SYSTEMS ENGINEERING PRINCIPLES AND PRACTICE

WILEY SERIES IN SYSTEMS ENGINEERING AND MANAGEMENT

Andrew P. Sage, Editor

A complete list of the titles in this series appears at the end of this volume.

SYSTEMS ENGINEERING PRINCIPLES AND PRACTICE

SECOND EDITION

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To Alexander Kossiakoff,

who never took "no" for an answer and refused to believe that anything was impossible. He was an extraordinary problem solver, instructor, mentor, and friend.

Samuel J. Seymour

Steven M. Biemer

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PREFACE TO THE SECOND EDITION

It is an incredible honor and privilege to follow in the footsteps of an individual who had a profound influence on the course of history and the field of systems engineering. Since publication of the first edition of this book, the field of systems engineering has seen significant advances, including a significant increase in recognition of the discipline, as measured by the number of conferences, symposia, journals, articles, and books available on this crucial subject. Clearly, the field has reached a high level of maturity and is destined for continued growth. Unfortunately, the field has also seen some sorrowful losses, including one of the original authors, Alexander Kossiakoff, who passed away just 2 years after the publication of the book. His vision, innovation, excitement, and perseverance were contagious to all who worked with him and he is missed by the community. Fortunately, his vision remains and continues to be the driving force behind this book. It is with great pride that we dedicate this second edition to the enduring legacy of Alexander Ivanovitch Kossiakoff.

ALEXANDER KOSSIAKOFF, 1914–2005

Alexander Kossiakoff, known to so many as "Kossy," gave shape and direction to the Johns Hopkins University Applied Physics Laboratory as its director from 1969 to 1980. His work helped defend our nation, enhance the capabilities of our military, pushed technology in new and exciting directions, and bring successive new generations to an understanding of the unique challenges and opportunities of systems engineering. In 1980, recognizing the need to improve the training and education of technical professionals, he started the master of science degree program at Johns Hopkins University in Technical Management and later expanded it to Systems Engineering, one of the first programs of its kind.

Today, the systems engineering program he founded is the largest part-time graduate program in the United States, with students enrolled from around the world in classroom, distance, and organizational partnership venues; it continues to evolve as the field expands and teaching venues embrace new technologies, setting the standard for graduate programs in systems engineering. The first edition of the book is the foundational systems engineering textbook for colleges and universities worldwide.

OBJECTIVES OF THE SECOND EDITION

Traditional engineering disciplines do not provide the training, education, and experience necessary to ensure the successful development of a large, complex system program from inception to operational use. The advocacy of the systems engineering viewpoint and the goal for the practitioners to think like a systems engineer are still the major premises of this book.

This second edition of *Systems Engineering Principles and Practice* continues to be intended as a graduate-level textbook for courses introducing the field and practice of systems engineering. We continue the tradition of utilizing models to assist students in grasping abstract concepts presented in the book. The five basic models of the first edition are retained, with only minor refinements to reflect current thinking. Additionally, the emphasis on application and practice is retained throughout and focuses on students pursuing their educational careers in parallel with their professional careers. Detailed mathematics and other technical fields are not explored in depth, providing the greatest range of students who may benefit, nor are traditional engineering disciplines provided in detail, which would violate the book's intended scope.

The updates and additions to the first edition revolve around the changes occurring in the field of systems engineering since the original publication. Special attention was made in the following areas:

- *The Systems Engineer's Career.* An expanded discussion is presented on the career of the systems engineer. In recent years, systems engineering has been recognized by many companies and organizations as a separate field, and the position of "systems engineer" has been formalized. Therefore, we present a model of the systems engineer's career to help guide prospective professionals.
- *The Systems Engineering Landscape.* The only new chapter introduced in the second edition is titled by the same name and reinforces the concept of the systems engineering viewpoint. Expanded discussions of the implications of this viewpoint have been offered.
- *System Boundaries.* Supplemental material has been introduced defining and expanding our discussion on the concept of the system boundary. Through the use of the book in graduate-level education, the authors recognized an inherent misunderstanding of this concept—students in general have been unable to recognize the boundary between the system and its environment. This area has been strengthened throughout the book.
- *System Complexity.* Significant research in the area of system complexity is now available and has been addressed. Concepts such as system of systems engineering, complex systems management, and enterprise systems engineering are introduced to the student as a hierarchy of complexity, of which systems engineering forms the foundation.
- *Systems Architecting.* Since the original publication, the field of systems architecting has expanded significantly, and the tools, techniques, and practices of this

field have been incorporated into the concept exploration and definition chapters. New models and frameworks for both traditional structured analysis and object-oriented analysis techniques are described and examples are provided, including an expanded description of the Unified Modeling Language and the Systems Modeling Language. Finally, the extension of these new methodologies, model-based systems engineering, is introduced.

