

Systems Engineering

A 21st Century Systems Methodology

Derek K. Hitchins

FIET, FRAeS, FCMI, INCOSE Fellow



John Wiley & Sons, Ltd

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West Sussex PO19 8SQ, England
Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
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John Wiley & Sons Inc., 111 River Street, Hoboken, NJ 07030, USA

Jossey-Bass, 989 Market Street, San Francisco, CA 94103-1741, USA

Wiley-VCH Verlag GmbH, Boschstr. 12, D-69469 Weinheim, Germany

John Wiley & Sons Australia Ltd, 42 McDougall Street, Milton, Queensland 4064, Australia

John Wiley & Sons (Asia) Pte Ltd, 2 Clementi Loop #02-01, Jin Xing Distripark, Singapore 129809

John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, ONT, L5R 4J3

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic books.

Anniversary Logo Design: Richard J. Pacifico

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0470-05856-5

Typeset in 9/11pt Times by Integra Software Services Pvt. Ltd, Pondicherry, India

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

*To my beloved wife,
without whom . . . very little.*

Contents

FOREWORD	xix
PREFACE	xxi
 PART I SYSTEMS: ADVANCES IN SYSTEMS SCIENCE AND THINKING	 1
1 SYSTEMS PHILOSOPHY	3
Emerging Systems Movement	3
The Nature of Systems	5
Causality and Teleology	6
Emergence	7
Life and the Second Law	7
Entropy and Work in Human Organizations	8
Entropy Cycling	9
General Systems Theory and Open Systems	9
Boulding's Classification of Systems	9
Parallels and Isomorphisms	10
The Concept of the Open System	11
Understanding Open System Behavior	12
Gestalt and Holism	13
Indivisibility	14
Interaction dynamics	14
Stability and Steady-state	15
The Systems Approach	16
Systems Thinking	17
Functionalism and the Organismic Analogy	18
The organismic analogy	18
The machine metaphor	19
Mechanistic Control Concepts	19
Organismic Control Concepts	20
Basic Percepts, Concepts and Precepts	21
Emergence and hierarchy	21
Systems as comprised of interacting parts, themselves systems	22
Variety in whole systems	22

Potential synthesis of open systems with desired emergent properties: systems engineering	23
Problem space and solution space	24
Evolving adaptive systems	25
Self-organized criticality	26
Weak chaos	27
System precepts	27
Assignment	29
2 ADVANCES IN SYSTEMS SCIENCE	31
System Theory, System Science	31
Conservation Laws and Transport Phenomena	32
Queuing Phenomena	33
Chaotic Phenomena	35
Lepidoptera Lorenzii?	35
Generating chaos	35
Self-similarity	39
Fractals	39
Period doubling	41
Information: Conserved, or Non-conserved?	42
Systems Science as Natural Science and Social Science	43
Behavior	43
Interpretation and categorization	44
Tacit knowledge	44
World models and world views	44
Interpretation	45
Belief system	45
Instinct and archetype	46
Social and Cultural Anthropology	49
Social Capital	50
Social Genotype	50
Managing Complexity	51
Aggregation of emergent properties	52
Anti-chaos	53
Systems Life Cycles and Entropic Cycling	54
Principle of system reactions	54
Principle of system cohesion	55
Principle of adaptation	55
Principle of connected variety	56
Principle of limited variety	56
Principle of preferred patterns	57
Principle of cyclic progression (entropic cycling)	57
System life cycles: the Unified Systems Hypothesis	58
System longevity: system decay	60
Summary	61
Assignment	62
3 ADVANCES IN SYSTEMS THINKING	63
Scope, Limits and Values	63
Rich pictures	64
Causality and causal loop models	65

Dynamic simulation of phenomena	68
Dynamic interactive systems simulation	71
Behavior modeling	72
Systems Thinking and the Scientific Method	73
Representing and Modeling Systems	74
Nonlinear Systems Thinking	78
Summary	80
Assignments	81

4 SYSTEMS ENGINEERING PHILOSOPHY 83

Why Systems Engineering is Important	83
Early Examples Set the Style	84
Battle of Britain	84
NASA's Apollo	85
Is it 'Systems'?	86
Is it Engineering?	86
Problem Solving, Resolving and Dissolving	87
Systems Engineering: Definitions and Descriptions	88
The Real Objectives of Systems Engineering	91
Strategies for Solving, Resolving or Dissolving the Problem	92
Self-organizing Systems	94
System of Systems	94
Bottom-up Integration	96
Completing the 'Whole' of Systems Engineering . . .	97
Summary	99
Assignments	101

