

Part I

Primer

COPYRIGHTED MATERIAL

Chapter 1

Introduction

Sys-tem (sĭs' təm) *n.*

1. A group of interacting, interrelated, or interdependent elements forming a complex whole.
2. A functionally related group of elements, especially:
 - a. The human body regarded as a functional physiological unit.
 - b. An organism as a whole, especially with regard to its vital processes or functions.
 - c. A group of physiologically or anatomically complementary organs or parts: *the nervous system; the skeletal system.*
 - d. A group of interacting mechanical or electrical components.
 - e. A network of structures and channels, as for communication, travel, or distribution.
 - f. A network of related computer software, hardware, and data transmission devices.
3. An organized set of interrelated ideas or principles.
4. A social, economic, or political organizational form.
5. A naturally occurring group of objects or phenomena: the solar system.
6. A set of objects or phenomena grouped together for classification or analysis.
7. A condition of harmonious, orderly interaction.
8. An organized and coordinated method; a procedure.
9. The prevailing social order; the establishment. Used with: *You can't beat the system.*

[Late Latin *systema*, *systemat-*, from Greek *sustēma*, from *sunistanai*, to combine: *sun-*, *syn-* + *histanai*, set up, establish.]

Source: Answers.com: American Heritage

In the systems approach, concentration is on the analysis and design of the whole, as distinct from . . . the components or parts . . . The systems approach relates the

technology to the need, the social to the technological aspects; it starts by insisting on a clear understanding of exactly what the problem is and the goal that should dominate the solution and lead to the criteria for evaluating alternative avenues . . . The systems approach is the application of logic and common sense on a sophisticated technological basis . . . It provides for simulation and modeling so as to make possible predicting the performance before the entire system is brought into being. And it makes feasible the selection of the best approach from the many alternatives.

(Ramo, 1969, pp. 11–12)

1.1 WHAT IS A SYSTEM?

A system is a set of elements so interconnected as to aid in driving toward a defined goal. There are three operative parts to this short definition. First is the existence of a set of elements—that is, a group of objects with some characteristics in common. All the passengers who have flown in a Boeing 787 or all the books written on systems engineering form a set, but mere membership in a definable set is not sufficient to form a system according to our definition. Second, the objects must be interconnected or influence one another. The members of a football team then would qualify as a system because each individual’s performance influences the other members. See Ackoff (1971) for an interesting taxonomy of systems concepts (also see Whitehead *et al.*, 2014).

Finally, the interconnected elements must have been formed to achieve some defined goal or objective. A random collection of people or things, even if they are in close proximity and thus influence each other in some sense, would not for this reason form a meaningful system. A football team meets this third condition of purposefulness, because it seeks a common goal. While these three components of our working definition fit within American Heritage’s definitions, we should note that we are restricting our attention to “goal-directed” or purposeful systems, and thus our use of the term is narrower than a layman’s intuition might indicate.¹

It must be possible to estimate how well a system is doing in its drive toward the goal, or how closely one design option or another approaches the ideal—that is, more or less closely achieves the goal. We call this measure of progress or achievement the *Index of Performance (IP)* (alternatively, *Measures of Effectiveness [MOE]*, *Performance Measures [PM]*, *etc.*). Proper choice of an Index of Performance is crucial in successful system design. A measurable and meaningful measure of performance is simple enough in concept, although one sometimes has difficulty in conveying its importance to a client. It is typically complex and challenging in practice, however, to establish an index that is both measurable and meaningful. The temptation is to count what can be counted if what really matters seems indefinable. Much justifiable criticism has been directed at system analysts in this regard (Hoos, 1972; Syme *et al.*, 2011). The Index of Performance concept is discussed in detail in Section 2.3.

Our definition of a system permits components, or the entire system in fact, to be of living form. The complexity of biological systems and social systems is such that complete mathematical descriptions are difficult, or impossible, with our present state of knowledge. We must content ourselves in such a situation with statistical or qualitative descriptions of the influence of elements one on another, rather than complete analytic and explicit functional relationships. This presents obvious objective obstacles, as well as more subtle subjective difficulties. It requires maturity by the system team members to work across disciplinary boundaries toward a common goal when their disciplinary methodologies are different not only in detail but in kind.

From these efforts at definition, we are forced to conclude that the words “system,” “subsystem,” and “parameter” do not have an objective meaning, independent of context. The electric utility of a region, for example, could be a system, or a subsystem, or could establish the value of a parameter depending on the observer’s point of view of the situation. An engineer for the Detroit Edison Company (DTE Energy) could think of his electric utility as a system. Yet, he would readily admit that it is a subsystem in the Michigan Electric Coordinated System (MECS), which in turn is connected to the power pool covering the northeastern portion of the United States and eastern Canada. On the other hand, the city planner can ignore the system aspect of Detroit Edison and think of it merely supplying energy at a certain dollar cost. This is so if it is reasonable for him to assume that electricity can be provided in any reasonable amount to any point within the region. In this sense, the cost of electricity is a regional parameter. The massive Northeast U.S. power failure in 2003, along with the resulting repercussions directly affecting over 50 million people, clearly illustrates the regional nature of these systems.

That the function of an object and its relationship to neighboring objects depends on the observer’s viewpoint must not be considered unusual. Koestler, for example, argues persuasively that this is true for all organisms as well as social organizations. For these units, which we have called “systems,” he coins the term “holon.”

But “wholes” and “parts” in this absolute sense just do not exist anywhere, either in the domain of living organisms or of social organizations. What we find are intermediate structures or a series of levels in an ascending order of complexity: sub-wholes which display, according to the way you look at them, some of the characteristics commonly attributed to wholes and some of the characteristics commonly attributed to parts. . . . The members of a hierarchy, like the Roman god Janus, all have two faces looking in opposite directions: the face turned toward the subordinate levels is that of a self-contained whole; the face turned upward toward the apex, that of a dependent part. One is the face of the master, the other the face of the servant. This “Janus effect” is a fundamental characteristic of sub-wholes in all types of hierarchies.

(Koestler, 1971)

This issue is further confused by the recent extensive use of the term “system-of-systems” or SoS, which refers to systems whose level of complexity creates emergent behavior and where the level of decision making and stakeholder values becomes difficult to determine.

Some uses of the term SoS apply to extremely *complicated* systems with many independently functioning but highly integrated subsystems such as might be found in a modern commercial or military aircraft or in an advanced manufacturing system with all of its associated logistics. While the system is, indeed, *complicated* and much care must be taken to understand, model, design, optimize, and test all of the many interfaces and scenarios under which the system must perform, the system is still very much the product of careful design around well thought-out functional requirements and operational objectives.

Other uses of the term SoS apply to systems that exhibit great *complexity* in which the emergent interactions and outcomes are difficult to model or anticipate and may not reflect any particular design intent, for better or worse. In this case, use of the word “system” may be applied without ever acknowledging or agreeing on the major objectives of the “system”—as in health care system, education system, economic system, and environmental system—and the best we can do is attempt to describe and understand the emergent behavior, regardless of whether or not we can influence or control the outcome.

The more formal use of SoS has been led by the U.S. Department of Defense and associated organizations (see Nielsen (2015), for an overview of SoS). Whether such SoS requires different methodologies is up for debate; however, the discussion has been evolving for over 60 years, with efforts in the 1980s and earlier on “meta-systems” methodology and S2 (*e.g.*, Sage (1981), Eisner *et al.* (1991), Jackson and Keys (1984)).

1.2 TERMINOLOGY CONFUSION

Because one is often introduced to system analysis in a specific context, it may be confusing subsequently to find the method used in an entirely different context. Engineering students, for example, may follow a “systems” curriculum that specializes in automatic control, communications theory, computer science, information retrieval, and so on, and which entirely excludes general system planning and policy-oriented questions (Brown and Scherer, 2000; Pyster *et al.*, 2012). Students of management may think of fiscal control or ERP (Enterprise Resource Planning) “systems” when they use the phrase “system analysis.” We have sewage systems, social systems, and fantasy football team selection systems. Perhaps Koestler was wise to avoid the word “system” entirely, but then again, he only renamed the problem. Here is an example of a dual use of the word “system” that resulted in initial confusion by members of a government advisory panel.

