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PRACTICAL CREATIVITY AND INNOVATION IN SYSTEMS ENGINEERING

AVNER ENGEL

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Practical Creativity and Innovation in Systems Engineering

WILEY SERIES IN SYSTEMS ENGINEERING AND MANAGEMENT

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Front Cover
Iconic of Japanese gardens, the Zen-Style Garden is designed to invite contemplation and seclusion. This image is part of a dry rock garden consisting of gravel and massive boulders placed by Hoichi Kurisu. Photo courtesy of Frederik Meijer Gardens & Sculpture Park, Grand Rapids, Michigan, USA.

Practical Creativity and Innovation in Systems Engineering

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To Rachel

Contents

Preface

The aim of this book is to acquaint systems engineers with the practical art of creativity and innovation. The concept of creativity has evolved throughout history. The Greeks considered poetry the only legitimate creative practice. That is, poets, as opposed to artisans, merchants, and even nobility could create poetry freely with no restrictions or rules. Later, the Romans considered the visual arts as a creative practice, too. However, during the Middle Ages, creativity evolved to strictly mean God's creations. Therefore, the concept of creativity was no longer applicable to any human activity. Thereafter, during the Renaissance and beyond, creativity slowly progressed to imply freedom of expression in the arts. Only at the turn of the twentieth century did the concept of creativity began to be applied to science and engineering.

The basic premise of this book is that creative abilities of human beings are not fixed, inborn traits but, rather, are changing over their lifetime. For example, researchers show that children exhibit remarkable abilities to look at problems and come up with new, different, and creative solutions. However, as they grow to adulthood, these abilities diminish substantially. Fortunately, creative skills can also be learned. Many studies show that well-designed training programs enhance creativity across different domains and criteria. Hopefully, engineers adopting some of the creative methods discussed in this book will achieve improved creative skills as well.

Another premise of this book is that many creative engineers are stalled in their innovative efforts by organizations that claim to promote innovation but that, in fact, crush such efforts. Indeed, it is the author's impression (as well as other researchers) that, beyond boasting, the vast majority of companies and other organizations are creativity-averse. Naturally, creative engineers working for such organizations are frustrated and discouraged. Not less important are the accumulated losses for the organizations themselves as well as to society at large from neglecting many creative ideas without due consideration. The book attempts to explore this phenomenon and offer practical advice to organizations as well as to the multitudes of demoralized engineers. In particular, engineers are advised to expand their professional and intellectual horizons, seek to reduce risks inherent in their new ideas, and learn to obtain colleagues' support as well as deal with reactionary management. In short, adopt a more entrepreneurial attitude.

This book is organized in five parts: Part I: Introduction, contains material about the principles of the book and its content. Part II: Systems Engineering, describes basic systems engineering concepts and a partial and abbreviated summary of Standard 15288 systems' life cycle processes. In addition, this part includes a recommended set of creative methods for each life cycle process. Finally, this part provides some philosophical thoughts about engineering. Part III: Creative Methods, the heart of the book, provides an extensive repertoire of practical creative methods engineers may use. Part IV: Promoting Innovative Culture, deals with ways and means to enhance innovative culture within organizations. In addition, this part provides advice to creative engineers employed by non-creative organizations. Finally, Part V: Creative and Innovative Case Study, presents an exemplary creative and innovative research and implementation undertaking.

Fundamentally, this book is written with two categories of audience in mind. The first category is composed of practicing engineers in general and system engineers in particular as well as first- and second-line technical managers. These people may be employed by various development and manufacturing industries (e.g. aerospace, automobile, communication, healthcare equipment, etc.), by various civilian agencies (e.g. NASA, ESA, etc.) or with the military (e.g. Air Force, Navy, Army, etc.). The second category is composed of faculties and students within universities and colleges who are involved in Systems, Electrical, Aerospace, Mechanical, and Industrial Engineering. This book may be used as a supplemental graduate level textbook in creativity and innovation courses related to systems engineering. Selected portions of the book may be covered in one or two semesters.