5 SYSTEM MODELS 103

The Open System	103
Simple Nesting and Recursive Models	105
Social Genotype — a Notional Model	106
Cybernetic Models	107
Models of Systems Architecture	108
Beers' Viable Systems Model	110
Open-loop Control Models	112
The 5-layer Systems Model	113
Layer 1: product/subsystem engineering	114
Layer 2: project systems engineering	117
The essence of systems engineering	120
Layer 4: industrial systems engineering	121
Layer 5: Socio-economic systems engineering	122
In Pursuit of Emergence — the Generic Reference Model of any System	124
Whence emergence? Can we purposefully 'design-in' emergence?	124
The generic reference model (GRM) concept	125
Function management	128
Behavior management	130
The generic reference form model	132
The Generic Reference Model in List Form	133

The GRM and the Systems Approach	135
Instantiated layered GRM	138
Does the GRM capture emergence?	141
Comparing the GRM	141
Summary	142
Assignment	142
CASE A: JAPANESE LEAN VOLUME SUPPLY SYSTEMS	145
Introduction	145
Investigation	148
The open system viewpoint	149
Market pull vs production push	152
Kaizen and the assembly line	154
Keiretsu	157
Summary	158
PART II SYSTEMS METHODOLOGY	161
6 OVERVIEW OF THE SYSTEMS METHODOLOGY	163
What is the Systems Methodology?	163
The Social and Economic Potential of the Systems Methodology	164
Systems Methodology — a Paradigm	165
Aspects of the Systems Methodology	165
The scientific dimension	165
The logic and epistemological dimensions	166
The time dimension	167
The cultural/political/behavioral dimensions	168
The moral and ethical dimensions	168
The social dimension	168
The organizational dimension	169
The economic dimension	169
The technological dimension	171
Systems Methodology: Conceptual Model	172
Create a (Better) Systems Methodology?	178
Create an Intelligent, Auto-adaptive, Evolving Solution System?	179
Auto-adaptation and the intelligent enterprise	180
Summary	181
Assignment	182
7 SM1: ADDRESSING COMPLEX ISSUES AND PROBLEMS	185
Problem-solving Paradigms	185
Linear, Complex, Nonlinear and Intelligent System Behavior	186
System Dysfunctions: the POETIC Acronym	186
Soft Systems Approaches	187
Degrees of intervention	188
Consensual Methods	189

Brainstorming	190
Nominal group technique (NGT)	190
Idea writing	190
Warfield's interpretive structural modeling (ISM)	191
Checkland's Soft Systems Methodology (SSM) in Intervention	192
Hitchins' Rigorous Soft Method (RSM) in Intervention	195
Summary	200
Assignment	200

CASE B: THE PRACTICE INTERVENTION **201**

Situation	201
Off-line Informal Investigation using the Rigorous Soft Method (RSM)	202
Hands-on Intervention — using NGT and ISM	208
Comparing the Hands-off RSM Investigation and the Hands-on Intervention	216
Summary	217

8 SM2: EXPLORING THE SOLUTION SPACE **219**

Introduction	219
Approach	219
Boundaries and finite states	220
Environments, influences and interactions	221
Structure and dynamics	222
Resource needs	222
Summary	223
Assignment	224

9 SM3 AND 4: FOCUSING SOLUTION SYSTEM PURPOSE **225**

SM3: Solution System Purpose	225
Threats and strategies	226
SM4: Developing a Concept of Operations (CONOPS)	228
Assignments	230

CASE C: THE TOTAL WEAPON SYSTEM CONCEPT **231**

<i>C (1): The Battle of Britain Command and Control System</i>	231
Introduction	231
Interacting Systems	233
Working up the System — Operational Systems Engineering	234
Let Battle Commence	235
AVM Keith Parks' tactics	238
Battle of Britain Simulation	238
Running the BoB simulation	239
<i>C (2): The Lightning — Realizing the Total Weapon Systems Concept</i>	244
Introduction	244
The Lightning	245
Optimizing the Design	247