A panel of engineers was requested by the federal government to establish the future research and development needs in the field of high-speed ground transportation (HSGT) (U.S. Department of Commerce, 1967; Herbert, 1968). The panel originally conceived the study in the categories shown in Figure 1.1. It soon became apparent, however, to the “system” subpanel that a number of the tasks, which they had been asked to consider, fell into the category we will call “general system planning.” Such items as subsystem interaction, reliability, and system management are

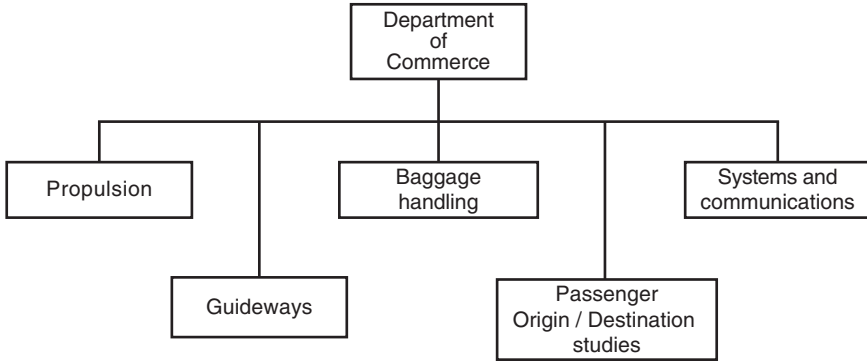


Figure 1.1 The original HSGT study concept. The Department of Commerce wished to assemble a study team to establish the concept of high-speed ground transportation (HSGT) on a conceptually correct basis. Originally, it felt that the study should have the five units shown above. However, when the team of experts assembled, they discovered that there existed considerable confusion as to the meaning of the “systems and communications” unit.

included in this category. Yet what about communications and control, the question of a single, overall centralized control computer system versus many individual machines, or the reporting of the position and velocity of individual vehicles? Just as surely, these are more specific “systems.” Thus, the final report of the HSGT panel was organized as shown in Figure 1.2. This is a more functional arrangement, and it helped the panel to produce a less confusing and thus more useful report.

Thus far we have discussed the difference between the general or “comprehensive” system viewpoint we take in this text, *i.e.*, the specific problem at issue, plus all

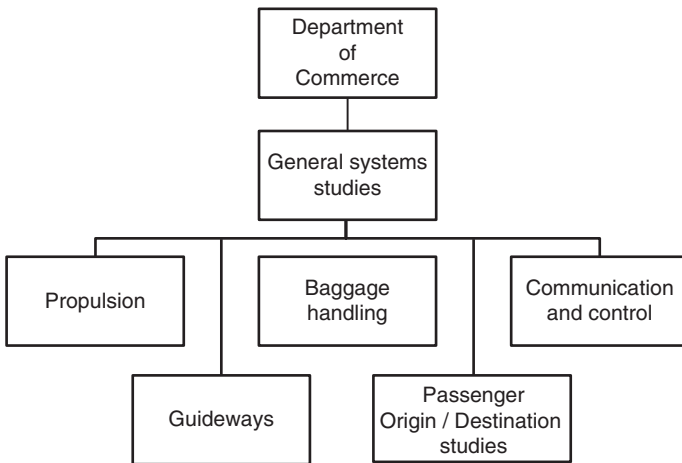


Figure 1.2 The final HSGT report formulation. Here we see the general systems aspect of the problem broken out and placed in the overall coordinating position. Now the term “communication and control system” is less ambiguous.

of the interactions and impacts of the specific issue with its setting, including policy issues and a more localized, exclusively technological “control system” point of view. There are at least three additional semantic difficulties to be discussed.

In the early twenty-first century, as the U.S. populace was tiring of the prolonged war in Iraq and Afghanistan, the military sought an option that would allow it to capitalize on its technological superiority and reduce its reliance on soldiers in harm’s way (and concomitant casualty rates). There was an insatiable demand to meet insurgencies in locales such as Syria, Libya, and Somalia, in addition to Iraq, Afghanistan, and Yemen. To meet this demand, unmanned drones seemed to be a cost-effective option.

So, for more than 10 years, to varying levels of success, pilots flew their television monitors, rather than strapping into their F-16s; Maverick and Ice Man were still graduating from Top Gun in Miramar only to sit at a Game Boy™ machine and shoot images on a screen.

However, as always, the Law of Unintended Consequences reared its ugly head—in 2015, as demand increased for drone operations in Yemen and Syria, the daily mission rates dropped from 65 to 60, as an increasing number of the 1,200 fighter pilots in the Air Force were completing their tours of duty and opting not to re-enlist.

The reason for this dilemma faced by the military was that pilots were facing new types of stresses—rather than flying from aircraft carriers in the Gulf Sea or from airbases in Bahrain, they were flying Reaper and Predator drones via satellite links in the United States. The perceived benefit was that the pilots were living safely, away from SAMs (surface to air missiles). However, while they were with their families, the constant shift back and forth between war and family activities created, in effect, a feeling of perpetual deployment.

Col. James Cluff, the commander of the Air Force’s 432nd Wing, stated, “Having our folks make that mental shift every day, driving into the gate and thinking, ‘All right, I’ve got my war face on, and I’m going to the fight,’ and then driving out of the gate and stopping at Walmart [*sic*] to pick up a carton of milk or going to the soccer game on the way home—and the fact that you can’t talk about most of what you do at home—all those stressors together are what is putting pressure on the family, putting pressure on the airman.”²

The Government Accountability Office (GAO) conducted a study and released its findings in April 2014.³ It found that while high-performing organizations, such as the Air Force, manage human capital to identify and target the optimum number of individuals to fill its drone group personnel needs, it fails to account for all tasks these units complete. Air Force officials stated that, as a result, the crew ratio for drone efforts was too low, but the Air Force did not update it. It recognized that low crew ratios diminished combat capability and cause flight safety to suffer, that high work demands on drone pilots limited the time they have available for training and development, and it negatively affected their work–life balance, but the Air Force failed to utilize direct feedback from drone pilots to develop its approach to managing challenges related to recruiting, retention, training, and development of drone pilots.

The failure of the Air Force to examine and implement this issue from a holistic systems approach meant that, while it might have some short-term successes, it would ultimately have a failed initiative on its hands because it failed to analyze the challenge faced by pilots to balance their war-fighting roles with their personal lives. It needed to change its methods and metrics rapidly, applying an approach like the one we describe in this text.

Later in the chapter, we indicate that *operations research* (OR) may be considered an immediate precursor of systems analysis (SA). Thus, one may fairly inquire as to exactly the difference between the two. In Section 1.10, we will see that B. L. R. Smith (RAND, 1966) argues that when RAND added an explicit policy component to OR studies, a new synthesis was achieved. Thus for us, system analysis equals an analytic OR study, plus a policy analysis.

Symbolically, then, Smith might say

$$SA = OR + PA$$

In other words, in modern usage, SA is a more general design philosophy than is OR, and it exhibits marks that are readily observable to an outside inquirer. See Section 1.3 for further discussion on this matter.

Finally, one may ask if SA differs from “system design” and/or “systems engineering.” In a precise technical sense, “analysis” is defined as taking apart into constituent elements, while “design” generally means “synthesis” or combining elements into a functional new whole. Unfortunately for all of us interested in precise terminology, the common use of “system analysis” in the literature almost always includes not merely an “analytic” phase, but also the development or recommendations for the solution or amelioration of the problem at hand—that is, “design” or synthesis. Following this usage, we include in the term “SA” that wider sense of synthesis.

