# SYSTEMS ENGINEERING AND MANAGEMENT FOR SUSTAINABLE DEVELOPMENT

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**Contents**





**Summary**

Sustainable development refers to the fulfillment of human needs through simultaneous socio-economic and technological progress and conservation of the earth's natural resource systems. This theme will discuss the key role of systems engineering and systems management as a provider of the knowledge principles and practices that help realize this integration of economic, technological, natural resource, and environmental efficiency and effectiveness, and support equity in fulfillment of human needs as well.

Sustainable world progress is dependent upon continued economic, social, cultural, and technological progress. To achieve this, careful attention must also be paid to preservation of the earth's natural resources. Sustainable development is a term generally associated with the achievement of increased techno-economic growth and

preservation of the environment and natural resources. It requires the development of enlightened institutions and infrastructure and appropriate risk management to assure intergenerational equity, intragenerational equity, and biodiversity conservation. Each of these issues taken separately poses major challenges for systems engineering and systems management, as does the aggregate issue as well.

A simple functional definition of systems engineering is that it is the art and science of producing a product or a service, based on phased efforts that involve *definition* of the desired end result of the effort followed by *development* of the product or service and culminating with *deployment* of this in an operational setting that satisfies user needs. The product system or service system is functional, reliable, of high quality, and trustworthy; and has been developed within cost and time constraints through use of an appropriate set of methods and tools. In this theme, we are concerned with the engineering of large-scale systems, or systems engineering. We are especially concerned with strategic level systems engineering and the technical direction efforts needed to bring about the engineering of a system, or systems management. We are also very concerned with the role of these in sustainable development.

This theme will discuss: basic principles of systems engineering and management for sustainable development, including: cost effectiveness assessment; decision assessment, tradeoffs, conflict resolution and negotiation; research and development policy; industrial ecology; and risk management strategies for sustainability. The emphasis throughout will be upon the development of appropriate life-cycles for processes that assist in the attainment of sustainable development, and in the use of appropriate policies and systems management approaches to ensure successful application of these processes.

## 1. Introduction

Systems engineering is a management technology, as suggested in Figure 1. Technology refers to the organization, application, and delivery of scientific knowledge for the betterment of a client group. This is a functional definition of technology as a fundamentally human activity. A technology inherently involves a purposeful human extension of one or more natural processes. Management involves the interaction of the organization with the environment. A purpose of management is to enable organizations to better cope with their environments so as to achieve purposeful goals and objectives. Consequently, a management technology involves the interaction of technology, organizations concerned with both the evolution and use of technologies, and the environment. Information and associated knowledge represent the adhesive that enables these interactions and are very important quantities that are assumed to be present in the management technology that is systems engineering. This strongly couples notions of systems engineering with those of technical direction or systems management of technological development, rather than exclusively with one or more of the methods of systems engineering, important as they may be for the ultimate success of systems engineering and systems management efforts.

There are three different life-cycles for technology evolution: system planning and marketing; research, development, test and evaluation (RDT&E); and system acquisition, production, or procurement. These are all generally needed for the evolution of trustworthy products and services, and each primarily involves use of one of the three types of knowledge: knowledge perspectives, knowledge principles, and knowledge practices.

Systems engineers are concerned with the appropriate definition, development, and deployment of systems. These comprise a set of phases for a systems engineering life-cycle. There are many ways to describe the life-cycle phases of systems engineering processes. Each of these models, and those that are outgrowths of them, are comprised of the three phases of definition, development, and deployment. For pragmatic reasons, a typical life-cycle will almost always contain more than three phases. Generally, they take on a “waterfall” like pattern, although there are a number of modifications of the basic waterfall, or “grand-design life-cycle,” to allow for needed incremental and evolutionary development of systems.

Management of the systems engineering process, which is called systems management, is very necessary for success. There are many examples of systems engineering failures at the level of systems management. Often, one result of these failures is that the purpose, function, and structure of a new system are not identified sufficiently before the system is defined, developed, and deployed. These failures are generally the result of costly mistakes that could have been avoided. A major objective of systems engineering, at the strategic level of systems management, is to take proactive measures to avoid these difficulties and also to ensure sustainability.