Finally, readers should note that this book does not pursue new theories or theses with regards to creativity and innovation. To the contrary, the author seeks to acquaint systems engineers with well-established facets of creativity and innovation. In order to achieve this objective, the author drew upon his engineering experience, communicated with many people, and collected information from many sources, books, articles, internet blogs, and the like (giving credit where credit's due). Bibliographies at the end of each part of the book identify invaluable sources for deeper understanding of the various subject matters discussed in the book. The author gained much knowledge from these resources and is indebted to the individuals, researchers, and experts who created them.

Acknowledgments

Many people have generously contributed to the writing of this book. To all of them, I would like to express my sincere gratitude and appreciation.

In particular, I wish to thank Shalom Shachar, formerly from the Israel Aerospace Industries, and Professor Tyson Browning from the Texas Christian University, tireless colleagues and friends, much of whose scientific and engineering writings and words of wisdom are embedded in this book.

The AMISA project, funded by the European Commission, focused my attention onto the value of creativity and innovation within systems engineering. My appreciation goes to all the consortium members and in particular to Professor Yoram Reich of the Tel Aviv University for his steadfast support and advice and also to Michael Garber of Adi Mainly Software (AMS), who developed the DFA-Tool software package, which embodies the Architecture Option model.

Two people had direct impact on the manuscript of the book. Professor Shulamith Kreitler of the Tel Aviv University encouraged my book project and advised me on its structure. Professor Cecilia Haskins of the Norwegian University of Science and Technology volunteered to review the manuscript and contributed numerous and valuable suggestions to improve it. Also, I would like to thank my good friend, Menachem Cahani (Pampam) for contributing two caricatures to the book. I am indebted to them both. I would also like to express my deep appreciation to the dedicated and tireless Wiley editing team, especially to Victoria Bradshaw and Grace Paulin, as well as to Cheryl Ferguson for her diligent assistance with preparing the manuscript.

Several researchers empowered me to share their research with the readers of this book, and I am beholden to them all: Professor Sang Joon Lee of the Pohang University of Science and Technology, South Korea on biomimicry engineering, Professor Emeritus Ravi Jain of the University of the Pacific, California, on managing research, development, and innovation, Professor Christian Richter Østergaard of the Aalborg University, Denmark, on innovation and employee diversity, Inger Danilda of Quadruple Learning, Sweden, and Jennie Granat Thorslund of the Swedish Governmental Agency for

Innovation Systems (VINNOVA) on gendered innovation, and lastly, Professor T.K. DAS of the City University of New York on cognitive biases.

My deep appreciation also goes to the Standards Institution of Israel (SII), which permitted me, on behalf of the International Organization for Standardization (ISO), to reproduce a partial and abridged portion of the International Standard ISO/IEC/IEEE 15288. My thanks also go to the Royal Academy of Engineering, London, United Kingdom, for permission to reproduce intriguing portions of papers presented during seminars on the philosophy of engineering held at the academy in June 2010.

Most of all, my deepest thanks go to my wife, Rachel, and my sons, Ofer, Amir, Jonathan, and Michael, who encouraged my book efforts with advice, patience and love.

Avner Engel
Tel-Aviv, Israel

Part I

Introduction

"One must still have chaos in oneself to be able to give birth to a dancing star."

Friedrich Nietzsche (1844–1900)

1.1 Introduction to Part I

The aim of this book is to acquaint engineers in general and systems engineers in particular with the practical art of creativity and innovation. Systems engineers are people with a capacity to understand many engineering, scientific, and management disciplines. In addition, systems engineers tend to examine issues in a holistic way considering the total system life cycle. This capacity is obtained through formal education, as well as experience in leading multidisciplinary teams in creating, manufacturing, and maintaining complex systems within sustainable environments.[1]

The basic premise of this book is that creative abilities of human beings are not fixed, inborn traits but, rather, change over their lifetime. For example, in the late 1960s and early 1970s, George Land tested the level of creativity among children and adults.[2] The results, presented in Figure 1.1, are quite shocking. According to the study, 98% of five-year-old children could be categorized as geniuses in terms of their abilities to look at problems and come up with new, different, and creative solutions. This percentage drops to 2% within the average adults' population. Land and Jarman (1998) concluded from this longitudinal study that non-creative behavior is learned.