What of the term “systems engineering?” In the older and narrower usage, “engineering” includes analysis and synthesis, but it is restricted to the design and operation of physical devices, that is, hardware design. However, in the broader and more modern sense, systems engineering (SE) includes all of the matters we include within the term systems analysis. Systems engineering, in fact, has its roots in classical control theory where the “system” was described in terms of an initial system state, controls (*e.g.*, designed to achieve the “desired” state of the system), transfer functions (that modeled the conversion from the initial state into the desired state), exogenous factors (that influenced the transfer function’s performance), a new system state, and feedback to the control function. All of this is characterized by latency, accuracy, response, and other measures of system performance. This approach to analyzing physical systems has expanded to large dynamic systems where the “stocks and flows” (see Senge (2006) or Meadows and Wright (2008)) include social systems, environmental systems, economic systems, and other large-scale complex systems involving technology, policy, legal and regulatory issues, and social and cultural considerations. This concept of systems engineering is broader than a view based primarily on the life cycle of physical systems and focuses

extensively on the *analysis* that leads to effective design of systems. Thus for us in this text:

$$SE = SA$$

Numerous books describe the process of systems engineering,⁴ including systems engineering handbooks developed by NASA, DOD, Boeing, and so on. Currently, there is also considerable discussion on the concept of SoS—that is, systems that are of significant complexity and order that they require methodologies beyond the classic systems methodologies that are all basically derivatives of MIL-499B.⁵ The emphasis of this book, however, is not on the formal process of systems engineering eloquently described in the footnoted books (and the synonym of the word system: “Method”), but on the systems analysis component as described above and the associated thought processes.

1.3 SYSTEMS ANALYSIS EQUALS OPERATIONS RESEARCH PLUS POLICY ANALYSIS

We will see in a later section of this chapter (see Section 1.10) that the RAND approach to systems analysis began with operations research and added a policy analysis component. We subscribe to that approach in this text. Of course, defining a term using two other ill-defined terms doesn’t help very much. So we should feel obliged to define OR and PA. Fortunately a number of students of the field have defined OR and Table 1.1 gives a collection of these definitions.

We notice the frequent occurrence of terms such as “scientific” and “mathematical” in these definitions; also there is the use of “optimization” and the emphasis on the concept of a “client.” The term “client” itself does not appear, but synonyms such as “executive authority,” “organization,” “society,” and so on, do. Thus, while the details differ among these definitions, a common basis emerges. We could go on with this definitional exercise to discover the typical analytic techniques of OR, such as linear programming, queuing theory, optimization techniques, simulation methods, and so on.

“Policy analysis” is a little more difficult to limit. But, if we note how RAND came to include the policy analysis aspect, matters become clearer. RAND knew from working with the military mind that it is hierarchal, a primary attribute of a Tayloristic value set. Taylorism, as we shall see, includes a rigid separation of “thinking” by managers from “doing” by workers. Thus, the U.S. Air Force, RAND’s original sole sponsor, tended to come to it with orders to do a certain analysis. When RAND analysts asked “why,” they were rebuffed. But as we will see, the Tayloristic mind-set is not suitable for creative analysis of new issues. The system analyst must know the goals of the issue and the underlying values from which the goals are formed to conduct an analysis properly. In the Air Force’s view, this took RAND out of the realm of OR into management’s territory, Policy Analysis. So RAND simply included policy analysis in its definition of what it did and that helped matters somewhat.

Table 1.1 Some typical definitions of operations research

<p>“OR is simply the application of scientific method (<i>i.e.</i>, quantitative, analytic thinking with empiric checking) to the problems of an executive authority.”</p>	<p>—Waddington 1973</p>
<p>“OR is the application of scientific ideas and methods to improve the efficiency of an industrial process, an organization or, in the most general of senses, the working of any part of society.”</p>	<p>—Friend <i>et al.</i>, 1988</p>
<p>“Operations Research (O.R.), or operational research in the U.K, is a discipline that deals with the application of advanced analytical methods to help make better decisions.”</p>	<p>—INFORMS, 2015</p>
<p>“Though there is no ‘official definition’ of Operational Research (‘Operations Research’ in the US), it can be described as a scientific approach to the solution of problems in the management of complex systems.”</p>	<p>—EURO: The Association of European Operational Research Societies 2015</p>
<p>“Operations Research is the quantitative study of the operations of a complex organisation and the prediction of the effects of changes in conditions for the guidance of executives in obtaining the maximum effectiveness from available resources.”</p>	<p>—Brown and Easterfield 1951</p>
<p>“Operations research (operational research in Britain) as understood today is essentially identical to systems analysis.”</p>	<p>—Principia Cybernetica Web 2015</p>
<p>“Operations research is a vast branch of mathematics which encompasses many diverse areas of minimization and optimization.”</p>	<p>—Wolfram MathWorld, 2015</p>
<p>“OR, let us say, is the securing of improvement in social systems by means of scientific method.”</p>	<p>—Churchman, 1970</p>
<p>“Operations research analysts use advanced mathematical and analytical methods to help organizations investigate complex issues, identify and solve problems, and make better decisions.”</p>	<p>—U.S. Bureau of Labor Statistics, 2015</p>

1.4 ATTRIBUTES OF LARGE-SCALE SYSTEMS

In this text we will concentrate on a particular aspect of the field called large-scale systems. How does a large-scale system differ from a non-large-scale system? Almost certainly there is a policy component to the issue under consideration. Generally, a large-scale problem is not merely one containing many components, although that can occur. The usage has become common to differentiate between (a) the low-order, well-defined physical system to which almost all of the

mathematical theory of operations research is directed and (b) larger, more complex issues with a policy component. By “policy component,” we generally mean that the goals of the system and the index of performance are subject to the personal standards and judgment of the client. The typical large-scale system will have many of the following attributes:

Policy Component. In addition to the physical infrastructure, or the so-called engineering component, a large-scale system often contains a social or “policy” component whose effectiveness must be evaluated by its accord with general social, governmental, or other high-order judgments, rather than by simple economic efficiency.

High Order. A large-scale system (LSS), or “General System,” will usually have a large number of discernible subsystems or parts. These parts can be quite different from one another and may be interconnected in complex ways. Some of the elements of the large-scale system may include living elements as linkages. In addition, social, economic, political, environmental, and technological considerations will often be involved.

Complex to Describe. Because of the large number and variety of its elements, the LSS is often difficult to describe analytically or to model precisely via dynamic computer simulation.

Lengthy Installation. Because of the cost and effort needed for its installation, the LSS may take a number of years to construct and install. Thus special care is needed with respect to graceful phasing-in of the new system and phasing-out of the old system that it replaces.

Unique. Often the LSS will be unique in its overall concept. Thus special care must be given to careful preliminary design and complete analysis. The designer will not be able to correct design errors in early models later in the production run, if only one is to be built.

Prior Complete Testing Impractical. Because of the size and cost of the LSS, it may be impractical to construct a test prototype prior to installation of the operating system, or even to assemble the complete system off-site for preliminary testing. We are thinking here of complete subway systems, and so on.

One could cite an almost endless list of LSS, of which the following are a few examples:

- The “Big Dig” transportation project in Boston (1982–2002)
- The information technology infrastructure for the Department of Homeland Security
- President Reagan’s “Star Wars” initiative in the 1980s
- A Manned Mars Mission (considered in Chapter 2)
- The complete water supply for a large system (or any infrastructure component)—think of Flint, Michigan, in 2015–2016 (and beyond)

- The integrated Highway/Rail/Air/River transportation system for a developing nation such as Colombia, funded by the World Bank in the 1960s
- The long-range business plan for a complex international corporation such as Royal Dutch Shell in the months before the 1970s OPEC oil crisis
- The New Orleans flood containment system (levees, pumps, drainage, staff, policies, and so on, or the flood evacuation process)
- The U.S. Social Security System
- The World Wide Web (The Web)
- The Mexico–United States border
- The Health Insurance component of the Affordable Care Act

1.5 TRANSPORTATION SYSTEMS: AN EXAMPLE OF A LARGE-SCALE SYSTEM

Intelligent transportation systems (ITS) involve the use of disparate technologies to improve, typically without capacity increases, the performance of a transportation system. The preliminary analysis, design, and installation of an ITS is complex and lengthy. The system is of high order. It may involve numerous subsystems, from transit rail to freeways to arterial signal systems. Some of the elements may be analyzed in exact details—for example, individual intersection signals and the associated control computers. Other elements may submit to statistical analysis; passenger origin/demand studies are an example. Design data are typically necessary from disparate sources, such as the U.S. Census origin/destination data and local traffic management centers. Financial estimates of system operation will be less precise, but still well within the bounds of approximate analysis. Connected vehicles and high-speed automated platoons of vehicles will introduce new dimensions of risks and radically change our vision of the interstate highway system, and such systems are being tested throughout the world. But other elements upon which the success of the system rests seem to be beyond analytic description.