The Jamming Problem	249
Digital Data Links to the Rescue	249
The trial	250
Conclusions	251
10 SM5: ARCHITECTING/DESIGNING SYSTEM SOLUTIONS	253
Approach	253
The Functional Design Process	255
The Physical Design Process	258
Output/outcome	261
Summary	262
Assignment	263
11 SM6: OPTIMIZE SOLUTION SYSTEM DESIGN	265
Approach	265
Methods, Tools and Techniques	266
Cost and capability	266
Optimizing the whole	266
Disaster relief example	268
The naval destroyer example	269
Optimizing supply and logistic systems designs	272
Understanding the Design in Context	273
To be Linear or Nonlinear: That is the Question	274
Verification and Validation	275
Summary	276
Assignment	277
12 SM7: CREATE AND PROVE SOLUTION SYSTEM (SOS)	279
Introduction	279
Requirement Specifications	280
Manifesting Different 'Kinds' of System	281
Organizational considerations	283
Integration considerations	283
Operational systems engineering — continual optimization in operation	285
Component of the Whole SoS	285
Summary	287
Assignments	288
13 THE SYSTEMS METHODOLOGY — ELABORATED	289
Ideal World vs Real World	289
The Systems Methodology — as Products	290
The Systems Methodology as a Whole	290
The Systems Methodology — as Process?	291
Outer loop — inner loop design	293
Outer loop, inner loop and systems engineering	294

The Systems Methodology — in Parts and Phases	294
Summary	298
Assignment	299
14 SETTING THE SYSTEMS METHODOLOGY TO WORK	301
Systems Methodology in Phases	301
Systems Methodology as HASs	302
Systems Methodology as Tools	303
Organization for Applying the Systems Methodology and for Systems Engineering	304
SM GANTT charts	306
Teams of teams	307
Team of teams and inner/outer loops	308
Team of teams and system of systems	309
Summary	311
Assignments	311
CASE D: ARCHITECTING A DEFENSE CAPABILITY	313
Note	313
SM1: Explore Problem Space	313
Mojave Maneuvers	313
The 'Real' issue?	319
SM2: Explore Solution Space	320
SM3: Focus SoS Purpose	321
Prime directive and semantic analysis	321
Measures of effectiveness (MOEs)	322
Strategies to achieve objectives, overcome threats	322
Nonlethal weapons	323
Functions from strategies	324
SM4: Develop SoS High-level CONOPS	325
SM5: Part 1. Design Solution System — Functional Design	327
SM5/3 instantiate internal functions	327
SM5/2 instantiate internal behavior	328
SM5/4 assemble SoS internal functions — minimize configuration entropy	329
SM5/5 partition into solution system interacting subsystems	329
SM5/6: Develop SoS internal architecture	330
SM5/7: Formulate Solution System Overview	330
SM5: Part 2. Design Solution System — Functional/Physical Design	332
Intermediate task!	332
SM5/11 Identifying an Option	333
Transportable land element (TLE) design concept	335
UMA/RPVs and weapons	337
Swarming and formation control	339
The chameleon TLE — internal design concept	339
The VSTOL transport aircraft/operations HQ/logistics support	341
SM5/12 Re-do Steps 2–5/7 for each Interacting Subsystem within Optional SoS (Containing System)	342
Command and Control	343
Fractal C ²	344

Design Summary	345
SM6/1 Instantiate as Single Organismic Blue SoS Dynamic Model	345
SM6/1 and 6/2 Instantiate Blue MLF2010 and Red Opposition	346
Summary	347
Conclusion	348

PART III SYSTEMS METHODOLOGY AND SYSTEMS ENGINEERING 349

15 SYSTEMS ENGINEERING — THE REAL DEAL 351

Distinguishing Systems Engineering From the ‘Look-alikes’	351
Distinguishing Systems Engineering From the Engineering of Systems	353
Human — part of the system, or user of the artifact?	353
Linear vs nonlinear	353
Top-down vs bottom-up	354
Flavors of Systems Engineering	354
Unprecedented, one-off systems	354
Evolving systems	355
Extant operational systems	356
Volume manufacturing/supply systems	357
Systems Engineering ‘Strategies’	357
The waterfall	358
The spiral	360
Concurrent	361
Chaos	362
Functional, Project and Program Management	363
‘Eine Kleine Systems Engineering Archaeology’	365
M’Pherson’s system design framework	365
M’Pherson’s design hierarchy for a complex system	366
M’Pherson’s systems engineering organization in project management	367
SEAMS	368
Systems Architectures	370
The effect of systems architecture	371
Systems architectural strengths and weaknesses	371
Architecture analogies	374
Contained and encapsulated systems viewpoints	376
Purposeful Systems Architectures	377
Layered architectures	379
ISO open systems interconnect	380
Command and control architectures	381
Enterprise architectures	382
Human Activity Systems	383
Why human activity systems?	383
The human-machine divide	384
Self-organizing HASs	385
Training	385
Societal Systems	386
Social engineering	389
Summary	392
Assignment	393