1 Adapted from: Urban Dictionary, http://www.urbandictionary.com/define.php?term=super-systems-engineer. Accessed: July, 2017.
2 See: TEDxTucson George Land, The failure of success, https://www.youtube.com/watch?v=ZfKMq-rYtnc. Accessed: July, 2017.

Practical Creativity and Innovation in Systems Engineering, First Edition. Avner Engel.

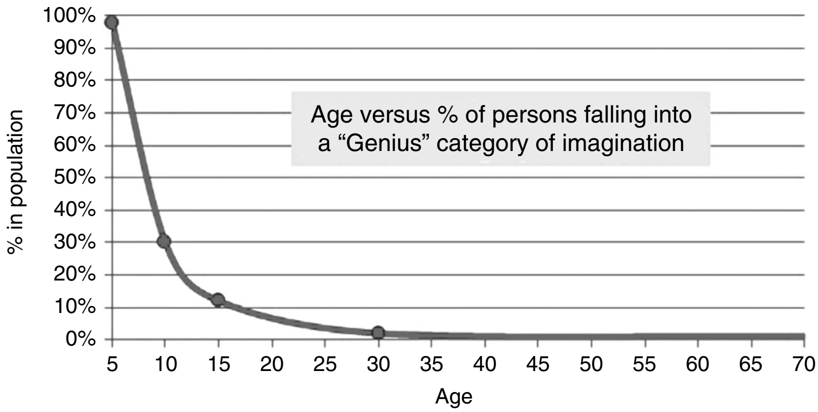

Figure 1.1 Age versus imagination

Fortunately, creativity skills can also be learned. For example, Scott et al. (2004) analyzed some 70 studies related to creativity training and concluded that well-designed training programs promoted distinct creativity performance gains across different domains and criteria. Hopefully, engineers adopting some of the creative methods discussed in this book will achieve improved creative skills as well.

Another premise of this book is that many creative engineers are stalled in their innovative efforts by organizations that claim to promote innovation but, in fact, consistently crush such efforts. Indeed, it is the author's impression (as well as other researchers[3]) that, beyond boasting, the vast majority of companies and other organizations are creativity-averse. Naturally, creative engineers working for such organizations are frustrated and discouraged. Not less important are the accumulated losses for the organizations themselves as well as to society at large from neglecting many creative ideas without due consideration. The book attempts to explore this phenomenon and offer practical advice to organizations as well as to the multitudes of demoralized engineers. In particular, engineers are advised to expand their professional and intellectual horizons, seek to reduce risks inherent in their new ideas, and learn to obtain colleagues' support as well as deal with reactionary management. In short, adopt a more entrepreneurial attitude.

Beyond this introductory chapter, Part I of this book provides some key points and a short outline related to the other four parts of the book, namely: (1) systems engineering, (2) creative methods, (3) promoting innovative

3 See for example T. Amabile, "How to Kill Creativity," https://hbr.org/1998/09/how-to-kill-creativity. Accessed: July, 2017.

culture, and (4) creative and innovative case study. In addition, Part I closes with a relevant bibliography. Figure 1.2 depicts the overall structure and contents of the entire book.

