trade-off study has to make multiple assumptions about parameters in the model(s). The parameters typically include shapes of the value curves, swing weights, scores on the performance measures, and other variables that are used to calculate the scores. There may be some uncertainty about what numerical value each parameter should have. The best practice is to perform sensitivity analysis to determine if the best alternative changes when the parameter settings are varied across a reasonable range. Based on the sensitivity analysis, additional effort should be devoted to understanding and modeling the most sensitive variables (Madni, 2015).

1.7.1.7 Not Identifying Uncertainty and Performing Probabilistic Analysis Deterministic trade-off studies ignore uncertainties. Since uncertainty and risk are inherent in the life cycle of new systems, this omission is problematic. When decision analysis is used, it is easy to identify key uncertainties in deterministic models using deterministic sensitivity analysis, assess the uncertainties, and perform probabilistic analysis using Monte Carlo simulation, decision trees, influence diagrams, or probability management decisions (Parnell et al., 2011; Parnell et al., 2013). The impact of not modeling uncertainty is that we forgo the opportunity to understand the sources of risk early in the system life cycle when it is invariably easier to avoid, mitigate, or manage risks.

1.7.1.8 Not Improving Alternatives Several trade-off studies assess only proposed alternatives and never consider improving them. With several bad alternatives, even a "correctly performed" trade-off study can do no better than identify a bad alternative! Keeney calls the focus on existing options Alternative-Focused Thinking and advocates using Value-Focused Thinking to define our values, create decision opportunities, use our values to create better alternatives, and improve the proposed alternatives (Keeney, 1992). The decision analysis model provides useful data for Value-Focused Thinking, since it defines the ideal alternative and the gaps between the best alternative and the ideal alternative.

1.7.1.9 Failure to Integrate Trade-Off Study Uncertainty Analysis with System/Program Risk Assessments Uncertainty analysis performed in trade-off studies should be integrated with the system/program risk assessment process.

Unfortunately, many times trade-off studies do a good job of analyzing uncertainty, but the results are not integrated into the system risk management process. On many programs, risk analysis is performed using a simple risk matrix with likelihood on the rows (columns) and consequences on the columns (rows). In this case, the risks being analyzed may or may not be linked to trade-off studies. An alternative approach is to use the trade-off analysis value and cost models to perform risk assessment. This approach may result in better assessment of the likelihood and consequences (the loss in potential value) of the risk. In addition, the results of the risk analysis can be used to identify the need for additional trade-off studies to mitigate or manage risk.

1.7.1.10 Failure to Use Trade-Off Models on Subsequent Studies On some programs, each trade-off study is unique and there is no traceability between the results in one life cycle stage and the subsequent stages. This means the systems engineering organization might have been using very different value trade-offs for the same system without knowing it. A great deal of effort can go into developing trade-off study value models in early life cycle stages. The best practice is to use information from previous trade-off study value models (if available) and improve and tailor the model for subsequent studies. Using improved models can make the analysis results more accurate as well as more credible to decision-makers, stakeholders, and SMEs.

1.7.2 Mistakes of Commission

In addition to the 10 mistakes of omission, there are 6 common mistakes of commission.

1.7.2.1 Performing an Advocacy Study Trade-off studies work best when a creative set of alternatives that span the decision space are developed (Madni, 2013). It is worth noting that the final decision will be only as good as the alternatives that are considered. Some project managers and systems engineers inappropriately convert a trade-off study to a biased advocacy study (Parnell et al., 2013). They advocate the alternative they recommend and use the study to highlight the weaknesses of other alternatives. Advocacy studies put a significant burden on the decision-makers and stakeholders to identify and ask the hard questions to make sure that the other potential alternatives do not provide higher value/lower risk than the advocated alternative. Decision-makers and stakeholders should insist on a clear definition of the opportunity and on a set of creative, feasible alternatives that cover the full range of possibilities to create value, including verified and validated data and selection criteria that are free of bias.

1.7.2.2 Objectives and/or Measures Not Credible Trade-off studies require the development of a complete set of system objectives and measures. To meet the mathematical requirements of MODA, a nonoverlapping set of direct objectives is needed. In systems engineering, a great deal of effort is spent on identifying and analyzing system functions. The list of system functions can provide a good foundation for the development of objectives and value measures by constructing a functional value hierarchy (Buede & Miller, 2009; Parnell et al., 2011). The functional hierarchy has functions at the top level(s), then the objectives for each function, and value measures for each objective.

1.7.2.3 Using Measure Scores Instead of Normalized Value Functions Trade-off studies require the ability to compare performance on one measure with performance on other measures. If we have converted every measure level into a common currency, for example, dollars, we can use dollars as the metric. If decision-makers are unwilling to use dollars, we can use MODA to quantify the value as a function of the capability versus the cost. MODA uses the value functions to enable this trade-off analysis. The value functions (sometimes called scoring functions) convert a value measure score into a normalized measure of value on a common scale. The most common scales are 0–1, 0–10, and 0–100. Value functions assess returns to scale on the range of the value measure score. Value functions usually are of four types: linear, diminishing returns, increasing returns, and *S*-curve (increasing, then linear, then decreasing returns). The value function will be increasing (for a maximize objective) or decreasing (for a minimize function). The value functions allow us to compare apples and oranges. These functions must at least be on an interval scale (Keeney, 1992). Zero value on an interval scale means the minimum acceptable value and does not mean the lack of value. If a ratio scale is used, zero value would mean no value. The best practice is to obtain the shape of the curve and the rationale for the curve shape before you assess points on the curve. This will provide very useful information when a decision-maker or stakeholder challenges the value judgments of one or more alternatives. See Chapter 2 for additional information.

1.7.2.4 Use of Importance Weights Instead of Swing Weights A critical mistake in trade-off studies is using importance weights instead of swing weights. MODA quantitatively assesses the trade-offs between conflicting objectives by evaluating the alternative's contribution to the value measures (a score converted to value by single-dimensional value functions) and the importance of each value measure across the range of variation of the value measure (the swing weight). Every MODA book identifies this as a major problem. For example, "some experimentation with different ranges will quickly show that it is possible to change the rankings of the alternatives by changing the range that is used for each evaluation measure. This does not seem reasonable. The solution is to use swing weights" (Kirkwood, 1997). Swing weights play a key role in the additive value model presented in Chapter 2. The swing weights depend on the measure scales' importance and range. The word "swing" refers to varying the range of the value measure from its minimum acceptable level to its ideal