RISK MANAGEMENT AND RISK-BASED DECISION-MAKING

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Contents

Summary

This chapter provides a background on risk assessment and management. We illustrate modeling for risk analysis and how to deal with risk in potentially hazardous situations. A number of approaches are discussed, including fault tree analysis and hierarchical-multi-objective tradeoff analysis.

1. Introduction

Physical large-scale infrastructures, including water resources, transportation, telecommunications, and electric power, are complex, interconnected, and are planned, developed, operated, and maintained under conditions of risk and uncertainty. These characteristics render their modeling and thus their risk management a complex task. (The terms *risk* and *uncertainty* will be formally defined in subsequent sections.) To assess and manage the risk of complex systems such as physical infrastructures, it is vital to understand the inter- and intra-connectedness among their various subsystems. To do so we must embrace a *Gestalt* holistic vision.

For example, the complexity of water and related land systems is due primarily to their large number of constituencies and interdependent subsystems. In our quest to model this complexity, however, over the years we have developed and adopted relatively manageable models that often oversimplify some fundamental attributes of these systems. Most water distribution networks consist of a vast number of interconnected components - e.g., the distribution network, pumps, pipes, and treatment plants. In addition, a hierarchy of institutional and organizational structures--e.g., federal, state, county, and city - is involved in the decision-making process. The degree of physical and institutional coupling that exists among the subsystems (e.g., the budget constraint imposed on the overall system), further complicates their modeling as well as management. In the maintenance of water distribution systems, different replacement/repair strategies for varying subsystems often have unexpected impacts on the overall system; the demands for the resources and their appropriate allocations likewise have diverse impacts on a system's reliability.

The following statement seems as relevant today as it was three decades ago [Haimes 1977]:

In studying large-scale systems with technological, societal, and environmental aspects, the efforts in the modeling as well as in the optimization (solution of the system model) are magnified and often overwhelm the analysis. This is due to the high dimensionality (very large number of variables) and complexity (non-linearity in the coupling and interactions among the variables) of the resulting models.

2. The Complexity of Risk Modeling; Assessment and Management of Large-Scale Systems

Quantitative risk assessment and management must be built on sound modeling. Systems engineering assists in the decision-making process by selecting the best alternative policies subject to all pertinent objectives and constraints, using a plethora of modeling, simulation, optimization techniques, and other decision-making tools. It is very difficult to understand, let alone manage, the thousands, and maybe millions, of components of interconnected systems without models.

The process of system modeling is grounded on art and science. A mathematical model is a set of equations that describes and represents the essence of the real system. It uncovers the various aspects of the problem, identifies the functional relationships among all the critical components and elements of the system and its environment, establishes measures of effectiveness and constraints, and thus indicates what data should be collected to deal with the problem quantitatively. To represent adequately the essence of the interconnectedness of systems such as physical infrastructures, the analyst must acknowledge their inherent complexity - non-linear, probabilistic, and dynamic - and the often chaotic human interfacing and decision-making. Further complicating the modeling process is the need to address the following most common attributes of large-scale physical infrastructures:

- the science and engineering that govern the behavior of the system;
- the large number of interconnected components within the infrastructure system itself and its interaction with other infrastructures and/or systems;

- the inherent nature of the system in terms of its constituencies, power brokers, stake-holders, and users, its hierarchical, organizational, and functional decision-making structure;
- the multiple non-commensurate objectives and sub-objectives, including all types of important and relevant risks;
- the various time horizons - immediate, short-, intermediate -, and long-term; and
- the host of institutional, legal, and other socioeconomic conditions that require consideration.

Indeed, risk management of large-scale systems must address the myriad considerations that transcend scientific, technological, economic, political, geographic, and legal dimensions. These considerations may explain the difficulties of modeling such systems, and particularly, of quantifying the risks resulting from natural and man-made hazards. It is not surprising, therefore, that new models, methodologies, and procedures are being explored to fill a real need. Policymakers - the ultimate users of these procedures - have greeted some of these modeling approaches and risk assessment methodologies with opinions ranging from overall support to outright skepticism. Many systems-analysis studies (risk-assessment studies are no exception) have often been conducted in isolation from the policymakers and commissioned agencies responsible for implementing any results of these analyses. In 1996, for example, the General Accounting Office sextensively studied ways to improve the management of federally funded computerized models. The GAO identified 519 federally funded models developed or used in the Pacific Northwest area of the United States. Fifty-seven of these models were selected for detailed review, each having cost over $100,000 to develop. Although successfully developed models can be of assistance in the management of federal programs, the GAO found that many model-development efforts experienced large cost overruns, prolonged delays in completion, and total user dissatisfaction with the information obtained from the model.