- *Decision Making and Support.* The chapter on systems engineering decision tools has been updated and expanded to introduce the systems engineering student to the variety of decisions required in this field, and the modern processes, tools, and techniques that are available for use. The chapter has also been moved from the original special topics part of the book.
- *Software Systems Engineering*. The chapter on software systems engineering has been extensively revised to incorporate modern software engineering techniques, principles, and concepts. Descriptions of modern software development life cycle models, such as the agile development model, have been expanded to reflect current practices. Moreover, the section on capability maturity models has been updated to reflect the current integrated model. This chapter has also been moved out of the special topics part and introduced as a full partner of advanced development and engineering design.

In addition to the topics mentioned above, the chapter summaries have been reformatted for easier understanding, and the lists of problems and references have been updated and expanded. Lastly, feedback, opinions, and recommendations from graduate students have been incorporated where the wording or presentation was awkward or unclear.

CONTENT DESCRIPTION

This book continues to be used to support the core courses of the Johns Hopkins University Master of Science in Systems Engineering program and is now a primary textbook used throughout the United States and in several other countries. Many programs have transitioned to online or distance instruction; the second edition was written with distance teaching in mind, and offers additional examples.

The length of the book has grown, with the updates and new material reflecting the expansion of the field itself.

The second edition now has four parts:

- *Part I.* The Foundation of Systems Engineering, consisting of Chapters 1–5, describes the origins and structure of modern systems, the current field of systems engineering, the structured development process of complex systems, and the organization of system development projects.
- *Part II.* Concept Development, consisting of Chapters 6–9, describes the early stages of the system life cycle in which a need for a new system is demonstrated,

its requirements identified, alternative implementations developed, and key program and technical decisions made.

- *Part III.* Engineering Development, consisting of Chapters 10–13, describes the later stages of the system life cycle, in which the system building blocks are engineered (to include both software and hardware subsystems) and the total system is integrated and evaluated in an operational environment.
- *Part IV.* Postdevelopment, consisting of Chapters 14 and 15, describes the roles of systems in the production, operation, and support phases of the system life cycle and what domain knowledge of these phases a systems engineer should acquire.

Each chapter contains a summary, homework problems, and bibliography.

ACKNOWLEDGMENTS

The authors of the second edition gratefully acknowledge the family of Dr. Kossiakoff and Mr. William Sweet for their encouragement and support of a second edition to the original book. As with the first edition, the authors gratefully acknowledge the many contributions made by the present and past faculties of the Johns Hopkins University Systems Engineering graduate program. Their sharp insight and recommendations on improvements to the first edition have been invaluable in framing this publication. Particular thanks are due to E. A. Smyth for his insightful review of the manuscript.

Finally, we are exceedingly grateful to our families—Judy Seymour and Michele and August Biemer—for their encouragement, patience, and unfailing support, even when they were continually asked to sacrifice, and the end never seemed to be within reach.

Much of the work in preparing this book was supported as part of the educational mission of the Johns Hopkins University Applied Physics Laboratory.

Samuel J. Seymour
Steven M. Biemer
2010

PREFACE TO THE FIRST EDITION

Learning how to be a successful systems engineer is entirely different from learning how to excel at a traditional engineering discipline. It requires developing the ability to think in a special way, to acquire the "systems engineering viewpoint," and to make the central objective the system as a whole and the success of its mission. The systems engineer faces three directions: the system user's needs and concerns, the project manager's financial and schedule constraints, and the capabilities and ambitions of the engineering specialists who have to develop and build the elements of the system. This requires learning enough of the language and basic principles of each of the three constituencies to understand their requirements and to negotiate balanced solutions acceptable to all. The role of interdisciplinary leadership is the key contribution and principal challenge of systems engineering and it is absolutely indispensable to the successful development of modern complex systems.

1.1 OBJECTIVES

Systems Engineering Principles and Practice is a textbook designed to help students learn to think like systems engineers. Students seeking to learn systems engineering after mastering a traditional engineering discipline often find the subject highly abstract and ambiguous. To help make systems engineering more tangible and easier to grasp, the book provides several models: (1) a hierarchical model of complex systems, showing them to be composed of a set of commonly occurring building blocks or components; (2) a system life cycle model derived from existing models but more explicitly related to evolving engineering activities and participants; (3) a model of the steps in the systems engineering method and their iterative application to each phase of the life cycle; (4) a concept of "materialization" that represents the stepwise evolution of an abstract concept to an engineered, integrated, and validated system; and (5) repeated references to the specific responsibilities of systems engineers as they evolve during the system life cycle and to the scope of what a systems engineer must know to perform these effectively. The book's significantly different approach is intended to complement the several excellent existing textbooks that concentrate on the quantitative and analytical aspects of systems engineering.