Part I: Introduction, true to its name, provides an introductory material to this book. Part II: Systems Engineering, describes basic systems engineering concepts as well as a partial and abbreviated depiction of Standard 15288 systems' life cycle processes. In addition, for each process, the book identifies a relevant small set of recommended creative methods. Finally, this part presents some intriguing philosophical insights about engineering. Part III: Creative Methods, provides an extensive repertoire of practical creative methods. Part IV: Promoting Innovative Culture, describes ways and means to enhance innovative culture within organizations. In addition, this part provides advice to creative engineers employed by non-creative organizations. Part V: Creative and Innovative Case Study, describes an exemplary creative and innovative case study. Lastly, the back matter of the book contains relevant appendices.

The book contains a massive number of visuals. This is because the author believes engineers (and probably other people) tend to focus on visuals as their

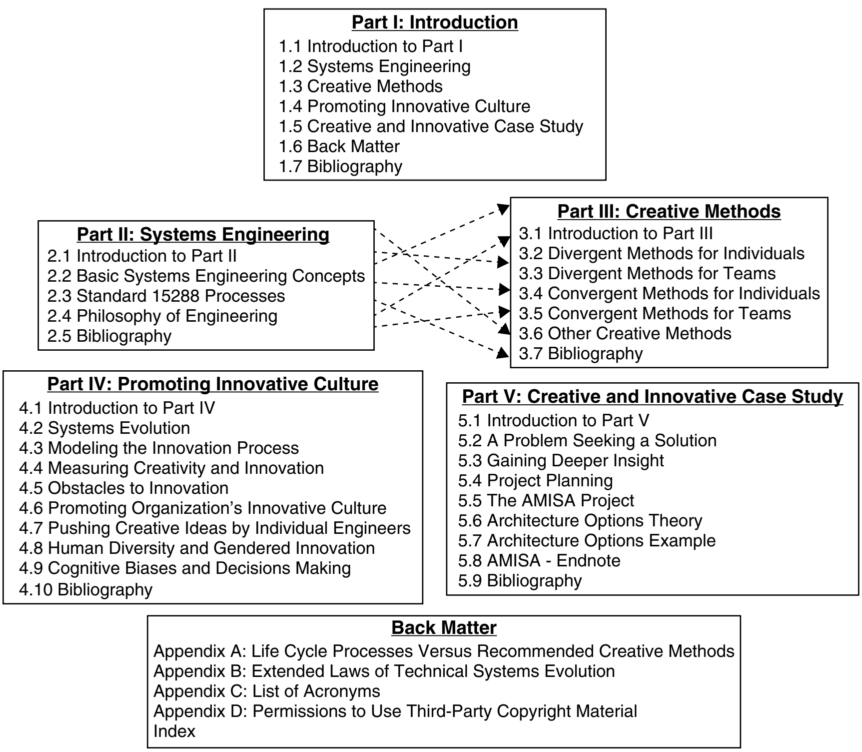

Figure 1.2 Book's overall structure

immediate and primary source of understanding. Many of these visuals require permission to use third-party copyright so, in order to reduce clutter and ease the reading process, these permissions are provided in Appendix D.

Finally, readers should note that this book does not pursue new theories or theses with regards to creativity and innovation. To the contrary, the author seeks to acquaint systems engineers with well-established facets of creativity and innovation. In order to achieve this objective, the author drew on his engineering experience, communicated with many people, and collected information from many sources, books, articles, internet blogs, and the like (giving credit where credit's due). Sections on further reading at the end of individual chapters, as well as the bibliographies at the end of each part of the book, identify invaluable sources for deeper understanding of the various subject matters discussed in this book. The author gained much knowledge from these resources and is indebted to the individuals, researchers, and experts who created them.

1.2 Systems Engineering

There are many books dedicated to the art of systems engineering, and it is not the purpose of this book to devote much space to this subject. Therefore, the intent of Part II is to construct scaffolding, bridging the gap between the domain of systems engineering and the domains of creativity and innovation. This is done by identifying some basic systems engineering concepts and then describing some 30 systems' life cycle processes in accordance with an abridged International Standard ISO/IEC/IEEE 15288. Each life cycle process is then associated with a specific and relevant set of recommended creative methods. Systems engineers can use these and other creative methods described in Part III to expand their creative skills and enhance their engineering output. Finally, this part provides some philosophical thoughts about engineering.