16 SYSTEMS CREATION: HAND OF PURPOSE, ROOT OF EMERGENCE 395

The Hand of Purpose Flowing Through Human and Machine	395
Preserving Interfunctional Connections in Functional-to-physical Mapping	397
Emphasizing the Process View	400
Design, Integration and Test	402
Summary	403
Assignment	404

CASE E: THE POLICE COMMAND AND CONTROL SYSTEM 405

The Problem Space	405
Social engineering — irresponsible liberalization?	406
Political correctness: the new secular religion	408
Politics in policing — tough on crime, tough on the causes...	409
The Solution Space	410
Policing in a democracy	410
Changes in policing	411
Hawks, doves, liberals and terrorists	412
Social atomization, fear of crime, and the reactive spiral	412
Progressive reduction in the state of stability	414
The terrorism issue	416
Remedial Solution Concepts	416
Proactive policing, gearing and reactive demand	416
Terrorism changes the picture...	417
Cost-effectiveness of deterrent, crime prevention policing	418
Recruiting proactive police	418
Peacemaking, peacekeeping and peace building: Levels 1, 2 and 3 policing	419
Concepts of Operations	420
Policing models	420
Intelligence-led proactive policing	421
Designing a Solution System	421
Summary and Conclusion	423

CASE F: FIGHTER AVIONICS SYSTEM DESIGN 425

The Problem Space	425
Prescribed Solution	426
Designing the Solution System	426
Flies in the ointment	426
Fighting the aircraft — the missing CONOPS	427
Government reluctance	429
Systems concepts — triangulating ghosts	430
Systems concepts — LANCE	430
Conclusions	431

17 SOS ENGINEERING PRINCIPLES AND PRACTICES 433

Creating, Developing and Evolving a SoS	433
Limitations in SE for SoS	434

Strategy for SoS Engineering	435
'Spinning plates'	436
Continual redesign	436
SoS Architectures	437
SoS pipeline architecture	437
SoS complementary architecture	439
SoS — Unified Whole, or Dissociated Set?	441
Managing Change in a SoS	443
System of Systems Engineering	444
Summary	445
Assignment	446
CASE G: DEFENSE PROCUREMENT IN THE 21ST CENTURY	447
The Problem Space	447
Difficulties in predicting the need	447
Cutting edge of technology — was defense, now commerce	449
Bureaucracy blunting the cutting edge for defense	449
Security	451
Conceptual Remedial Solutions	452
CONOPS	454
System Design	457
Conclusions	458
18 SYSTEMS ENGINEERING: INTELLIGENT SYSTEMS	459
Introduction	459
What is an Intelligent System?	460
Defining Intelligence	461
Kinds of intelligence	461
Intelligence and survival	461
Predicting the future	462
About Making Decisions	463
What Characterizes a Learning Organization/Intelligent Enterprise ...?	465
Situation Facing Intelligent Enterprises	466
Making intelligent choices — intelligent enterprise model	468
Innovative decision-making model	469
Learning and Intelligent Behavior	471
Keeping the Enterprise Intelligent	472
Continual redesign — reprise	473
Summary	473
Assignment	474
CASE H: GLOBAL WARMING, CLIMATE CHANGE AND ENERGY	477
Energy, Demands, Resources and Reserves	477
Global Warming and Climate Change	478
Choices	478

Controlling rising greenhouse gas levels	479
Measures to ameliorate the effects of climate change	479
Rational and Irrational Alternative Energy Sources	480
Hydroelectricity	480
Wind power	481
Tidal flow	481
Wave power	482
Moon power	482
Biomass solar power	482
Alternative summary	483
Nuclear Energy	483
Future Imperfect...	484
Dyson spheres	485
Nuclear winter	485
Volcanic effects on climate	485
Industrial pollution	485
The Case for Active Climate Control	486
Risk from 'doing too little, too late'	486
Remedial Solution Concept	487
Appreciating the problem	487
Regulating the solar constant	488
The L_1 cloud concept	489
L_1 cloud CONOPS	490
The L_1 sunshield concept	490
Sunshield construction	491
L_1 sunshield concept of operations	493
Comparative timescales	493
Risks	494
Critique	494
REFERENCES	497
INDEX	499

Foreword

Derek Hitchins is truly a long term pioneer in systems engineering. He had a variety of experiences, initially serving in the Royal Air Force until his retirement after 22 years service. He subsequently held positions in the public and private sector in a variety of positions including serving as the UK Technical Director for the NATO Air Command and Control System (ACCS), and in two leading systems engineering companies in the UK as Marketing Director, Business Development Director and Technical Director. He first became an academic in 1988.

