SECTION 2

SYSTEMS ENGINEERING AND SYSTEMS MANAGEMENT

The origins of systems engineering concepts are indeterminate, although the complexity of weapons systems and other military systems during World War II helped formalize the practice. It would be impossible to approach anything near optimization of today's complex systems without the use of systems engineering. It should be no surprise that an important element of systems engineering is the partitioning of a system into smaller components that are more readily managed. But this leads to the necessity for careful, considered communication between and among engineers working on distinctive subsystems, attention to interdisciplinary issues, and an overall management philosophy (and practice) that fosters good communication and good systems engineering at all phases of a system's life cycle.

The two chapters in this section are designed to define the various facets of systems engineering and systems management and to identify some of the techniques and procedures employed in its practice. D.C.

In This Section:

On the CD-ROM:

- Sage, A. P., and W. B. Rouse, "Discretionary Uses of Systems Engineering."
- Sage, A. P., and W. B. Rouse, "Levels of Understanding, Knowledge Management, and Systems Engineering."

CHAPTER 2.1

INTRODUCTION TO SYSTEMS ENGINEERING

Andrew P. Sage, William B. Rouse

FACETS AND DEFINITIONS

In this chapter, we summarize relevant facets of systems engineering support for management that we believe are essential to the definition, development, and deployment of innovative technologies that feature electronics engineering contributions.

Systems engineering generally involves breaking down a large problem into smaller component problems that are more easily resolved, determining the solution to this collection of subproblems, and then aggregating the solutions such that, hopefully, resolution to the initial larger problem or issue results.

A simple functional definition of systems engineering is that systems engineering is the art and science of producing a product or a service, or a process—based on phased efforts that involve *definition* or the desired end result of the effort followed by *development* of the product or service or process, and culminating with *deployment* of this in an operational setting—that satisfies user needs. The 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.

PURPOSES AND APPLICATIONS

The purposes of systems engineering can be defined as follows: *Systems engineering is management technology to assist and support policymaking, planning, decision-making, and associated resource allocation or action deployment*. Systems engineers accomplish this by quantitative and qualitative *formulation, analysis*, and *interpretation* of the impacts of action alternatives on the needs perspectives, the institutional perspectives, and the value perspectives of their clients or customers. Each of these three steps is generally needed in solving systems engineering problems. Issue formulation is an effort 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 generation of potential alternate courses of action. Issue analysis enables us to determine the impacts of the identified alternative courses of action, including possible refinement of these alternatives. Issue interpretation helps to rank order the alternatives in terms of need satisfaction and to select one for implementation or additional study.

This particular listing of three systems engineering steps and their descriptions is rather formal. Issues are often resolved this way, especially when there is initially only limited experiential familiarity with the issue under consideration. The steps of formulation, analysis, and interpretation may also be accomplished on an "as-if" basis by application of a variety of often-useful heuristic approaches. These may well be quite appropriate in situations where the problem solver is experientially familiar with the task at hand and the environment into which the task is embedded, so as to enable development of an appropriate context for issue resolution. This requires information. It also requires knowledge, as information embedded into experience-based context and environment, and this may lead to very useful heuristic approaches to use of this knowledge.

The systems approach gains ready acceptance if one or more of these characteristics apply:

1. Complexity cannot be otherwise addressed, and a completely intuitive and unorchestrated approach simply will not work.
2. We are dealing with high-risk situations, and the consequences of errors are too large to be acceptable.
3. There are major investments involved and the potential loss of financial resources because use of inefficient processes to engineer the system is unacceptable.

HUMAN AND SOCIETAL FACTORS

One of the most essential notions is that systems engineering does not deal exclusively with physical products. While the ultimate aim of systems engineering efforts may well be to produce a physical product or service, there are humans and organizations involved, as well as technologies.

Systems engineering and systems management concern more than the specific technical efforts that occur inside a factory. One of the major needs is for a multiple perspective viewpoint across the various issues affecting the engineering of systems. Fundamentally, systems engineers act as brokers and communicators of knowledge across the various stakeholders having interest in a given issue concerned with product or service deployment. These certainly include the enterprise organization for which a system is being engineered. It also includes the technology implementation organization(s) that will be responsible for the detailed internal design efforts needed to bring about a system. This is represented in Fig. 2.1.1. The issues being considered may also

		Information interrogatives				Knowledge interrogatives	
		Entities (what)	Time (when)	Locations (where)	People (who)	Functions/ activities (how)	Purpose/ motivation (why)
Stakeholders	Policy makers						
	Planners						
	Enterprise owners						
	Systems engineers/ architects						
	Builders						
	Impacted publics						

FIGURE 2.1.1 Perspectives of stakeholders to systems engineering and management issues.