Chapter 2.2 describes basic systems engineering concepts. More specifically, it includes four basic concepts, namely: (1) organizations and projects concepts, (2) system concepts, (3) life cycle concepts, and (4) process concepts.

Chapter 2.3 describes systems life cycle processes harmonized with Standard 15288. The standard clusters these life cycle processes into four groups: (1) agreement process group, (2) organizational project-enabling process group, (3) technical management process group, and (4) technical process group.

Chapter 2.4 describes some key issues in philosophy of engineering. This includes: (1) engineering and truth, (2) The logic of engineering design, (3) the context and nature of engineering design, (4) roles and rules and the modeling of socio-technical systems, and (5) engineering as synthesis – doing right things and doing things right.

1.3 Creative Methods

Creativity may be defined as "The ability to transcend traditional ideas, rules, patterns, relationships, or the like, and to create meaningful new ideas, forms, interpretations, etc."[4] According to Teresa Amabile (1998), creativity is composed of three components: expertise, creative thinking, and motivation (Figure 1.3). Expertise consists of everything a person knows. Among others, this includes technical, procedural, and intellectual knowledge a person may possess. Creative thinking refers to ones' abilities to create meaningful new ideas and blend existing ideas together in new structures. Lastly, motivation determines what people will actually do. Extrinsic motivation comes from outside a person by way of offering person amenities like money, promotion, and the like. Intrinsic motivation, on the other hand, stems from a person's internal desire to pursue one's passion and interest.

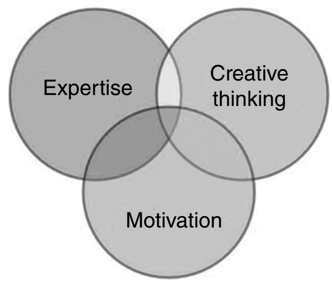

Figure 1.3 Three components of creativity

Fundamentally, creative methods may be partitioned along two axes: (1) divergent versus convergent creative methods and (2) creative methods primarily used by individuals versus teams. Along the first axis, divergent creative methods help in generating multiple creative solutions, whereas convergent creative methods help in trimming the number of creative solutions. Along the second axis, some creative methods are primarily appropriate for individuals, whereas other creative methods are primarily appropriate for teams.

Chapter 3.2 describes divergent methods for individuals, including: (1) lateral thinking, (2) resolving contradictions, (3) biomimicry engineering, and (4) visual creativity.

Chapter 3.3 describes divergent methods for teams, including: (1) classic brainstorming, (2) six thinking hats, (3) SWOT analysis, (4) SCAMPER analysis, and (5) focus groups.

Chapter 3.4 describes convergent methods for individuals, including: (1) PMI analysis, (2) morphological analysis, (3) decision tree analysis, (4) value analysis / value engineering, and (5) Pareto analysis.

Chapter 3.5 describes convergent methods for teams, including: (1) Delphi method, (2) SAST analysis, (3) cause-and-effect diagrams, (4) Kano model analysis, and (5) group decisions.

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4 See Dictionary.com, http://www.dictionary.com/browse/creativity. Accessed: July 2017.

Chapter 3.6 describes other creative methods, including: (1) process map analysis, (2) nine screens analysis, (3) technology forecasting, (4) Design Structure Matrix analysis, (5) failure mode effect analysis, (6) anticipatory failure determination, and (7) conflict analysis and resolution.

1.4 Promoting Innovative Culture

Innovation may be defined as "the process of translating an idea or invention into a good or service that creates value or for which customers will pay."[5] Now readers can appreciate the fundamental difference between creativity and innovation. Whereas creativity refers to conceiving new and unique ideas, innovation implies introducing new systems, artifacts, processes, and the like into the market.