He was the inaugural president of the UK Chapter of the International Council on Systems Engineering (INCOSE), and also the inaugural chairman of the Institution of Electrical Engineers (IEE) Professional Group on Systems Engineering. He has also been a member of the UK Defense Scientific Advisory Board.

His current research is into system engineering on a broad scale, including: system thinking, system requirements, social psychology and anthropology, command and control system design, and world-class systems engineering. He published his first book titled *Putting Systems to Work* in 1992, and a second book titled *Advanced Systems Thinking, Engineering and Management* in 2003. He has also completed an on-line electronic book titled *Getting to Grips with Complexity* which examines complexity, what is it, how it comes about, and how we can exploit. This, and a description of his other works can be found at <http://www.hitchins.net/SysBooks.html>.

He has accomplished much that should support establishment of systems engineering as the dominant paradigm for managing complexity in industry. His work has done much to develop a large scope view of systems engineering comprising product, project, business, industry and socio-economic levels. His apparent objective in this is to support systems engineering as the route to simultaneous effectiveness, efficiency and quality in industry, government, and education.

This 400 page new work describes this image of systems engineering. It is comprised of 3 major parts and 18 chapters within these parts. There are:

- I SYSTEMS – ADVANCES IN SYSTEMS SCIENCE AND THINKING (1 Systems Philosophy, 2 Advances in Systems Science, 3 Advances in Systems thinking, 4 Systems Engineering Philosophy, 5 System Models)
- II SYSTEMS METHODOLOGY (6 Overview of Systems Methodology, 7 Addressing complex issues and problems, 8 Exploring the Solution Space, 9 Focusing Solution System Purpose, 10 Architecting/Designing system Solutions, 11 Optimize Solution System Design, 12 Create and Prove Solution Systems, 13 Systems Methodology–Elaborated, Setting the Systems Methodology to Work)

III SYSTEMS METHODOLOGY AND SYSTEMS ENGINEERING (15, Systems Engineering – The Real Deal, 16 Systems Creation: Hand of Purpose, Root of Emergence, 17 System of Systems Engineering Principles and Practices, 18 Systems Engineering: Intelligent Systems)

In addition, at appropriate places in the text, 8 pragmatic case studies, based strongly on the systems engineering experiences of the author, are used to good advantage. These are:

- A Japanese Lean Volume Supply Systems
- B Practice Intervention
- C Total Weapon System Concept
- D Architecting a Defense Capability
- E Police Command and Control System
- F Fighter Avionics System Design
- G Defense Procurement in the 21st Century
- H Global Warming, Climate Change and Energy

This book is about the ways to address and resolve problems, from small scale to those of very large scale and scope. This work *Systems Engineering: A 21st Century Systems Methodology* addresses a large variety of problems, and discusses how they might be solved both in theory and in practice. The wide variety of case study presentations illustrate both how issues have been approached in the past and how they might be addressed more effectively in the future.

The author, Derek Hitchins, is familiar with the evolution of systems engineering from its initiation around a half century ago to the present time and has made a number of definitive contributions to system engineering methodology. He demonstrates this knowledge well in this work. In particular, the book presents a systems methodology that can in principle be employed when confronting a very large set of issues and synthesizing potentially appropriate resolution for them. That one single methodology can address systems of all kinds from small technological systems to global socioeconomic systems involving humans, technologies, and organizations may seem unlikely. Such a methodological process has been the goal of systems engineers - thinkers, analysts, architects, integrators, and designers - for several decades. The author sets forth the claim that this has only now become possible as a result of new work. Through use of this approach, he suggests that it should be possible to prove and potentially disprove the acceptability, suitability, viability and optimality of potential resolution to a variety of complex contemporary issues.

There can be no question but what systems engineering pioneer Derek Hitchins has produced a valuable work. It is steeped in its discussions of the early works of other pioneer systems engineers. It is steeped in its knowledge of recent contributions to systems engineering methodology. It is steeped in its synthesis of these into new methodological processes for systems engineering that are original with Professor Hitchins. Thus, it is a distinct pleasure to welcome this book by Professor Hitchins into the Wiley Series on Systems Engineering and Management.