For example, *the demographics* of the urban region may change dramatically in 30 years. A 2011 study shows that, within a period of 5 years, one-half of the families in a typical American community have changed their place of residence (He and Schachter, 2003; for details see Molloy *et al.* (2011)). Housing prices, which dramatically affect traffic congestion and have major ITS implications, soared in the 2000s and also doubling in a 5-year time frame; however, the bubble burst in 2008–2009 as a result of the financial and economic downturn (Anonymous, 2005a). Thus, if the return on investment of several ITS technologies is calculated on the basis of a 30-year operating life, one must extrapolate over six half-lives of the demographic base that the system is designed to serve—a rather risky process. Another example involves the driving habits of new generations, such as the “millennials,” who are exhibiting different driving behaviors (fewer getting driver licenses, more Über, *etc.*) (Dutzik *et al.*, 2014).

Political questions are even more difficult with which to grapple than are demographic ones. For example, the so-called “U.S. Highway Trust Fund” is a special-purpose federal gasoline tax with a limited set of permissible uses that Congress reauthorizes every 5 years. In general, funds are returned to the states to reimburse approved state highway construction and reconstruction and other transportation infrastructure investments based on a complicated allocation formula. The highway trust fund eligibility criteria have been expanded to include investments in ITS as well as transit, bicycle, and pedestrian improvements. The larger issue is that, as we drive fewer miles in more efficient (or electric) vehicles, the gasoline tax has become a less reliable source of funding for highways and other transportation investments. At present, we anticipate the highway trust fund becoming exhausted because we refuse to raise the federal gas tax (last raised in 1992), which is linked to “gallons” rather than “vehicle miles driven” or the wholesale price of gasoline.⁶ This is a political question that will have a greater impact on the benefit–cost studies for deploying ITS than almost any technological factor.

Another example is photo-red systems, where camera systems can be installed to detect and issue tickets to vehicles that run red lights (Anonymous, 2005b). Systems can be operated by local or state governments, or they can be operated by for-profit companies via a profit-sharing formula with localities. Evaluation of such systems has proved their capability in terms of technology, accident reductions, and economic viability; however, considerable political opposition has limited their deployment in the United States, where the opposition is based on claims of invasion of privacy or claims of increasing accident rates. Some regions have turned off effective and proven photo-red cameras, against the wishes of police agencies, for political reasons (Stockwell, 2005). As a result, since their initial deployment in the United States in the late 1960s, red-light cameras remain an enigma due to conflicting goals and values, misinformation, and plain politics. However, in other parts of the world, such as The Netherlands, such technologies are widely used and accepted, not only for red lights, but also for excessive speed.

Sociological factors are most difficult of all to predict. What will be an acceptable level of urban pollution produced by a transportation system? What is an acceptable level of delay on the highways? What will be the performance requirements placed by federal diktat on the next generation of individual vehicles and transit vehicles? What safety needs, real and perceived, must be met by ITS technology in the future? What will be the timing and level of acceptance of “driverless vehicles?” What about questions of “ambiance” and “user-friendliness?”

All of the above factors also contribute to the complexity of description of the system as well. For example, it is not easy to define “the city” or region for which one is analyzing the transportation needs. Should the Metropolitan Planning Organization (MPO) definition or the Standard Metropolitan Statistical Area (SMSA) definition be used? There are over 30 definitions of the word “city” in current use (Gibson, 1977), and federal regulations require that, to qualify for federal matching funds, a regional approach must be taken in the analysis rather than a parochial one limited to political boundaries.

The typical urban transportation system takes a long time to install. The Bay Area Rapid Transit (BART) system in San Francisco–Oakland took over a decade to design and construct, while the Washington, D.C., Metropolitan Area subway has been in planning and construction even longer. The most recent extension, the Silver Line, has been under consideration since 1968 (when the Metro system was originally built), and in actual development stages since 1995. Detroit has discussed and planned its subway for over 35 years, and as yet not a spadeful of earth has been moved. Some of the links of the interstate highway system initiated under Eisenhower are as yet untouched after 60 years. In the meantime, the existing transport networks must continue to function, and indeed many of the elements of the existing transport system must continue to function even after the new system is installed. After 18 years of planning and construction and almost \$15 billion in costs, the Big Dig in Boston was one of the largest civil works projects in history. The official planning phase started in 1982 and construction work was performed between 1991 and 2006. The project concluded in December 2007, under a cloud of controversy, as the most expensive highway project in U.S. history. The Big Dig served, in Thomas Hughes' book (Hughes, 1998), as a classic example of the difficulties of employing systems engineering in large-scale public systems.

Each ITS system is unique. Certainly, many of the individual components are identical to those used in other systems, and indeed commonality with other systems is highly to be desired. Doubtless also, much of the design and construction experience obtained from earlier work should be transferable. But the particular combination of elements and the interconnections among subsystems will be unlike those faced elsewhere.

Some engineers are uninterested in issues of public policy, and they may choose their careers to be able to focus on the design of physical objects and to avoid "people problems." One might imagine such focused individuals designing traction drives and electronic controls for subways, but one cannot long escape from the real world. Many of the initial problems faced by BART were due to selection of inexperienced contractors who used untried and untested techniques. When certain BART engineers warned against this, they were fired, and eventually BART authorities were required by law to pay damages to these courageous, "whistle-blowing" professionals.

Finally, it is patently impractical to set up a complete ITS somewhere for a lengthy test period, prior to installing it in its final location. This means that components and subsystems must be carefully field-tested prior to final installation. It further means that extraordinary care must be given to the system aspect as opposed to the component aspect of the analysis. Time spent on computer simulation of the operation of the system in the preliminary design phase, long before bending metal, will more than repay itself, for example. Such a computer simulation should be specifically designed to test system performance aspects.

For example, it is possible to mock up on computers interface systems and system controls. Then various conditions could be entered into the simulated system, without the user's knowledge, to test his and the system's response. It should also be

possible to vary vehicle volumes, passenger loadings, route choices, station locations, and so on, on the simulated system to test the response to off-design-center operating conditions. The analyst should be able to demonstrate that as off-design-center conditions become more and more pronounced, the system undergoes graceful degradation, as opposed to sudden and catastrophic collapse. Yet rarely, if ever, is such a comprehensive simulation study actually conducted in practice that actually involves the complete human–computer interface (HCI).

For example, suppose a rapid transit system is to be controlled by a central control computer that is programmed to dispatch units in accordance with historical traffic variations. Suppose a main artery near the city center is cut off in a sudden emergency. What will the central computer do? Or suppose the central computer itself fails. Does the whole system halt in a catastrophic collapse? The alternative to “catastrophic collapse” is “graceful degradation.” If control degenerates to separate sector computers and then back to the individual units operated by hand, at reduced speed in the face of a major emergency, performance of the system has gracefully degraded.

It is apparent that ITS are often constructed and operated with little or no thought given to overall policy questions such as those we have just raised. It also seems likely that traditionally trained transportation designers and operators would ignore or resist policy-oriented analyses if they were made. Should this surprise or dismay the system analyst? Not at all. It is the normal state of affairs, *even though we know that these problems will occur!*

In Chapter 6 of Smith’s book on RAND (Smith, 1966), he gives an excellent description of a pivotal study done by RAND on the location of bases of the Strategic Air Command (SAC) of the U.S. Air Force. This was one of the earliest studies anywhere in which a clear policy-oriented approach was adopted. This approach heavily influenced RAND’s subsequent development of a “strategic sense” and may be viewed as the progenitor of the modern policy-oriented system study. A.J. Wohlstetter, the task leader, was faced with precisely the same problems . . . first, in beginning this analysis, and second, in persuading the Air Force decision makers to accept and act on the conclusions of the study . . . as the analyst of a mass transit system or any other large-scale system would face in working with non-military decision makers. Smith’s historical text, and especially Chapter 6, should be required reading for all analysts of large-scale systems.