There is a natural conflict between the creative person, the dreamer, and the innovative person, the top-notch, down-to-earth leader and manager. This is why individuals rarely combine these two attributes within one person. Towering above them all is Moses (approx. 1390–1270 BC) the biblical prophet who presented the most fundamental and concise laws of ethics and worship and brought forth the creative idea of releasing the Israelites (and by extension, all mankind) from slavery in Egypt (Figure 1.4). Then, during 40 years of wandering in the desert, he forged a nation and a culture that propagated throughout the world to this day.

Innovation culture is the work environment that engineers and leaders cultivate within organizations in order to nurture individualistic thinking and give fair hearing to the implementation of new and often unorthodox ideas. Accordingly, this chapter examines the following issues: How do systems evolve? How should we model the innovation process? How is creativity and innovation measured? What are the obstacles to innovation? How can an organization promote its innovative culture? and, most importantly, how can an organization push creative ideas by individual engineers? Finally, this part of the book discusses human diversity and gendered innovation as well as cognitive biases and decisions making.

Chapter 4.2 describes systems evolution, including: (1) modeling systems evolution, S-curve, and (2) laws of systems evolution.

Chapter 4.3 describes modeling the innovation process, including: (1) classes and types of innovations, (2) technological innovation process, and (3) innovation funding.

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5 See BusinessDictionary.com, http://www.businessdictionary.com/definition/innovation.html. Accessed: July 2017.

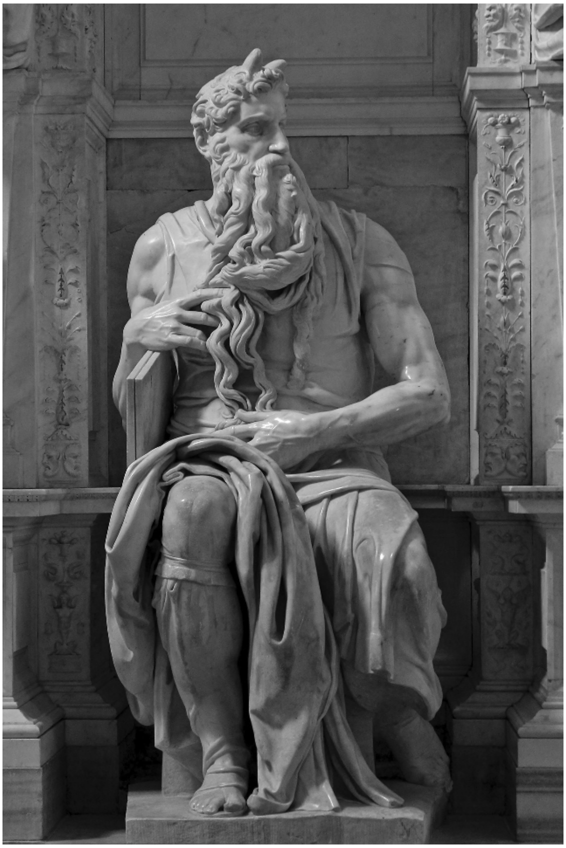

Figure 1.4 Moses, a creative and innovative giant

Chapter 4.4 describes measuring creativity and innovation, including: (1) defining innovation objectives, (2) measuring the innovation process, and (3) innovation capability maturity model.

Chapter 4.5 describes obstacles to innovation, including: (1) human habits factors, (2) cost factors, (3) institutional factors, (4) knowledge factors, (5) market factors, and (6) innovation obstacles and classes of innovations.

Chapter 4.6 describes promoting organization's innovative culture, including: (1) innovation and leadership, (2) innovation and organization, (3) innovation and people, (4) innovation and assets, (5) innovation and culture, (6) innovation and values, (7) innovation and processes, (8) innovation and tools, and (9) ascent to innovation – practical steps.

