# Systems Engineering

## A 21st Century Systems Methodology

**Derek K. Hitchins**

*FIET, FRAeS, FCMI, INCOSE Fellow*

John Wiley & Sons, Ltd

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BICENTENNIAL 1807 WILEY 2007 BICENTENNIAL

John Wiley & Sons, Ltd

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West Sussex PO19 8SQ, England

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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

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 *Problematique* 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 *Problematique* 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 *Problematique*. *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