1.6 SYSTEMS INTEGRATION

We have pointed out that confusion exists as to the meaning of the term “systems analysis.” This confusion has been partially resolved by coining a new phrase “systems integration” (SI). *Systems integration* is a logical, objective procedure for applying (in an efficient, timely manner) new and/or expanded performance requirements to the design, procurement, installation, and operation of an operational configuration consisting of distinct modules (or subsystems), each of which may embody inherent constraints or limitations.

This definition of SI contains a number of key terms. “Logical, objective procedure” means that the process is defensible to external critics and that all of the steps have a built-in audit trail. “Efficient and timely” implies that the process will not be unduly burdened with delays and bureaucratic procedures that increase cost to the client and delay deployment of the system. “Design, procurement, installation, and operation” indicates that the SI process will be employed throughout the entire process. It further implies that life cycle costing will be considered and that retrofits, extensions of system capability, and the like, will be built-in. The concept of “distinct modules” with inherent limits or constraints is central to the concept of SI. Systems Integration would be unnecessary if the entire configuration to be deployed were a stand-alone device without intimate connections with other devices previously deployed or to be deployed under a later procurement, and if the device were designed and constructed *de novo* by a single party with complete design responsibility. No such animal exists in the modern world, of course, and thus the ubiquitous necessity for SI.

At a tactical level, SI is involved with ensuring that specific hardware and software components will fit together smoothly in a configuration. Indeed at this level, SI is often referred to as “configuration management.” But at a broader, more strategic level, SI is concerned with interpreting overall performance needs of a sponsor into technical performance specifications and then the creation of a full options field from which to select those option profiles that best meet the client’s needs.

A number of pitfalls exist in the process. Among them are the following:

- Failure to provide a clear audit trail through the SI process.
- Breaks or discontinuities in the SI process caused by intuitive leaps from a general requirements level to a specific hardware configuration, without objective development of the steps in the process.
- Failure to assess completely the full range of client requirements including operation of the proposed system over the full time horizon required.
- Failure to evaluate full life-cycle costing.
- Failure to provide in advance for maintenance and periodic upgrades and retrofits during the system life cycle.

As we continue with our detailed discussion of the phases of systems analysis, we will see that this new term “systems integration” is synonymous. Over the last two decades, the term “system architecting” has also become prevalent. Defined as “the art and science of designing and building systems,” it follows the same analogy as systems integration; once again, *for our purposes*, we will use the term interchangeably with systems analysis (Rechtin and Maier, 1997).

1.7 WHAT MAKES A “SYSTEMS ANALYSIS” DIFFERENT?

Almost the whole of the remainder of this text will be devoted to the systems analysis methodology and how to perform an SA. But, before we begin, we wonder if this

notion of system analysis is merely a mental discipline or a training regime through which we put ourselves, or if, on the other hand, there are distinctive marks or attributes that an external observer could use to detect that SA has been used. Even if it were only a mental discipline, SA could be valuable. For example, “Zen” is said to help warriors and athletes, even though it is “only” a mental attitude. We will argue that the SA methodology is more than just an attitude, however.

Even if there are external marks to SA, these marks might be of no functional value. For example, the marks might be only cosmetic, as when special jargon (of which we have a considerable amount) is used. However, we will argue that the marks of SA are more than cosmetic. There are recognizable characteristics in a well-done SA that enable an external observer to recognize it as such. Not every SA will display all of these marks, but the fewer that are evident, the further the analysis diverges from a paradigmatic system study. The following distinguishing eight marks define a systems study.

1. *The “Top-Down” Nature of the Study.* The well-done system analysis starts with an analysis of the general goals of the effort and proceeds to the specific. This is a reversal of the approach often advocated in engineering design. The reader will find a comparison of the “top-down” approach and the “bottom-up” incremental approach in Chapters 2 and 3. These two design philosophies are sometimes considered antithetical, but this is not so. One does not choose one or the other in a systems analysis. In SA, top-down alternates with bottom-up, in an iterative manner.
2. *A Goal-Centered Approach.* The goal-oriented approach contrasts with the step-by-step or chronological or “laundry-list” approach. A system analysis starts by determining the situation or condition after the system under design is complete and operating successfully and works backward from there to determine the specifications of the intermediate links. This approach is discussed in detail in Section 2.2.
3. *Rational Objective Basis for Analysis.* Rationality and objectivity are hallmarks of the scientific method and in engineering design. By “rational” we mean based on carefully gathered evidence weighed and analyzed using a logical procedure, and by “objective” we mean fair, balanced, unbiased, and free from personal whim. These features are not common in the political arena. Lawyers, for example, are not constrained by these criteria. A legal brief will include all of the arguments for a given position, even if some of the arguments are self-contradictory. The reader of such a brief is expected to pick any of the arguments that are pleasing, provided only that support for the advocate’s position is obtained.
4. *An Analytic/Quantitative Component Plus a Policy Component.* Operations research (or equivalently management science, decision analytics, etc.) is a major component of SA, as we will see. OR contributes the analytic, quantitative component to systems analysis. The addition of the policy component makes SA unique. See Section 1.3.

5. *A Generalized Problem That Includes the Problem Setting.* The word “generalize” here means to expand or broaden the scope of, as opposed to the alternate meaning of “generalizing from the particular to a broader class.” A properly done SA always includes a consideration of the problem environment. It includes consideration of all of the stakeholders, non-users as well as users. By “generalized problem” we mean a core of mathematical quantification and analysis, plus the addition of human factors, considerations, and the policy component where indicated, all in the context within which the issue at hand is embedded, and specifically including the client on whose behalf the analysis is being conducted. See Section 3.2 for a more complete explanation of the rationale for “generalizing” the problem.
6. *Optimization, often through Analytical Modeling and Simulation.* Identification of the critical parameters of the problem and calculation of their optimum setting to maximize the index of performance is a basic characteristic in SA. Often this iteration and optimization is best accomplished by use of computer simulation.
7. *Explicit Analysis of the Operative Values Assumed, and Declaration of the Analyst’s Biases or Interests.* Effective handling of the policy component in an SA requires that the operative value system be analyzed. This is the so-called “axiological component” of the analysis.
8. *Problem/Client Orientation Rather Than Technique or Abstract Orientation.* SA is client-oriented not technique-oriented. Maslow (1969) makes the importance of this distinction abundantly clear. Neither OR studies nor SA are conducted for their intrinsic value or the entertainment of the analysts.

This listing isn’t designed to justify or explain these marks of SA. The remainder of the text is designed to do that. Here we merely wish to point out the unique characteristics of the SA approach, so that the reader can be alert for them as they occur in the text. Whether SA is effective and where it should be applied will also be made clear (one hopes!) in the remaining chapters.

1.8 DISTANT ROOTS OF SYSTEMS ANALYSIS

Frederick Winslow Taylor is among the earliest of the zealots in the cult of industrial efficiency, and by his somewhat extreme stands he made himself a favorite target, beginning in his lifetime and continuing to the present. As Ellul (1964, 1973) points out, Taylor viewed “the shop” as a totally autonomous entity. He had no concern for the purpose to which the product produced would be put or for the external goals of the shop workers. Only efficient production mattered. This analytic suboptimization approach is still common, but it lacks contextual integrity. One should read Taylor’s own words to get the flavor (Taylor, 1911).

Taylor is the exemplar of what McGregor (1960) labeled “Theory X” management style. Taylor viewed workers as objects rather than as individuals, but he should not be viewed as deliberately ignoring the human content of work. That is a

concept developed only many years after Taylor's death. While one might expect opposition to Taylor's new method by many workers, we are surprised that Taylor failed to be acclaimed widely by managers. Copley (1923) makes clear in his laudatory biography that Taylor had considerable difficulty in winning converts among employers. His undivided allegiance to pure efficiency drove away many of those whose profits he would have served. Only an inherited income allowed him to continue his crusade.

One may note with interest that the military services were early converts to Taylorism. In 1907, there were efforts to apply Taylor's methods at the Brooklyn Navy Yard. The military were also among the first to use operations research in World War II. In conventional wisdom, the military mind is not often credited as a flexible or innovating instrument, yet the fact remains it led the way in scientific management and operations research. Why?