System management and integration issues are of major importance in determining the effectiveness, efficiency, and overall functionality of system designs. To achieve a high measure of functionality, it must be possible for a system design to be efficiently and effectively produced, used, maintained, retrofitted, and modified throughout all phases of its life-cycle. This begins with need conceptualization and identification, and continues through specification of system requirements and architectures, to ultimate system installation, operational implementation or deployment, evaluation, and maintenance throughout a productive system lifetime.

There are many difficulties associated with the production of functional, reliable, and trustworthy systems of large scale and scope. These potential difficulties, when they are allowed to develop, can create many problems that are difficult to resolve. They include:

- inconsistent, incomplete, and otherwise imperfect system requirements and specifications
- system requirements that do not provide for change as user needs evolve over time
- lack of proper concern for satisfying the functional needs of the customer and inappropriate attention to assurance that the overall life-cycle of product development and use is conservative of natural resource use
- much attention to solving the defined problem correctly, but much less attention to being sure that the correct problem has been defined
- poorly defined management structures for product, or service, development and deployment.

These lead to delivered products and services that are difficult to use, do not solve the intended problems, operate in an unreliable fashion, are not maintainable, are overly consumptive of natural resources and damaging to the environment, and that – as a result – are only used for a very short time. Sometimes these failures are so great that operational products and services are never even fully developed, much less operationally deployed, before plans for the product or system are abruptly canceled.

These same studies generally show that the major problems associated with the production of trustworthy systems have more do with the organization and management of complexity than with direct technological concerns that affect individual subsystems and specific physical science areas. Often the major concern should be more associated with the definition, development, use, and management of an appropriate production process or product line than it is with the actual product itself. Direct attention to the engineering of the product or service system without appropriate attention to the *process* needed to engineer a sustainable system will often lead to a low quality and expensive outcome that is unsustainable.

In many cases, if not most, proper application of one or more technologies is necessary to ameliorate an existing problem or fulfill an existing need through definition, development, and deployment of a system. However, successful application of technology to major problem areas must consider three levels at which solutions may be sought – symptoms, institutions, and values – or we may well be confronted with a technological system looking for a problem. This is especially the case when we approach problems only at the level of such symptoms as unemployment, bad housing, inadequate health care delivery, pollution, hunger, or poverty. A technological fix is found that addresses symptoms only, and the resulting "solutions" create the illusion that the outpouring of huge quantities of money to ameliorate symptoms will actually resolve the fundamental underlying problem. Attacking problems at the level of institutions would allow the design of new institutions and new organizations to make full and effective use of new technologies. This is generally a major improvement on what results when we consider problem abatement only at the level of removal of symptoms. Approaching issues at the level of values enables simultaneous adaptation of human needs, technological capabilities, and sustainability considerations. The need to replace product orientation with functionality orientation, along with the associated changes in consumption patterns, is basically a value change need.

Systems engineering efforts are very concerned with technical direction and management of the process of systems definition, development, and deployment, or systems management. Through adopting and applying the management technology of systems engineering, we aim to ensure that correct systems are designed, and not just that system products are correct according to some potentially ill-conceived notion of what the system should do. Appropriate metrics to enable efficient and effective error prevention and detection at the level of systems management and at the process and product level will result in systems engineering products that are "correct" in the broadest possible meaning of this term. To ensure that correct systems are produced requires that considerable emphasis be placed on the frontend of each of the systems engineering life-cycles.

In particular, there needs to be considerable emphasis on the accurate definition of a system – what it should do, and how people should interact with it – before one is produced and implemented. In turn, this requires emphasis upon conformity to system requirement specifications, and the development of standards to ensure the compatibility, inheritability, and sustainability of system products and services. Such areas as documentation and communication are important in all of this. Thus, we see the need for the technical direction and management technology efforts that comprise systems engineering, and the important role of process and systems management related concerns in this.