Andrew P. Sage
Editor, Wiley Series on Systems Engineering and Management
21 June 2007

Preface

Systems engineering has been recognized as a discipline for over half a century. It emerged from the study of whole systems and of *gestalt* that started in the first half of the 20th century, and was greatly accelerated by World War II, particularly by the advent of operational research, mathematical modeling and computer-based simulation. Some whole systems exhibited properties that were not exclusively evident in any of their parts, and it was found that these emergent properties, as they were called, could be synthesized by engaging the right system parts in the right way to create a unified whole that was potentially greater than the sum of its parts. Moreover, this seemed to be true for all kinds of systems.

This was, and is, more an organismic view than the mechanistic metaphor adopted by many engineers. Looking at whole systems in this way served, *inter alia*, to reduce perceived complexity. In particular, systems were seen as part of some greater ‘whole,’ open to, and interacting dynamically with, other systems within the environment of that greater whole — as an organ interacts with other organs within a body. Regarding the world in this way became known as ‘the systems approach,’ characterized by addressing whole problems and synthesizing whole solutions, principally to overcome perceived shortfalls in contemporary, piecemeal Cartesian reductionist practices in government, defense, and aerospace engineering.

In the second half of the 20th Century, systems engineering — a practical application of the systems approach — was instrumental in, and further developed during, NASA’s iconic Apollo program, and was widely used in such major defense programs as Polaris, Vanguard, Aegis, Strategic Defense Initiative (SDI), and many more, together with wide application in the developing nuclear power industries on both sides of the Atlantic.

For Apollo, systems engineering had clear goals: the limited rocket payload had to deliver a complete system for going to the Moon and back. The whole system had to comprise a variety of astronauts and technological subsystems operating in close harmony; these had to be organized, arranged, interconnected, modified, etc., so that they fitted within the volume, shape and mass limits, yet operated together as a *unified whole* and exhibiting requisite emergent properties. Achieving this involved continual compromise, test, training, revaluation, and compromise again, to eventually produce an optimum (best) solution, one that would do the seemingly impossible job. The process, notion, and achievement exemplified all that was best in systems engineering. So successful was the enterprise that today some are incredulous, preferring instead to believe in conspiracies to deceive the public and the opposition during this Cold War era.

Europeans who had contributed particularly to the Apollo program returned to their respective countries, taking with them the concepts, processes, methods and practices that they had learned. So, systems engineering was widely adopted, notably by aerospace and defense organizations operating under the NATO umbrella.

The approach adopted by the military, however, changed: it became aimed, not so much towards achieving the unprecedented, innovative and emergent — such as Apollo — as it was aimed at meeting the requirements of military and government customers in terms of timescales, budgets and life cycles. Military engineering staffs pursued a linear mechanistic business-management approach, assuming and stating standards and requirements, decomposing those requirements into discrete functions and subfunctions for the solution system to perform. Then there was ‘specialty engineering,’ including Life Cycle Cost, Supportability, Reliability, Maintainability, Human Engineering, Safety, Electromagnetic Compatibility, Testability, Software, Producibility and Manufacturability, Value Analysis and Design to Cost. Life Cycle Cost, for example, was considered under such headings as:

- predicted costs for basic engineering;
- test and evaluation;
- experimental tooling;
- manufacturing and quality engineering;
- recurring production costs;
- nonrecurring production costs;
- logistics and maintenance support;
- operational costs and disposal costs.

Each of these cost headings was further broken down into many subheadings, in an attempt to cover all conceivable eventualities. The practices created such complexity and complication that the net result became referred to as ‘paper engineering,’ that is, the filling of forms and the ticking of boxes. Ironically, the fundamental concept of ‘systems’ as a way of managing complexity had been turned on its head by this complicated parody of the original. And the notion of ‘system’ in the defense engineering management context seemed to refer more to the thoroughness and comprehensiveness of the reductionist engineering management approach, than to any sense, in system terms, of the whole being greater than the sum of the parts.

US aerospace companies continued to design and engineer excellent aircraft, ships, tanks, etc. Defense engineering management, despite its undoubted high cost overhead, did not appear to detract from the factory design/manufacture of the products; on the other hand, it undoubtedly helped in the provision of through-life support facilities for operational systems.

Not all areas of defense were amenable to this reductionist approach: command and control (C^2) was one such, which, together with non-defense air traffic management, police, fire and ambulance services, government services and many more, constitute a class of systems dubbed IDA (information–decision–action) systems. IDA systems are sociotechnical systems: teams of people undertake tasks, using technological support facilities for acquiring, handling, storing and presenting information, and for supporting decision-making. IDA systems can be highly technological; on the other hand, they can be virtually technology free, depending solely on humans, their intellects and ability to communicate. An individual is, *de facto*, an IDA system in his or her own right.