Chapter 4.7 describes pushing creative ideas by individual engineers, including: (1) large organizations seldom innovate, (2) characteristics of innovative engineers, and (3) innovation advice to creative engineers.

Chapter 4.8 describes human diversity and gendered innovation, including: (1) human diversity, (2) shift in gender paradigm, (3) gender disparity and innovation implications, (4) advancing gendered innovation, and (5) gendered innovation example.

Chapter 4.9 describes cognitive biases and decisions making, including: (1) cognitive biases, and (2) cognitive biases and strategic decisions.

1.5 Creative and Innovative Case Study

The purpose of Part V is to tell the story of an exemplary creative and innovative case study that started in 2003 and continued to 2016. The research question that emerged over time was: "How can adaptability[6] be designed into systems so that they will provide maximum lifetime value to stakeholders?"

The WOW factor was revealed in two papers (Engel and Browning, 2006, 2008) proposing to solve the problem using well-accepted economic theories: the financial option theory (FOT) and the transaction cost theory (TCT). Transforming each theory into the engineering domain and then blending them together was dubbed the architecture option (AO).

Transitioning to the innovation portion, a consortium (AMISA[7]) composed of two universities, four industries, and two small and medium enterprises (SMEs) were created. Then, a three-year funding request for a research project costing €4 million was submitted to the European Commission (EC), and after approval, the AMISA project started on April 2011, ending three years later.

End-project reports from the AMISA participants confirmed that the AO approach was indeed helpful, allowing participants to increase product adaptability, cost-efficiency, lifespan, and overall value. According to a post-project review by the EC, this research delivered a "step-change" in the performance of European industry, characterized by a higher reactivity to market needs and more economically compatible products and services. Bottom line, the AMISA partners seem to understand the importance of designing systems for future unforeseen upgrades, yet no partner truly incorporated this approach into their day-to-day systems' design operations.

Chapter 5.2 describes the problem at hand, including: (1) the problem and its inception and (2) initial funding effort.

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6 According to the Merriam-Webster dictionary, to adapt means "to make fit, often by modification" (…from the outside). Adaptability is distinguished from "Flexibility," which is derived from the Latin word *flexus* and literally refers to what is capable of withstanding stress without injury and figuratively to what may naturally adjust itself as needed.

7 AMISA stands for: "Architecting Manufacturing Industries and Systems for Adaptability."

Chapter 5.3 describes how the people involved in this undertaking gained deeper insight. It includes: (1) the problem and the approach, (2) main ideas of the proposed work, (3) measurable project objectives, (4) basis for predicting the objectives, and (5) systems adaptability – state of the art.

Chapter 5.4 describes the project planning, including: (1) project planned activities, (2) detailed work package descriptions, (3) risks and contingency plans, (4) management structure and procedures, (5) project participants, and (6) resources needed.

Chapter 5.5 describes the AMISA project, including: (1) AMISA initiation, (2) identifying the DFA state of the art, (3) establishing requirements for AMISA, (4) implementing a software support tool, (5) developing six pilot projects, (6) generating deliverables, (7) planning exploitation beyond AMISA, (8) disseminating project results, (9) assessing the AMISA project, (10) consortium meetings, and (11) EC summary of the project.

Chapter 5.6 describes architecture options theory, including: (1) financial and engineering options, (2) transaction cost and interface cost, (3) architecture adaptability value, (4) Design Structure Matrix, and (5) dynamic system value modeling.

Chapter 5.7 describes an AO example, including: (1) general architecture option process, and (2) AO example – solid state power amplifier (SSPA).

Chapter 5.8 provides a summation of the AMISA project.

Note
Readers mostly interested in the creative aspects of this case study are advised to focus on chapters 5.2, 5.3, 5.6, and 5.7. Readers primarily interested in the innovative aspects of this case study are advised to consider chapters 5.4 and 5.5.

1.6 Back Matter

The back matter part of the book contains several relevant appendices and the index.