The GAO study classified the problems encountered in model development into three categories: (1) 70% attributable to inadequate management planning, (2) 15% attributable to inadequate management commitment, and (3) 15% attributable to inadequate management coordination. Basically, these problems stem from the simple fact that model credibility and reliability (i.e., appropriate representation of the essence of the complexity of the systems being modeled) were either lacking or inadequately communicated to management.

Other major modeling impediments faced by natural and behavioral scientists, engineers, and other professionals stem from the dynamic and evolving non-deterministic processes that govern the interactions among the system’s components. Deterministic models are those in which each variable and parameter can be assigned a definite fixed number or a series of fixed numbers for any given set of conditions. In probabilistic (stochastic) models, the principles of uncertainty and variability are introduced. Neither the variables nor the parameters used to describe the input-output relationships and the structure of the elements and the constraints are known precisely.

When facing the task of modeling large-scale infrastructure systems, with an overwhelming number of subsystems and interacting components, it is natural to tend to aggregation and to reductionist modeling tools. *Aggregation* assumes sufficiently common characteristics among the components to merit linking them in one class or category. *Reductionism*, according to Webster's Third New International Dictionary, is "a procedure or theory of reducing complex data or phenomena to simple terms." Undisciplined reductionism of large-scale complex systems necessarily assumes overly simplistic relationships among their elements, and thus renders such models inadequate and not very useful. The study of complexity and complex systems has gained momentum, as is evidenced by the April 2, 1999 special issue of *Science* on "Complex Systems." For example, Gallagher and Appenzeller [1999], define a *complex system* as one whose properties are not fully explained by an understanding of its component parts. Selecting the appropriate level of aggregation and reductionism, modeling tools, time scale, physical scale, system boundary, model topology (e.g., level of non-linearity), model parameters, representative objectives and constraints, and the appropriate visions of the systems that should be modeled, constitutes the essence of the art and science of modeling.

Take the case of water resources systems. For generations, their complexity has defied a unified, holistic approach to their modeling and to understanding the influence of all critical, interactive, and coupled components of such systems. We know, for example, that the quality and quantity (Q&Q) of ground water of unconfined aquifer systems interact with and are functions of the Q&Q of surface water. Furthermore, the quality and quantity of surface and ground water (S&G) are functions of the quality of point and non-point discharges of treated or untreated effluents. In addition, the quality of S&G water is closely dependent on the land use and management practices of the watershed. Natural phenomena such as floods, droughts, hurricanes, climate change, and major earthquakes have their own critical influence on the Q&Q of S&G water. Water distribution infrastructure systems, which enable us to turn the faucet and expect clean water to flow without interruption, can and often do have their own impact on the Q&Q of S&G water. This is particularly true for aging and leaky infrastructures which deliver treated and untreated sewer water as well as clean water from natural sources. The following quote from a report by the National Council on Public Works Improvement [1988], which highlights the debilitating aging physical infrastructure in the US (and all around the world), is as representative of the state of the infrastructure today as it was in 1988:

After two years of study, the National Council on Public Works Improvement (the "Council") has found convincing evidence that the quality of America's infrastructure is barely adequate to fulfill current requirements, and insufficient to meet the demands of future economic growth and development.

Socioeconomic and other economic factors also have their roles to play in the Q&Q of S&G water. These include consumer water pricing, the cost of water and wastewater treatment, the cost of electric power, and water subsidies in the agricultural sector. Furthermore, advances in technology, industrial and manufacturing processes, agricultural practices, and improvements in manufacturing processes all directly affect the quality of the discharged water. Examples are the increased use of heavy metals in industry, and the impact of technology on the quantity of water used in the production of steel. Old steel production processes used about 200 tons of water per one ton of steel production; new technology uses less than 5 tons of water per one ton of produced steel. Finally, the ecology is an integral part of the quality of natural water resources.

In sum, the complexity of water resources and other infrastructure systems stems primarily from the close intricate couplings among many components and subsystems that span natural, man-made, socioeconomic, ecological, technological, geographical, and temporal factors. So far, this complexity has defied our ability to understand and model the above interconnectedness.