Taylor's invention of time and motion study, the efficient design of the workplace, development of optimized tools (from shovels to cutting steel), work scheduling, and incentive pay for workers allowed him to demonstrate spectacular increases in productivity where his methods were introduced. However, his dogmatism, arrogance, and unwillingness to persuade or explain, his demands for absolute loyalty from his associates, his efforts to stamp out heretical variations of his methods, his need for complete control, and his obsessive dedication to work, make him a suitable subject for retrospective psychoanalysis. He appears to have had a well-developed martyr complex and to have viewed his work as a calling of supreme importance, so much so that he dedicated his life, his fortune, and ultimately his health, to the cause.

Taylorism, or "scientific management" as he wished it to be called, made steady progress before World War II and became better known as industrial engineering and industrial management. The importance of increasing productivity was a lesson successfully taught by Taylor, and as less fanatic persons with broader and more humane concerns became involved and as the disciplined resistance of organized labor began to be felt, the worst excesses of early Taylorism in the American factory were trimmed away. Nevertheless, even today one carries a clipboard and stopwatch out onto a machine shop floor at one's own risk. Taylorism was probably appropriate for the educational and social maturity of workers 100 years ago, but it is widely felt to be inappropriate and retrograde today. The Tayloristic mind-set continues to be ubiquitous among American engineering educators.

1.9 IMMEDIATE PRECURSORS TO SYSTEMS ANALYSIS

The period immediately prior to World War II in Great Britain, *circa* 1937–1940, saw the development of what was called "operational research"; later, in the United States, this was called operations research. When the threat of Hitler was real, but before massive involvement by Great Britain, it became apparent to Churchill and his close advisors that only by deploying its severely limited forces in the most efficient manner could England hope to survive. Radar had been developed and the Spitfire was in production, but the number of operational units was severely limited.

Because of the traditional close connection of government leaders and the universities in Britain, Churchill felt comfortable in turning to a family friend who was professor of physics at Cambridge, Professor Lindemann (later Lord Cherwell). Lindemann drew Sir Henry Tizard, Sir Watson-Watt, and other academics into aiding the war effort (Birkenhead, 1962). Mathematicians and physicists were asked how best to deploy available weaponry in military operations.

This was new. Scientists were accustomed to being called upon to develop new weapons, but the matter of organizing their use lies at the heart of military science, it would seem. It is hard to see how a more conventional mind than Churchill's would have conceived such audacity. Statistical analysis groups were set up and controlled experiments were run (Morse, 1970). Bombing patterns were modified, and ocean convoy procedures were changed as a result of these studies. Because of the academic background of the early OR practitioners, a great deal of elegant and useful mathematics came into play: statistical analysis, queueing theory, probability theory, and so forth. See Chapter 1 of D. J. White's *Operational Research* for examples of typical military OR problems of the period (White, 1985).

New mathematics such as linear programming, dynamic programming, game theory, and decision analysis were later developed. OR began to influence industrial engineering and management after the war and crept into industrial practice. Because of the interesting theory involved, OR found a home in university curricula soon after the War. Courses were offered at Hull University by Swann; soon afterward, 1958–1959, the first graduate-degree program in OR was offered at Birmingham (D.J. White, personal communication).

Another, separate contribution of scientists and engineers in World War II was the development of the techniques of automatic control. As weapons became faster, larger, and more powerful, it became increasingly less practical to operate them by hand. The aerodynamic pressures on the control surfaces of large, high-speed bombers grew so great that mechanical boosters were necessary. Multiple machine guns mounted in these bombers were so heavy that gunners could not move them unaided. The gun turrets of naval warships had to be stabilized against ocean-wave motion if the guns were to be effective. Late in the war, automatic navigation systems for aircraft and ships, as well as ways of allowing radar automatically to direct weapons fire, were sought.

For these and other applications, design engineers first thought that simple mechanical and hydraulic boosters could be used to substitute for the muscles of humans. But in many cases when the boosters were added, the mechanisms failed to operate as expected. Sometimes the units did not work at all and in other cases the units went into wild, uncontrollable oscillations before destroying themselves. Many potentially valuable devices were rendered useless by these mysterious failures. For months it appeared that a fundamental limitation dictated by unknown laws of nature was at work.

Help came from an unexpected source. For a number of years, telephone engineers at the Bell Laboratories had been attempting to understand the oscillations set up in electronic amplifiers needed for long-distance telephony. Beginning with H.S. Black's investigations on the theory of negative feedback (Black, 1934) and

culminating in the classic work of Bode (Bode, 1945), the theoretical principles for analyzing and stabilizing feedback systems were laid bare. Workers at Bell Labs and at General Electric Laboratories reduced the theoretical principles to practice. Dramatic stories can be told of the stabilization of the B-29 bomber fire control system and of the Navy gyroscopically controlled gun laying systems, after unstable devices were in production and being installed on operational units. The best overall documentation of this wartime effort remains Volume 25 of the Radiation Laboratory series (James *et al.*, 1947).

From this beginning, the theory of feedback has been developed to include complex systems with many interacting elements and with humans as integral parts of various loops. Following the war, as analog computers became widespread in university and industrial research laboratories, feedback automatic-control theorists and others developed an intense interest in the concept and practice of dynamic computer simulation models of whole industrial processes, cities, and, some say, the world.

One further precursor of system analysis remains to be mentioned—econometrics. John Maynard Keynes was a seminal figure in economics in the period between World Wars I and II (Harrod, 1951). He early conceived that by manipulating and controlling certain parameters of a nation's economy, one could influence almost all other segments of the nation's economic life. When one proposes to influence the economy of a nation, much more is needed than merely qualitative descriptions of the processes involved. Keynes played a leading role in beginning the conversion of economics from a qualitative, descriptive art into a quantitative science that continues today. Keynes influenced the transition to quantitative economics or econometrics, not only by his prolific writing but also by playing an active role in the British government. He was also fortunate in attracting several brilliant and prolific individuals to become early followers, among them P.A. Samuelson (Stiglitz, 1966).

In 1941 Leontief published his classic work on input–output models, which is still widely used (Leontief, 1941). The Leontief economic model of a nation is a static representation. It provides within itself no predictive capability, although, of course, a series of such static descriptions can be used as a basis for extrapolation. Yet the immense expense of collecting even these static coefficients for a model of the United States that is sufficiently disaggregated to be of value is staggering. Even with the resources of the U.S. Government, data for 1967 were not published until 1974 (U.S. Department of Commerce, 1974)! Despite these difficulties, econometricians have pushed forward into dynamic modeling of the nation's economy. Among the leaders of this more recent effort was Lawrence Klein and his Wharton model (Klein, 1950; Klein and Goldberger, 1955; Anonymous, 1975). With increased use of advanced statistical techniques, dynamic modeling, and so on, econometrics and operations research now began to find common ground (Teil *et al.*, 1965).

Industrial management, operations research, automatic control system design, and econometrics appear to the systems analyst as precursors to his generalized discipline. Yet, active practitioners of each of these specialties might resent the implication that they are somehow being superseded by a new group of generalists. Thus, we need to remind ourselves that it is all in one's point of view. Perhaps we system

analysts ought to acknowledge our “parent disciplines” rather than calling them precursors.

1.10 DEVELOPMENT OF SYSTEMS ANALYSIS AS A DISTINCT DISCIPLINE: THE INFLUENCE OF RAND

Operations research emerged from World War II as a new and exciting approach to the organization of large-scale groups to accomplish specific goals. But why limit OR to the operational deployment of men and machines? Why not use it as well for discovering what new devices and processes are needed to meet defined goals? The need for a rational, objective process of analysis of all factors is especially relevant in the development of large weapons systems such as guided missile systems and in private industry in such complex undertakings as long-distance telephone networks and airline operations. The name “operations research,” always rather confining, seems inappropriate for this newer, broader mission, which includes operations as only one portion of the cycle of bringing a new device into being and using it efficiently. Terms such as “system analysis,” “system design,” “systems engineering,” and the “system approach” began to be more commonly used.