Contextual awareness interrogatives / Stakeholder views or perspectives	Entities (What)	Places (Where)	People (Who)	Timing (When)	Functions (how)	Purposes (Why)
Enterprise						
Systems engineering						
Implementation specialists						

FIGURE 2.1.2 Multiple perspectives framework for engineering a system.

include impacted publics and public sector policy-making bodies, especially when the system being engineered has public sector impacts and implications.

A reduced perspective version of this figure is shown in Fig. 2.1.2. The three rows here correspond to the enterprise perspective, which represents that of the group which desires the system, the systems engineering and management perspective, and the perspective of the group or organization that physically implements the system. The columns contain a total of six interrogatives. The first four of these (what, where, who, and when) generally correspond to structural elements or interrogatives needed to represent the structural issues associated with the phase (definition, development, and deployment) of the system being engineered. The "how" element or interrogative generally corresponds to a functional and activity-based representation of the phase of the system being engineered, and the "why" element generally corresponds to purposeful interrogatives associated with the phase of the system being engineered. It is generally felt that we may define subject matter from a structural, functional, or purposeful perspective. Thus, the representations shown in Figs. 2.1.1 and 2.1.2 are very useful and generally comprehensive ones.

The need for this multiple perspective viewpoint is a major one for successful systems engineering practice. It is a major need in developing an appropriate framework for a system to be engineered, as represented in Fig. 2.1.1.

Systems engineering, applied in its best sense, approaches the problem at three levels: symptoms, institutions and infrastructures, and values. Too often, problems are approached only at the level of symptoms: bad housing, inadequate healthcare delivery to the poor, pollution, hunger, and so forth. "Technological" fixes are developed, and the resulting hardware creates the illusion that solution of real-world problems requires merely the outpouring of huge quantities of funds. Attacking problems at the level of-institutions and infrastructures, such as to better enable humans and organizations to function, would allow the adaptation of existing organizations, as well as the design of new organizations and institutions, to make full and effective use of new technologies and technological innovations and to be fully responsive to potentially reengineered objectives and values. Thus, human and organizational issues are all important in seeking technological solutions. Approaching issues in a satisfactory manner at all three levels will guarantee not only that we resolve issues correctly, but will also guarantee that we resolve the correct issues.

BARRIERS TO ADOPTION

There are significant barriers to adoption of the full armament of systems engineering and management. However, a few central elements of this body of concepts, principles, processes, and methods and tools can be adopted and exploited quite easily. Perhaps most central is the basic question: What's the system? At the very least, the overall enterprise, rather than a particular product, is usually the system that provides the context for formulation, analysis, and interpretation. In many cases, it is important and useful to define the system as the enterprise, competitors, markets, and economy. This broader view enables clearer understanding of the full range of stakeholders and interests.

With the scope of the system defined, the choice among elements of the systems approach depends on the purpose of the effort at hand. It is useful to think of the purposes of the systems engineering and management approach to include understanding, prediction, control, adaptation and emergence, and design. Understanding why the system behaves as it does is a starting point. Predicting what it will do in the future is the next step. Affecting what it will do next, that is to say controlling it or planning for emergence and adaptation, is next. Finally, designing the system to achieve desired objectives involves the full scope of systems engineering and management. Adoption of the systems engineering and management approach involves deciding how to implement the associated activities so as to achieve organizational objectives.

Regarding barriers to adoption and use, it is quite possible to view these as elements of the overall system. This requires adding stakeholders and issues related to power, culture, and so forth. The tasks of formulation, analysis, and interpretation across each of the phases of a systems engineering effort are correspondingly more complicated, but there is, we hope, a greater opportunity for issue resolution by implementing them in a thoughtful manner.

There are many complex situations where the systems approach is warranted, but, being perceived as discretionary, does not gain wide acceptance. These are discussed on the accompanying CD-ROM under "Discretionary Uses of Systems Engineering" (Sage and Rouse).

THE SYSTEMS VIEWPOINT

The systems viewpoint stresses that there usually is not a single correct answer or solution to a large-scale issue. Instead, there are many different alternatives that can be developed and implemented depending on the objectives the system is to serve and the values and perspectives of the people and organizations with a stake in the solution such that they are rightfully called stakeholders. A system may be defined simply as a group of components that work together in order to achieve a specified purpose. Purposeful action is a basic characteristic of a system. A number of functions must be implemented in order to achieve these purposes. This means that systems have functions. They are designed to do specific tasks. Systems are often classified by their ultimate purpose: service-oriented, product-oriented, or process-oriented systems. We note here that the systems considered by systems engineers may be service systems, product systems, process systems, or management systems. The systems may be systems designed for use by an individual or by groups. These systems may be private sector systems, or they may be government or public sector systems.