There are many ingredients associated with the development of a trustworthy system. From a top down perspective, the following ingredients are surely present:

- systems engineering processes, including process development life-cycle and process configuration management (see also "Life-cycles")
- process risk management, operational level quality assurance and evaluation, and product risk and development standards (see also "Risk management")
- a pattern of systems issues that results in a proper geographic distribution of systems, and their evolution and emergence over time
- metrics for quality assurance and sustainability, and process and product evaluation
- metrics for cost estimation, and product cost and operational effectiveness evaluation (see also "Life-cycle costing")
- strategic quality assurance and management, or total quality management (see also "Total quality management")
- organizational cultures, leadership, and process maturity
- re-engineering at the levels of systems management, organizational processes and product lines, and product.

There are a number of related issues that concern enterprise management and systems integration, economic systems analysis, cognitive ergonomics, and system assessment and evaluation for trustworthiness and sustainability.

These ingredients and issues usually interact with one another, often strongly. One of the first aims of systems management must be to identify an appropriate process life-cycle that is sustainable and that will lead to production of a reliable and durable system. This life-cycle involves a sequence of phases.

These phases include identification of client requirements and the needs for the overall process and product to be sustainable, translation of these requirements into (hardware and) software requirement specifications, development of system architectures, detailed design and production of the system, operational implementation and evaluation, and maintenance of the delivered product or service over time. The precise life-cycle that is followed will depend upon the clients' needs. It will also depend upon such overall environmental factors as existing system components, or subsystems, into which a new system must be integrated, natural resource considerations, and the presence of existing software modules that may be retrofitted and reused as a part of the new system.

This need for system integration brings about a host of systems management and, in many cases, legal and regulatory issues that are much larger in scale and scope that those associated with product development only (see also "Systems integration"). In a similar manner, the development of appropriate system-level architectures is very important as the efficiency and effectiveness of systems architecture greatly affect the ease with which systems can be integrated and maintained and, therefore, of the extent to which an operational system is viewed as trustworthy in satisfying user functional needs, being of high quality, and sustainable (see also "Systems architectures").

Once an appropriate systemic process development life-cycle has been identified, configuration management plans are decided on (see also "Configuration management"). This involves defining a specific development process for the set of life-cycle tasks at hand. Metrics are needed to enable this to be done effectively. These are the metrics of cost analysis, or cost estimation for systems engineering. They include cost and economic estimation for software and information technology based systems. They also include effectiveness analysis or estimation of software productivity indices in various ways. This couples the notion of development of an information technology or software (or other) product to notions concerning the process needs associated with developing this product. It is becoming widely recognized that these metrics and indices must form part of a process management approach for process, and ultimately product, improvement if substantial progress is to be made in such important areas as sustainability.

Thus, there are a large number of issues associated with systems engineering as a catalyst for innovation, quality, and sustainable development. There are four principle messages developed that provide benchmarks for the efforts in this theme.

- Much contemporary thought concerning innovation, productivity, sustainability, and quality can be easily cast into a systems engineering and management framework.
- Industrial ecology, and information ecology and knowledge management efforts, and organizational and infrastructure re-engineering efforts are a natural compliment to systems engineering and management perspectives.
- The overall framework for sustainability can be valuably expressed within systems engineering and management.
- The information technology revolution provides the necessary tool base that, together with systems engineering and systems management, provides the wherewithal to allow the necessary process level improvements for the development of sustainable systems of all types.

Further, the relatively large number of ingredients required to accomplish the needed changes fit well within a systems engineering framework. Our discussions also illustrate that systems engineering constructs are useful not just for managing major systems engineering projects according to government and industry requirements, but also for creative management of the organization itself.

Here, we discuss some fundamental introductory considerations associated with the engineering of large-scale systems, or systems engineering. We begin by considering the need for systems engineering, and then providing several definitions of it. We next present a discussion of systems engineering processes or systems engineering life-cycles. A life-cycle is the product line, or process, that is used to create a product or service, or perhaps even another process. We will also discuss the three functional levels, or considerations, that are associated with systems engineering:

- systems methods and tools
- systems engineering life-cycle processes, or methodology
- systems management.