When many diverse parts of a large-scale system must be designed so as to work together in a harmonious whole, and especially when it is difficult or impractical to test the parts in advance of final assembly, a systematic approach is almost mandatory. The U.S. Air Force and AT&T were among the first organizations to recognize this. The Air Force set up a system command to study the overall problem of bringing the intercontinental ballistic missile into the U.S. defense arsenal, and in 1948 it sponsored the formation of the RAND Corporation (Smith, 1966). RAND’s charter was to develop and apply the system approach to a wide range of Air Force problems. RAND’s independence allowed it the necessary freedom to develop the skills needed for solving large, long-range problems without day-to-day interference and diversion of personnel to meet tactical emergencies. Later it was recognized that these new system skills being developed by RAND were of general applicability.

The Air Force supported RAND as an external contractor and it enjoyed rather wide freedoms. RAND paid excellent salaries, provided pleasant working conditions in a non-military atmosphere, and addressed challenging problems of its own selection from a shopping list proposed by the Air Force. One of the difficulties of professional life in a think tank such as Arthur D. Little, SRI, Calspan, Battelle, and so on, is the need continually to “sell one’s time.” This can lead to compromises in the kind of work undertaken and the quality of the results (Dickson, 1971). RAND was free of this concern.

RAND was a prime mover in the development of such theory as linear programming, decision theory, dynamic programming, Monte Carlo simulation, game theory, and PPBS (Planning and Performance Budgeting System). Its counsels were sought at the highest strategic levels. A young systems professional at RAND could influence the course of world events—a heady experience. Smith, in his well-done book, credits RAND with the original development of policy-oriented system

analysis. RAND began its work as a project office in Douglas Aircraft Company, doing standard operations research tasks for the Air Force.

In the early years . . . RAND studies tended to be engineering efforts or else analyses of rather low-level problems akin to what operations researchers did in World War II. The studies were elaborately mathematical in nature and showed little concern for integrating a number of complex variables, some qualitative in nature, into a broad context of some future 'system' whose contours and implications in terms of military effectiveness can only be dimly foreseen.

[Smith, 1966, p. 103]

Gradually, however, RAND personnel began to develop what Smith calls “a strategic sense.”

Something of a revolution took place in the 1950s which transformed the typical RAND systems analysis from a narrowly technical product into a novel application of numerous professional skills to a broad policy problem.

[Smith, 1966, p. 104]

While the proportion of broad-scale policy analysts at RAND never exceeded 15% of the professional staff at any one time, Smith argues that this policy flavor, or “strategic sense,” is what set RAND’s system studies apart from the more traditional, narrowly technical OR studies done by other organizations of the period, and which in effect created the wholly new area of policy science (Smith, 1966, p. 105).

In the 1960s, the influence of RAND began to wane. Competing organizations such as SDC, MITRE, and ANSER were spun off from RAND, but none were given as long a leash. The Viet Nam war was divisive for RAND; Daniel Ellsberg of the “Pentagon Papers” fame was a former RAND employee. Air Force support was cut back, and RAND sought and received permission to seek funding from other sources. This was a period of great social ferment, and when Mayor Lindsay invited RAND to set itself up in New York City and to apply system techniques to the organization of snow removal and garbage collection, RAND obliged. However, RAND/ NYC found that urban problems are more complex than aerospace system problems (Szanton, 1972).

Urban goals are often left obscure on principle, RAND/ NYC discovered to its befuddlement. The client is ill-defined, and lethargy, the *status quo*, and discrete incrementalism are the rule in urban bureaucracies. RAND/ NYC funding stopped in 1973. The RAND/ NYC experience seems to teach several things. Certainly, RAND’s system approach to social problems was superior to the earlier and equally well-intentioned State of California effort to enlist aerospace contractors to address pressing public issues at the state level (Gibson, 1977, pp. 59–91). Yet there remained much of the naïve, ingenuous, academic, abstract flavor in the RAND/ NYC studies and little of the experienced, realistic, slightly cynical, but still hopeful veteran. Perhaps the RAND/ NYC program needed fewer fresh Ph.D. Eagle Scouts and more NCIS agents.

RAND alumni moved into positions of influence throughout the Defense Department and into universities, carrying with them linear programming, queuing theory, dynamic programming, decision analysis, benefit–cost analysis, and the whole analytic tool kit now so familiar in operations research. RAND also helped define the general steps to be taken in a system analysis, including explicit development of goals and quantitative indices of performance, the development of alternative scenarios, trade-off studies, and the like.

Opposition came from simple inertia and reluctance to change. Other opposition to the “systems approach” was and is generated by the behavior of system analysts themselves. If one goes into an existing organization with an arrogant attitude of superiority, one is not likely to gain the cooperation of the old timers. There is also informed opposition to inflated claims of incompetent charlatans posing as skilled professionals. And finally there is opposition from those who understand quite clearly that an objective, careful analysis of the current situation is likely to uncover the existence of sloppy, comfortable or self-serving behavior and require a change of ways. Stockfish (1970) provides an anecdotal description of some of these sources of opposition to the installation of the system approach.

Other laboratories in the United States were also developing and utilizing the new tools in addition to RAND; of course, the Willow Run Research Center of the University of Michigan is among them. Out of Willow Run came the first comprehensive text on the design of large-scale systems, Goode and Machol (1957). Five years later, Hall’s classic text (Hall, 1962) appeared, based on his work at Bell Labs. Hall introduced for the first time a comprehensive, integrated general methodology for the analysis and synthesis of large-scale systems.

We’ve presented the case for systems analysis methodology, highlighted the difficulties and uniqueness of systems analysis in practice, and presented the origins of the discipline; now let’s get to the details and present a methodology for systems analysis.

NOTES

1. Some definitions of a system do not require goal-directed behavior, especially some from General Systems Theory; see Flood and Carson (1993).
2. Drew, C. and Philipps, D. (2015). As stress drives off drone operators, Air Force must cut flights. *New York Times*, June 16, 2015.
3. Government Accountability Office, GAO-14-316, Air Force: Actions Needed to Strengthen Management of Unmanned Aerial System Pilots, April 10, 2014.
4. See, for example, Buede (2000), Blanchard (2004), Sage and Armstrong (2000), Sage (1992), Daellenbach (1994), and Blanchard and Fabrycky (1998).
5. Military standard MIL-STD-499B, never formally released, was designed to address systems engineering as a whole. The prior standard that was released, MIL-STD-499A, focused on the management function of systems engineering. See Honour (1998).
6. See <https://www.transportation.gov/highway-trust-fund-ticker> for the U.S. Department of Transportation's "Highway Trust Fund Ticker" that shows the declining balance in the fund.