SYSTEMS THINKING

"Systems thinking" may be defined in part by the following elements (Senge, 1990):

1. Contemporary and future problems often come about because of what were presumed to be past solutions.
2. For every action, there is a reaction.
3. Short-term improvements often lead to long-term difficulties.
4. The easy solution may be no solution at all.
5. The solution may be worse than the problem.
6. Quick solutions, especially at the level of symptoms, often lead to more problems than existed initially. Thus, quick solutions may be counterproductive solutions.
7. Cause and effect are not necessarily related closely, either in time or in space. Sometimes actions implemented here and now will have impacts at a distance and much later time.
8. The actions that will produce the most effective results are not necessarily obvious at first glance.
9. Low cost and high effectiveness do not necessarily have to be subject to compensatory tradeoffs over all time.
10. The entirety of an issue is often more than the simple aggregation of the components of the issue.
11. The entire system, comprising the organization and its environment, must be considered together.

Systems thinking alone is insufficient for success of an organization. Other necessary disciplines include personal mastery through proficiency and lifelong learning; shared mental models of the organization's markets and competition; shared vision for the future of the organization; and team learning (Argyris and Schon, 1978).

Minimizing Ambiguity

Information and Knowledge. One of the major tasks of management planning and control is that of minimizing the ambiguity of the information that results from the organization's interaction with its external environment (Weick, 1979).

This task is primarily that of systems management or management control. It is done subject to the constraints imposed by the strategic plan of the organization. In this way, the information presented to those responsible for task control is unequivocal. This suggests that there are appropriate planning and control activities at each of the functional levels in an organization. The nature of these planning and control activities is different across these levels, however, as is the information that flows into them.

Various systems-based approaches to management experience periodic naissance and revival. Characteristically, these revivals are associated with the rediscovery that dynamic phenomena and feedback loops abound in the worlds of organizations. Another common motivation is rediscovery of the importance of getting "out of the box" of looking at microlevel details and looking at the "whole system" from both "inside the box" (system) and "outside the box" from the perspective of all the stakeholders who are impacted by the system.

KNOWLEDGE MANAGEMENT

Efficient Knowledge Conversion

Knowledge management in systems engineering, as in a more general sense, is a very broad concept, and involves many complex interactions between people, process, and technology. Depending on the objectives at hand, knowledge management activities may focus on the explicit or tacit knowledge, or may focus on an integrated approach that considers both explicit and tacit knowledge (Nonaka and Takeuchi, 1995). The Nonaka and Takeuchi theory of knowledge creation comprise four knowledge conversion stages as suggested in Fig. 2.1.3: socialization, externalization, combination, and internalization. The conversion takes place in five

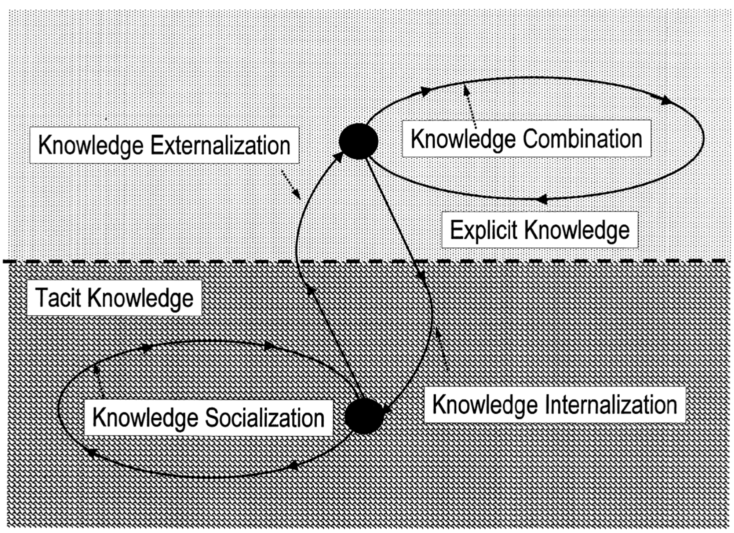
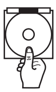


FIGURE 2.1.3 Representation of the four modes of knowledge conversion.

phases: sharing of tacit knowledge, creating concepts, justifying concepts, building an archetype, and cross-level knowledge. Critical to this theory is the concept of levels of knowledge: individual, group, organizational, and interorganization. Sharing primarily occurs during the socialization, externalization, and combination stages. During the socialization stage, sharing occurs primarily at the individual and group levels. In the externalization stage, knowledge is codified and shared at group and organizational levels. In the cross-leveling of knowledge phase, an enterprise shares knowledge both intra- and interorganizationally. This may result in different knowledge content being associated with some emerging issue and thereby enable knowledge creation.