Our major focus in most of this theme is on methods and processes both for systems engineering and for problem solving through use of a systems engineering approach. Here we aim to provide an overview of where we wish to go. We will also attempt to indicate what it is that systems engineers do, and what a large-scale system is. We will provide a brief indication of the history of systems engineering and will also discuss some of the associated challenges and pitfalls. In a subsequent section, we will discuss a framework or methodology for systems engineering. We will indicate that this framework is generally comprised of three fundamental steps:

- issue formulation, such as to identify the needs to be fulfilled and the requirements associated with these in terms of objectives to be satisfied, constraints and alterables that affect issue resolution, and the generation of potential alternate courses of action
- issue analysis, such as to enable us to determine the impacts of alternative courses of action, including possible refinement of these alternatives
- issue interpretation, such as to enable us to rank order the alternatives in terms of need satisfaction and to select one for implementation or additional study.

We will apply these systems engineering steps of formulation, analysis, and interpretation to a variety of situations that should enable us to develop an understanding of systems engineering and problem solving efforts.

## 2. Systems Engineers

What do systems engineers do? The answer to this question is ostensibly straightforward. They *define, develop, and deploy systems of all types*. The systems (products or services) they engineer usually involve many considerations associated with both the users or clients who want them and the implementation specialists who much ultimately produce or manufacture them. Thus, systems engineering is a human, organizational, and technology based effort that is inherently multi-disciplinary and transdisciplinary in nature. Often, it is said that systems engineers deal with systems that are large in scale and large in scope. Sometimes it is said that these systems are "complex:" they comprise many parts that are related to each other in ways that are often not fully understood, that evolve over time, and emerge in often unpredictable ways.

Systems engineers often lead teams of experts in various areas of disciplinary specialization who work together in efforts that are wide in scope, in that they involve human, economic, technical, environmental, and other considerations. This is sometimes called systems management. Many examples of large-scale systems can be found by looking at big projects that are typically coordinated by the systems engineering department of many modern companies. These include airport planning and operations, command-and-control systems, management information systems, software development projects, urban planning, plant layout and manufacturing operations, Internet and telecommunications systems, and especially the plethora of issues that affect sustainable development, to name but a few.

Often system engineers build relatively inexpensive models of proposed projects to refine and test new ideas. Such prototypes can save much time and money by allowing experimentation so as to avoid mistakes that, in the "real" system, could be very expensive and possibly even dangerous. System failures may be expensive to diagnose and correct, though they are often not difficult to detect. Because systems engineers know how to analyze and understand complicated situations, they are often called on to organize knowledge for executive decision-makers. In this role, they perform systems analyses to develop and evaluate policies and programs and typically function as consultants or as technical direction and staff support to management. Thus, in developing and implementing large-scale systems, systems engineers must also understand and appreciate human, organizational, and behavioral concerns, as well as concerns involving technology.

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perspective when dealing with many contemporary issues, including a chapter on transdisciplinarity in systems engineering and management.]

**Biographical Sketch**

**Andrew P. Sage** received the BSEE degree from the Citadel, the SMEE degree from MIT, and the Ph.D. from Purdue, the latter in 1960. He received honorary Doctor of Engineering degrees from the University of Waterloo in 1987 and from Dalhousie University in 1997. He has been a faculty member at several universities and, in 1984 he became First American Bank Professor of Information Technology and Engineering at George Mason University and the first Dean of the School of Information Technology and Engineering. In 1996, he was elected as Founding Dean Emeritus of the School and also was appointed as a University Professor. He is an elected Fellow of the Institute of Electrical and Electronics Engineers, the American Association for the Advancement of Science, and the International Council on Systems Engineering. He is editor of the John Wiley textbook series on Systems Engineering and Management, the INCOSE Wiley journal Systems Engineering and is co-editor of Information, Knowledge, and Systems Management. In 1994 he received the Donald G. Fink Prize from the IEEE, and a Superior Public Service Award for his service on the CNA Corporation Board of Trustees from the US Secretary of the Navy. In 2000, he received the Simon Ramo Medal from the IEEE in recognition of his contributions to systems engineering and an IEEE Third Millennium Medal. He has been elected to the US National Academy of Engineering in 2004. His interests include systems engineering and management efforts in a variety of application areas including systems integration and architecting, re-engineering, and industrial ecology and sustainable development.