REFERENCES

- Ackoff, R. L. (1971). Towards a system of systems concepts. *Manag. Sci.*, Vol. 17 No. 11, pp. 661–671.
- Anonymous (1975). Lawrence Klein and his forecasting machine. *Fortune*, March, p. 152ff.
- Anonymous (2005a). After the fall: Soaring house prices have given a huge boost to the world economy. What happens when they drop? *The Economist*, June 16.
- Anonymous (2005b). Little caution in Virginia. *Washington Post*, March 13, p. B06.
- Birkenhead, E. (1962). *The Professor and the Prime Minister*, Houghton Mifflin, Boston.
- Black, H. S. (1934). Stabilized feedback amplifiers. *Bell Syst. Tech.*, Vol. 13 No. 1, pp. 1–18.
- Blanchard, B. (2004). *Systems Engineering Management*, Wiley, Hoboken, NJ.
- Blanchard, B., and Fabrycky, W. J. (1998). *Systems Engineering and Analysis*, Prentice-Hall, Englewood Cliffs, NJ.
- Bode, H. W. (1945). *Network Analysis and Feedback Amplifier Design*, Van Nostrand, New York.
- Brown, R. G., and Easterfield, T. E. (1951). A proposed definition of operations research. *Oper. Res. Q.*, Vol. 2, No. 2, pp. 21–24.
- Brown, D., and Scherer, W. (2000). A comparison of systems engineering programs in the United States. *IEEE Trans. Syst. Man Cybern. C Appl. Rev.*, Vol. 30, No. 2, pp. 204–212.
- Buede, D. M. (2000). *The Engineering Design of Systems: Methods and Models*, John Wiley & Sons, Inc., Hoboken, NJ.
- Churchman, C. W. (1970). Operations research as a profession. *Manag. Sci.*, Vol. 17, No. 2, pp. B37–B53.
- Copley, F. B. (1923). *Frederick W. Taylor, Father of Scientific Management*, Vol. 2, Harper, New York.
- Daellenbach, H. (1994). *Systems and Decision Making: A Management Science Approach*, John Wiley & Sons, Inc., New York.
- Dickson, P. (1971). *Think Tanks*, Ballantine Books, New York.
- Drew, C., and Philipps D., (2015). As stress drives off drone operators, Air Force must cut flights. *New York Times*, June 16.
- Dutzik, T., Inglis, J., and Baxandall, P. (2104). *Millennials in Motion: Changing Travel Habits of Young Americans and the Implications for Public Policy*. U.S. PIRG Education Fund.
- Eisner, H., Marciniak, J., and McMillan, R. (1991). Computer-aided system of systems (S2) engineering. *1991 IEEE International Conference on Systems, Man, and Cybernetics, Decision Aiding for Complex Systems, Conference Proceedings*, IEEE.
- Ellul, J. (1964, 1973). *The Technological Society*, A. A. Knopf, New York (original French in 1954).
- EURO: The Association of European Operational Research Societies. (2015). <https://www.euro-online.org/web/pages/197/what-is-or>, (December 1, 2015).
- Flood, R., and Carson, E. (1993). *Dealing with Complexity*, 2nd edition, Plenum Press, New York.
- Friend, J. K., Michael, M. E., and John Stringer, J. (1988). The Institute for Operational Research: An initiative to extend the scope of OR. *J. Oper. Res. Soc.*, Vol. 39, No. 8, pp. 705–713.
- Gibson, J. E. (1977). *Designing the New City*, John Wiley & Sons, Inc., New York.
- Goode, H. H., and Machol, R. E. (1957). *System Engineering*, McGraw-Hill, New York.
- Government Accountability Office (2014). GAO-14-316, Air Force: Actions Needed to Strengthen Management of Unmanned Aerial System Pilots.
- Hall, A. D. (1962). *A Methodology for Systems Engineering*, Van Nostrand, Princeton, NJ.
- Harrod, R. F. (1951). *The Life of John Maynard Keynes*, St. Martin Press, London.
- He, W., and Schachter, J. P. (2003). *Internal Migration of the Older Population: 1995–2000*, CENSR-10, U.S. Census 2000, August.
- Herbert, G. R. (1968). High-speed ground transportation: a research challenge. *Proc. IEEE*, Vol. 56, No. 4, pp. 487–492.
- Honour, E. (1998). INCOSE: History of the International Council on Systems Engineering. *Syst. Eng.*, Vol. 1, No. 1, pp. 4–13.
- Hoos, I. R. (1972). *Systems Analysis in Public Policy*, University of California Press, Berkeley, CA.
- Hughes, T. (1998). *Rescuing Prometheus*, Pantheon Books, New York, Chapter V.
- INFORMS. (2015). <https://www.informs.org/About-INFORMS/What-is-Operations-Research> (December 1, 2015).
- Jackson, M. C., and Keys, P. (1984). Towards a system of systems methodologies. *J. Oper. Res. Soc.*, Vol. 35, No. (6), pp. 473–86.

- James, H. M., Nichols, N. B., and Phillips, R. S. (1947). *Theory of Servomechanisms*, McGraw-Hill, New York.
- Klein, L. R. (1950). *Economic Fluctuations in the United States, 1921–1941*, North Holland, Amsterdam.
- Klein, L. R., and Goldberger, A. S. (1955). *An Economic Model of the United States, 1929–1952*, North Holland, Amsterdam.
- Koestler, A. (1971). *The Ghost in the Machine*, Gateway Edition, Henry Regnery Co., Chicago, Chapter 3.
- Leontief, W. W. (1941). *The Structure of the American Economy, 1919–1939*, Oxford University Press, New York.
- Maslow, A. M. (1969). *The Psychology of Science*, Henry Regnery Co., Chicago.
- McGregor, D. (1960). *The Human Side of Enterprise*, McGraw-Hill, New York.
- Meadows, D. H., and Wright, D. (2008). *Thinking in Systems: A Primer*, Chelsea Green Publishing.
- Molloy, R., Smith, C. L., and Wozniak, A. K. (2011). Internal migration in the United States. *J Econ. Perspect.*, Vol. 25, No. 3, pp. 173–196.
- Morse, P. M. (1970). The history and development of operations research. In: *The Challenge to Systems Analysis*, G. J. Kelleher (Ed.), Wiley, New York, Chapter 3.
- Nielsen, C. B. *et al.* (2015). Systems of systems engineering: Basic concepts, model-based techniques, and research directions. *ACM Comput. Surv. (CSUR)*, Vol. 48, No. 2, p. 18.
- Principia Cybernetica Web. (2015). http://pespmc1.vub.ac.be/asc/operat_resea.html, (December 1, 2015).
- Pyster, A., *et al.* (2012). *Graduate Reference Curriculum for Systems Engineering (GRCSE®)*, The Trustees of the Stevens Institute of Technology, Hoboken, NJ.
- Ramo, S. (1969). *Cure for Chaos*, D. McKay Co., New York.
- Rechtin, E., and Maier, M. (1997). *The Art of Systems Architecting*, CRC Press, New York.
- Sage, A. P. (1981). Systems engineering: Fundamental limits and future prospects. *Proc. IEEE*, Vol. 69, No. 2, pp. 158–166.
- Sage, A. P. (1992). *Systems Engineering*, John Wiley & Sons, Inc., New York.
- Sage, A., and Armstrong, J. (2000). *Introduction to Systems Engineering*, John Wiley & Sons, Inc., New York.
- Senge, Peter M. (2006). *The Fifth Discipline: The Art and Practice of the Learning Organization*, Broadway Business.
- Smith, B. L. R. (1966). *The RAND Corporation*, Harvard University Press, Cambridge, MA.
- Stiglitz, J. E. (1966). *The Collected Scientific Works of P. A. Samuelson*, MIT Press, Cambridge, MA.
- Stockfish, J. A. (1970). The genesis of systems analysis with the bureaucracy. In: *The Challenge to Systems Analysis*, G. J. Kelleher (Ed.), Wiley, New York, Chapter 2.
- Stockwell, J. (2005). Red-light cameras stop rolling in N. Va.: Police lament the end of photo surveillance. *Washington Post*, July 3, p. C03.
- Syme, G. J., Bennett, D., Macpherson, D. K., and Thomas, J. F. (2011). Guidelines for policy modellers: 30 years on: New tricks or old dogs? MODSIM 2011: 19th International Congress on Modelling and Simulation, Perth, Western Australia.
- Szanton, P. L. (1972). Systems problems in the city. *Oper. Res.*, Vol. 20, pp. 465–473.
- Taylor, F. W. (1911). *Shop Management*, McGraw-Hill, New York.
- Teil, H., Bork, J. C. G., and Kloek, T. (1965). *Operations Research and Quantitative Economics*, McGraw-Hill, New York.
- U.S. Bureau of Labor Statistics. (2015). <http://www.bls.gov/ooh/math/operations-research-analysts.htm>, (December 1, 2015).
- U.S. Department of Commerce (1967). Research and development for high speed ground transportation. Clearinghouse for Federal Scientific and Technical Information, PB 1739, March 11.
- U.S. Department of Commerce (1974). Survey of Current Business, Vol. 54, No. 2.
- Waddington, C. H. (1973). *O. R. in World War 2: Operational Research Against the U-Boat*, Elek Science, London.
- White, D. J. (1985). *Operational Research*, John Wiley & Sons, Inc., New York.
- Whitehead, N. P., Scherer, W. T., and Smith, M. C. (2014). Systems thinking about systems thinking a proposal for a common language. *IEEE Syst. J.*, Vol. 99, pp. 1–12.
- Wolfram MathWorld. (2015). <http://mathworld.wolfram.com/OperationsResearch.html>, (December 1, 2015).