Typically, teams collect intelligence, assess situations, identify threats and opportunities, develop strategies and plans, decide courses of action — often based on incomplete, even incorrect, information — and implement their plans. The various parts of the IDA system have to act as a unified whole, exhibiting emergent properties, including responsiveness, timeliness, integrity, decisiveness and strategic/tactical flair. Systems engineering continued to develop in the conception, design, development, implementation, work-up and evolution of such nonlinear sociotechnical IDA systems.

It was, however, systems engineering more of the ‘whole exceeds the sum of the parts’ nature than of the ‘systemic engineering management’ variety adopted in the US for defense engineering.

Meanwhile, the 1990s saw a realization in the West that defense ‘systemic engineering management’ version of systems engineering was unsuccessful, even counterproductive. Japanese approaches to procurement and manufacturing were providing a powerful counter-example of how to do these things much more efficiently and effectively; Japanese methods were ‘joined up,’ consensual and synthetic, rather than piecemeal, authoritarian and reductionist. Recognizing the inevitable, the contemporary US administration led the way by discarding their military standards and systemic engineering management practices, seeking instead to adopt Japanese methods, styles and even culture in their revised approaches to defense procurement.

Damage had been done, however: the reputation of systems engineering was tarnished. Redundant US DoD military standards and practices had imprinted a persistent legacy of people, trained and experienced in the DoD practices, who still believed that those methods and practices were sound. Even the core ideas of what systems engineering was about had been subverted. Instead of being associated with innovation, creativity, managing complexity, excellence and integrity, it had become associated with complication, ‘gold-plating,’ introspection and the engineering philosophy of ‘giving the customer what he/she *wants*,’ as opposed to the original: solving the customer’s problem and providing the whole of what the customer *needs*.

The demand for world-class systems engineering persisted, however, and many realized that there had to be a way of creating better systems in all areas and walks of life. The ‘whole systems approach’ was the only rational answer when viewing complex issues and problems; piecemeal practices clearly did not work, more often than not exacerbating issues. Would-be systems engineering practitioners were uncertain as to how to proceed; few could recall the ideas, the vitality, the enthusiasm, the processes and the methods of earlier times. Whereas previously these had been handed down typically within major aerospace companies by successive generations of dedicated systems engineers, now employees might spend as little as three or four years in any one job. The legacy was frittered away.

There had been a vibrant pool of classic systems engineering know-how in the so-called ‘systems houses.’ These were companies, notably in the USA and Europe, which undertook the task of solving customers’ problems objectively by conceiving, designing and providing whole-system bespoke, or ‘turnkey,’ solutions. In general, they were not manufacturing companies — to manufacture would inevitably prejudice objectivity — but instead they either contracted engineering companies to make parts to specification, or selected suitable existing parts that were available in the marketplace and interfaced/integrated them so as to synthesize the whole solution. Systems houses valued their integrity as well as objectivity, and they were generally creative and innovative, but it was not a high-profit business, principally because they did not manufacture and sell hardware. Similarly, there was limited profit in IDA systems, with minimal hardware, some software development and some training of customer’s personnel.

The 1990s saw most systems houses driven out of the systems engineering business by the large aerospace companies, who offered to do the work of the systems houses, particularly concept, feasibility and project definition studies, often for nothing — an offer cash-strapped governments found too tempting to forego. Unfortunately, some aerospace companies were sometimes less than creative, and their solutions were invariably comprised of products from their own product range — not the objective, innovative solution that government was seeking. Further, they had little to offer in relation to IDA systems. This episode illustrated yet another example of the so-called Law of Unintended Consequences, which so often seems to associate with piecemeal initiatives by disjointed government.

Nothing if not resourceful, engineers in industry started to reinvent systems engineering. Instead of working at ‘whole system’ level as had the originators, engineers employed their

reductionist-engineering practices on parts of whole systems. Such linear practices assumed, fundamentally, that the whole is equal to the sum of the parts: no more, no less. So: create the right parts to perform the right functions; integrate/interface/join them to fit into some conceptual architecture; and the result is a product as required by a customer. It all seemed seductively simple and straightforward.