Particular attention is devoted to systems engineers as professionals, their responsibilities as part of a major system development project, and the knowledge, skills, and mind-set they must acquire to be successful. The book stresses that they must be innovative and resourceful, as well as systematic and disciplined. It describes the special functions and responsibilities of systems engineers in comparison with those of system analysts, design specialists, test engineers, project managers, and other members of the system development team. While the book describes the necessary processes that systems engineers must know and execute, it stresses the leadership, problem-solving, and innovative skills necessary for success.

The function of systems engineering as defined here is to "guide the engineering of complex systems." To learn how to be a good guide requires years of practice and the help and advice of a more experienced guide who knows "the way." The purpose of this book is to provide a significant measure of such help and advice through the organized collective experience of the authors and other contributors.

This book is intended for graduate engineers or scientists who aspire to or are already engaged in careers in systems engineering, project management, or engineering management. Its main audience is expected to be engineers educated in a single discipline, either hardware or software, who wish to broaden their knowledge so as to deal with systems problems. It is written with a minimum of mathematics and specialized jargon so that it should also be useful to managers of technical projects or organizations, as well as to senior undergraduates.

1.2 ORIGIN AND CONTENTS

The main portion of the book has been used for the past 5 years to support the five core courses of the Johns Hopkins University Master of Science in Systems Engineering program and is thoroughly class tested. It has also been used successfully as a text for distance course offerings. In addition, the book is well suited to support short courses and in-house training.

The book consists of 14 chapters grouped into five parts:

- *Part I.* The Foundations of Systems Engineering, consisting of Chapters 1–4, describes the origin and structure of modern systems, the stepwise development process of complex systems, and the organization of system development projects.
- *Part II.* Concept Development, consisting of Chapters 5–7, describes the first stage of the system life cycle in which a need for a new system is demonstrated, its requirements are developed, and a specific preferred implementation concept is selected.
- *Part III.* Engineering Development, consisting of Chapters 8–10, describes the second stage of the system life cycle, in which the system building blocks are engineered and the total system is integrated and evaluated in an operational environment.

- *Part IV.* Postdevelopment, consisting of Chapters 11 and 12, describes the role of systems engineering in the production, operation, and support phases of the system life cycle, and what domain knowledge of these phases in the system life cycle a systems engineer should acquire.
- *Part V.* Special Topics consists of Chapters 13 and 14. Chapter 13 describes the pervasive role of software throughout system development, and Chapter 14 addresses the application of modeling, simulation, and trade-off analysis as systems engineering decision tools.

Each chapter also contains a summary, homework problems, and a bibliography. A glossary of important terms is also included. The chapter summaries are formatted to facilitate their use in lecture viewgraphs.

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The authors gratefully acknowledge the many contributions made by the present and past faculties of the Johns Hopkins University Systems Engineering Masters program. Particular thanks are due to S. M. Biemer, J. B. Chism, R. S. Grossman, D. C. Mitchell, J. W. Schneider, R. M. Schulmeyer, T. P. Sleight, G. D. Smith, R. J. Thompson, and S. P. Yanek, for their astute criticism of passages that may have been dear to our hearts but are in need of repairs.

An even larger debt is owed to Ben E. Amster, who was one of the originators and the initial faculty of the Johns Hopkins University Systems Engineering program. Though not directly involved in the original writing, he enhanced the text and diagrams by adding many of his own insights and fine-tuned the entire text for meaning and clarity, applying his 30 years' experience as a systems engineer to great advantage.

We especially want to thank H. J. Gravagna for her outstanding expertise and inexhaustible patience in typing and editing the innumerable rewrites of the drafts of the manuscript. These were issued to successive classes of systems engineering students as the book evolved over the past 3 years. It was she who kept the focus on the final product and provided invaluable assistance with the production of this work.

Finally, we are eternally grateful to our wives, Arabelle and Kathleen, for their encouragement, patience, and unfailing support, especially when the written words came hard and the end seemed beyond our reach.

Much of the work in preparing this book was supported as part of the educational mission of the Johns Hopkins Applied Physics Laboratory.

ALEXANDER KOSSIAKOFF
WILLIAM N. SWEET
2002