The distinctions between data, information, and knowledge are important. Data represent points in space and time that relate to particular temporal or spatial points. Information is data that are potentially relevant to decision-making. Thus, information relates to description, definition, or outlook. Generally, information is responsive to questions that relate to structural issues of *what*, *when, where*, or *who*. Knowledge is information embedded in context and may comprise approach, method, practice, or strategy. Generally, knowledge is responsive to questions that relate to functional issues associated with a *how* interrogative, It is sometimes desirable to distinguish wisdom as a higher-level construct that represents insights, prototypes or models, or principles and which would be responsive to questions concerning purpose or *why*. If the distinction is not made, knowledge is needed to respond to the *how* and *why* questions that are generally associated with function and purpose. These six important questions or concerns might be collectively called "contextual awareness interrogatives."

Each of these six interrogatives is important and is needed to be responsive to broad scope inquire regarding modern transdisciplinary endeavors. Systems engineering is one such area.



Knowledge management involves levels of understanding that may differ for various actors in a systems project. For a more detailed discussion of this topic, see "Levels of Understanding, Knowledge Management, and Systems Engineering" (Sage and Rouse, 1999) on the accompanying CD-ROM.

Organizations are beginning to realize that knowledge is the most valuable asset of employees and the organization. This recognition must be converted into pragmatic action guidelines, plans, and specific approaches. Effective management of knowledge, which is assumed to be equivalent to effective management of the environmental factors that lead to enhanced learning and transfer of information into knowledge, also requires organizational investments in terms of financial capital for technology and human labor to ensure appropriate knowledge work processes. It also requires knowledge managers to facilitate identification, distribution, storage, use, and sharing of knowledge. Other issues include incentive systems and appropriate rewards for active knowledge creators, as well as the legalities and ethics of knowledge management. In each of these efforts, it is critical to regard technology as a potential enabler of human effort, not as a substitute for it.

BIBLIOGRAPHY

Argyris, C., and D. A. Schon, "Organizational Learning: A Theory of Action Perspective," Addison Wesley, 1978.

Brown, J. S., and P. Deguid, "The Social Life of Information," Harvard Business School Press, 2000.

Cook, S. D. N., and J. S. Brown, "Bridging Epistemologies: The Generative Dance Between Organizational Knowledge and Organizational Knowing," *Organization Science*, Vol. 10, No. 4, July–August 1999.

Morgan, G., "Images of Organization," Sage Publications, 1986.

Nonaka, I., and H. Takeuchi, "The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation," Oxford University Press, 1995.

Polanyi, M., "The Tacit Dimension," Doubleday, 1996.

Popper, K. R., "Objective Knowledge: An Evolutionary Approach," Clarendon Press, 1972.

Rouse, W. B., "Don't Jump to Solutions: Thirteen Delusions That Undermine Strategic Thinking," Jossey-Bass, 1998.

Rouse, W. B., "Essential Challenges of Strategic Management," Wiley, 2001.

Sage, A. P., "Systems Engineering," Wiley, 1992.

Sage, A. P., "Systems Management for Information Technology and Software Engineering," Wiley, 1995.

Sage, A. P., and C. D. Cuppan, "On the Systems Engineering and Management of Systems and Federations of Systems," *Information*, *Knowledge*, *and Systems Management*, Vol. 2, No. 4, 2001.

Sage, A. P., and W. B. Rouse (eds.), "Handbook of Systems Engineering and Management," Wiley, 1999.

Sage, A. P., and W. B. Rouse, "Information Systems Frontiers in Knowledge Management," *Information Systems Frontiers*, Vol. 1, No. 3, October 1999.

Senge, P. M., "The Fifth Discipline: The Art and Practice of the Learning Organization," Doubleday/Currency, 1990.

Von Krogh, G., K. Ichijo, and I. Nonaka, "Enabling Knowledge Creation: How to Unlock the Mystery of Tacit Knowledge and Release the Power of Innovation," Oxford University Press, 2000.

Weick, K. E., "The Social Psychology of Organizing," Addison Wesley, 1979.

Zachman, J., "A Framework for Information Systems Architecture," *IBM Systems Journal*, Vol. 26, No. 3, 1987.

Zachman, J., "Enterprise Architecture: The Issue of the Century," and "The Framework for Information Architecture," 2002, available at http://www.zifa.com/articles.htm.

ON THE CD-ROM

Sage, A. P., and W. B. Rouse, "Discretionary Uses of Systems Engineering."

Sage, A. P., and W. B. Rouse, "Levels of Understanding, Knowledge Management, and Systems Engineering."