Appendix A: Depicts a table associating systems' life cycle processes with recommended creative methods.
Appendix B: Provides an extended set of technical systems evolution laws.
Appendix C: Provides a list of relevant acronyms.
Appendix D: Provides permissions to use third-party copyright material.

An index of important terms.

1.7 Bibliography

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Part II

Systems Engineering

"All you need in this life is ignorance and confidence; then success is sure."
Mark Twain (1835–1910)

2.1 Introduction to Part II

The assumption embodied in this book is that there are sufficient books and other means from which to learn about system engineering, i.e. the author expects readers to be reasonably familiar with this art. The key motivation for including Part II in this book is to launch systems engineers onto the focal point of this book, namely, Part III: Creative Methods and Part IV: Promoting Innovative Culture. This is done by characterizing some basic systems engineering concepts and then providing a condensed and abridged description of systems life cycle processes as defined in the International Standard ISO/IEC/IEEE 15288.[1] Each life cycle process is then associated with a specific set of recommended creative methods, exemplifying potential benefits that systems engineers may attain by using creative methods.

Among others, standard 15288 provides a total of 30 processes covering the life cycle of virtually any engineered system. These processes are applicable at the system level and express a coherent and cohesive set that satisfies a variety of needs. In addition, the standard provides conformance criteria that users can easily understand and apply. Finally, the standard supports tailoring by adding or subtracting processes or their constituents, making these processes widely applicable, yet adaptable to individual needs.

1 A partial and abridged portion of the International Standard ISO/IEC/IEEE 15288, Systems and software engineering System life cycle processes, was reproduced with permission from the Standards Institution of Israel (SII) on behalf of the International Organization for Standardization (ISO). Copyright remains with ISO.

Engineering standards exhibit several advantages. First, they are developed by experts as well as practitioners. As such, they capture widespread communal engineering knowledge and experience. Second, engineering standards define common terminology, thus reducing confusion as well as communication problems. Lastly, engineering standards provide an effective tool guiding the various engineering processes in a methodic and organized manner.

Be that as it may, readers involved in developing, manufacturing, maintaining, or disposing engineered systems are urged to utilize the authentic standard 15288 and not substitute it with the following partial and abridged variation of the standard.

Some philosophical discussion about engineering and science in general concludes this part of the book.

Part II: Systems Engineering is composed of five chapters (Figure 2.1).

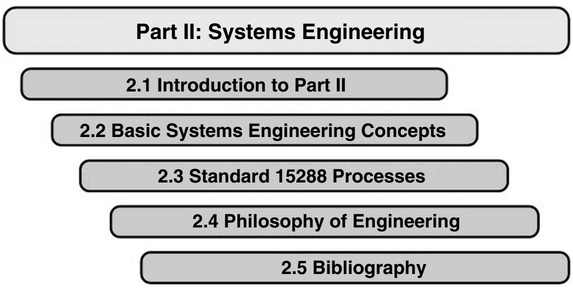

Figure 2.1 Structure and contents of Part II

Chapter 2.1 Introduction to Part II. This chapter describes the contents and structure of Part II.

Chapter 2.2 Basic Systems Engineering Concepts. This chapter describes the basic concepts of systems engineering, including (1) organizations and projects concepts, (2) system concepts, (3) life cycle concepts, and (4) process concepts.

Chapter 2.3 Standard 15288 Processes. This chapter summarizes portions of standard 15288 processes within the following four categories: (1) agreement processes, (2) organizational project-enabling processes, (3) technical management processes, and (4) technical processes.

Chapter 2.4 Philosophy of Engineering. This chapter provides illuminating philosophical thoughts about engineering, including: (1) engineering and truth, (2) the logic of engineering design, (3) the context and nature of engineering design, (4) roles and rules and the modeling of socio-technical systems, and (5) engineering as synthesis – doing right things and doing things right.

Chapter 2.5 Bibliography. This chapter provides bibliography related to Part II topics.