3. Systems Engineering, Risk Analysis and Large-Scale and Complex Systems

Risk-based decision-making and systems engineering are grounded on the same basic principles of holism and the *Gestalt* philosophy. Although some may view these as two distinct fields or disciplines, they reinforce and add synergy to each other, and constitute a unified approach to problem-solving. Many systems and risk analysts may actually be unaware of the common philosophical approaches that these disciplines share. Of course, the two fields differ in their historical evolution and technical maturity. However, both groups aspire to the *Gestalt*-holistic philosophy in their problem-solving and decision-making practices. Thus, they use similar methodological frameworks, which build on a plethora of theory, methods, tools, and techniques that constitute the instruments with which problems are studied, assessed, understood, managed, and solved, to the extent possible.

The *systems* concept has a long history. (The terms “systems engineering” and “systems analysis,” which may have different connotations to some individuals, will be used interchangeably here.) Although the term "system" itself was not emphasized in earlier writings, the history of this concept includes many illustrious names.

About 1912, German psychologists Max Wertheimer, Kurt Koffka, and Wolfgang Kohler founded the *Gestalt* psychology, which emphasizes the study of experience as a *unified whole*. *Gestalt* psychologists believe that *the whole is more important than the sum of its parts.* In 1948, Norbert Wiener published his seminal book *Cybernetics*. Indeed, the genesis of the development of computer technology, information theory, self-regulating machines, and feedback control is often attributed to Wiener.

Bertalanffy coined the term *General Systems Theory* around 1950. Kenneth Boulding, an economist, published his work on *General Empirical Theory* and claimed that it was the same as the General Systems Theory advocated by Bertalanffy. The Society for General Systems Research was organized in 1954 by the American Association for the Advancement of Science. The society's mission was to develop theoretical systems which would be applicable to more than one traditional field of knowledge.

Four decades ago, Bertalanffy noted that within the "systems approach," mechanistic and organismic trends and models tried to master systems either by “analysis," "linear (including circular) causality," "automata," "wholeness," "interaction," "dynamics" (or other terms used to circumscribe the difference). Major books on large-scale systems and hierarchical analyses emerged, primarily during the 1960s and 1970s: on decision analysis by Raiffa [1964], on systems theory and biology, edited by Mesarovic [1968], on modern systems research for the behavioral scientist, edited by Buckley [1968], on theory of hierarchical, multilevel systems by Mesarovic et al., [1970], on optimization theory for large systems by Lasdon [1970], and on optimization methods for large-scale systems, edited by Wismer [1971]. Other books are on hierarchical analyses of water resources systems: modeling and optimization of large-scale systems by Haimes [1977], a handbook of large-scale systems engineering applications, edited by Singh and Titli [1979], a systems and control encyclopedia, edited by Singh [1987], on metasystems methodology by Hall [1989], on hierarchical multi-objective analysis of large-scale systems by Haimes et al. [1990], on systems engineering by Sage [1992] and Sage and Rouse [1999], on systems-based risk analysis by Haimes [2004], and an encyclopedia of operations research and management science, edited by Gaas and Harris [1996]. There is also literature on large-scale systems: modeling, control, and fuzzy logic by Jamshidi [1997], and on process patterns - building large-scale systems using object technology by Ambler [1998].

Although the philosophy of risk analysis does not enjoy the same formal, historical documentation as the *systems* concept does, it has nevertheless an even longer tradition. Ancient civilizations adhered to structural strength, reliability, and safety, even if they did not call their practice “risk analysis.” Without complying with the basic tenets that guide today’s approach to risk analysis, how can we explain, for example, the durability of such structures as the pyramids in Egypt and Mexico?

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Biographical Sketch

Dr. Yacov Y. Haimes is the Founding Director (1987) of the University of Virginia's Center for Risk Management of Engineering Systems, and holds the Lawrence R. Quarles professorship in the School of Engineering and Applied Science. He is a member of the Systems and Information Engineering and Civil Engineering faculties. On the faculty of Case Western Reserve University for 17 years, he was Chair of the Systems Engineering Department. During the 1977-78 sabbatical years, he was an AAAS/AGU Congressional Science Fellow, joining the staff of the Executive Office of President Carter, and later the staff of the House Science and Technology Committee.

He is the recipient of several major awards in his field, including the Distinguished Achievement Award from the Society for Risk Analysis, the Georg Cantor Award from the International Society on Multiple Criteria Decision Making, and the Warren A. Hall Medal from the Universities Council on Water Resources. He is a Fellow of the following professional societies: AAAS, IEEE, ASCE, IWRA, AWRA, INCOSE, and the Society for Risk Analysis (SRA). He also served as President of SRA. He has published over 200 articles and technical papers, over 120 of which are in archival journals. He has authored/co-authored five books and edited 20 volumes. His most recent book is *Risk Modeling, Assessment, and Management*, John Wiley & Sons, published in 1998.