Of course, this did not work when there were humans in the system, as they were inconveniently variable and unpredictable. So, this engineers' version of systems engineering — sometimes referred to, confusingly, as 'the engineering of systems' — did not address such human activity systems, but concentrated on the creation of mechanical, electrical, electronic and electro-optical artifacts. Emergent properties did not exist; or if they did, they were incidental, and probably undesirable. IDA systems were unsuitable subjects, owing to their people content. Similarly, businesses and enterprises were inappropriate subjects for the 'engineering of systems.'

Degree courses in engineering appeared with the sexy term 'systems' added, to turn, e.g., electrical/electronic engineering into electrical/electronic systems engineering, aeronautical systems engineering, mechanical systems engineering, communications systems engineering, and so on, without there being any significant different in course material compared with the straight engineering courses. Similarly, aerospace and engineering companies added 'systems' into their titles, to 'add luster to their cluster,' as the contemporary saying had it, but without any significant change in principles, procedures or practices. And the wider application of systems engineering to sociotechnical and socioeconomic systems languished, at least in the West.

The notion 'system of systems' sprang into being to meet this perceived shortfall. The 'system of systems' (SoS) concept is still not entirely mature, but it seems to refer to the bringing together in some way of a number of extant, independent enterprises or businesses, and referring to the association as a system. Creating a system by integrating a number of extant subsystems has been practiced for many decades. An avionics system in a modern aircraft, for instance, can be created by purchasing and integrating several extant systems: primary and secondary radar systems; automatic flight control systems; attitude sensing and control systems; flight instrumentation systems; communications systems; navigation systems; etc, etc. Is an avionics system a 'system of systems'? It seems not. The jury seems to be still sitting on just what a SoS might be, and if it even qualifies as being a system at all, as opposed to an association, a collection, a family. . . , etc., of systems. Not to be thwarted by such niceties, academics advertised a new subject to be learned, promulgated and practiced: System of Systems Engineering (SoSE.)

Meanwhile, the Japanese global lean industrial supply systems continued to sweep the world, notably in the production of automobiles/motor vehicles. This was (sociotechnical) systems engineering resurgent, but in a different guise, and of a different culture: it was — and is — taking the West's largely reductionist manufacturing industries to the proverbial cleaners.

Throughout this period of change, researchers have been continuing to seek 'systems enlightenment.' So-called soft systems have emerged as a way of addressing complex and fuzzy problems, i.e., those where the objectives may be uncertain. Soft methods are aimed particularly at Human Activity Systems (HAS), and have an underlying concept and theory of systems with which the originators of systems engineering would have been entirely comfortable.

And, it also has to be said that there was a small body of practitioners and researchers who kept faith with the original systems approach to synthesizing all kinds of systems. Their continuing researches have identified new methods and techniques, and have underpinned them with systems science. Today, there are new ideas and new ways of conducting systems engineering that are not only scientifically sound, but also for which there is great need both on local and global scales.

World *Problematic* is a concept created by the Club of Rome to describe the set of the crucial problems facing humanity: environmental, political, cultural, social, economic, technological and psychological. The heart of the World *Problematic* lies in the mutual interdependence of these

problems, and in the long time delay between action/cause on the one hand and reaction/effect, often counterintuitive effect, on the other.

This book is about ways and means of addressing and solving problems, from the small-but-complex, perhaps even to those of the World *Problematic*. *Systems Engineering: A 21st Century Systems Methodology* addresses all kinds of problems, how they might be solved in theory, and how the solutions can be manifested in practice. It also presents a variety of case studies showing how different issues have been tackled in the recent past and how they might be addressed even more effectively in the future.

The book introduces a comprehensive systems methodology (SM) that can, in principle, be employed when tackling any issue or problem and creating a solution to solve it. That one, single methodology can address systems of all kinds from small, technological to global socioeconomic may seem unlikely. Such an SM has been the goal of systems thinkers, analysts, architects and designers for decades, however: it is only now becoming possible as a result of new tools, methods, science and ideas. The SM employs both established and new systems-scientific methods, with provability/falsifiability in mind throughout; it should be possible both to prove and disprove the acceptability, suitability, viability and optimality of potential solutions to a complex problem.

The SM is not a fixed-for-all-time entity. It is a morphing, evolving framework for the generation and management of information, independent of problem, solution, context, or environment, all of which are brought to the methodology by practitioners and proponents seeking to find answers to complex problems. The SM can be adapted, evolved and employed in the exploration and solution of problems of all kinds, at all levels, in any environment and on all scales, in the service of humankind and of our common environment. The Companion website for the book is <http://www.wiley.com/go/systemsengineering>.

Derek Hitchins
April, 2007

Part I

Systems: Advances in Systems Science and Thinking

