Second International Symposium on Engineering Systems
MIT Cambridge, Massachusetts, June 15-17- 2009

Models of Complex Enterprise Networks

W. B. Rouse, L. F. McGinnis, R. C. Basole, D. A. Bodner, W. C. Kessler

Tennenbaum Institute
Georgia Institute of Technology
Atlanta, GA 30332-0210 USA

ABSTRACT

This paper reports on an ongoing comparative study of network models of complex enterprises. The focus is on enterprises composed of a large number of organizations, often represented as a hierarchy of networks that relate people to processes, organizations, and broader social and economic structures and forces. We consider the roles that information and incentives play in such complex hierarchical networks. These networks are elaborated in terms of four characteristics: transformations, flows, controls, and social/organizational relationships. A model hierarchy is presented that relates these four characteristics to phenomena, representations, micro-models, macro-models, and modeling tools. Examples of global manufacturing and health care delivery are woven through these discussions of alternative representations and models. We conclude by providing a structured comparison of these two domains.

Key Words: Complex systems, network models, hierarchical models, engineering systems, global manufacturing, health care delivery.

1. Introduction

Enterprises are typically composed of a large number of organizations that provide products and services, as well as other organizations that play important roles in the enterprise ecosystem. Such enterprises can be represented as hierarchical networks as shown In Figure 1.

At the lowest foundational level, there are people working to create value, e.g., by assembling aircraft or automobiles, or providing medical care to patients. This work occurs in the context of the business processes of delivery operations. These processes may be formalized and visible -- perhaps also reengineered and optimized -- or they may be obscured by functional or departmental boundaries between, for example, engineering and manufacturing, or between orthopedics and radiology.

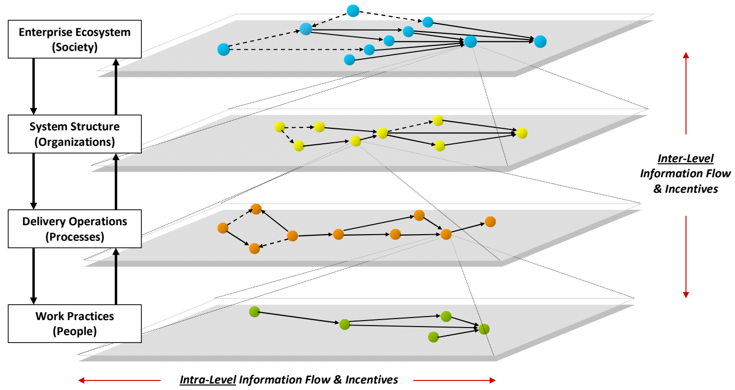

Figure 1. Hierarchical Enterprise Network

Work practices and business processes occur in the context of organizations. Often they occur both within and across organizations. The realization of products such as aircraft and automobiles typically involves hundreds and perhaps thousands of organizations. Of late, many of these organizations are involved, not just in manufacturing and assembly, but also in design and development, and product support. Many health systems are federations of large numbers of small independent organizations, perhaps having buildings, parking lots and, if fortunate, information systems in common. This fragmentation can make process design and operation difficult (Rouse, 2008).

All of these organizations – the extended enterprise – operate within the context of the ecosystem defined by society in terms of economic, social, political, and legal processes that incentivize or inhibit organizations in a range of ways. For global enterprises, such as those producing aircraft and automobiles, export policies, local content requirements, technology restrictions, taxes and tariffs, and so on provide strong shaping forces on enterprise strategy formulation and execution. Cultural norms for health care, wellness, education, and productivity, including the tension between individual and institutional responsibility, have an enormous impact on the potential to engineer a system to provide affordable, quality health care for all.

Our approach to complex enterprise networks focuses on the hierarchy of ends and means shown in Figure 2. The emphasis is on the delivery of value in the context of an enterprise ecosystem, at all levels of the hierarchy. The value-driven nature of enterprises is common to high performing enterprises of all types.

Whether the ecosystem is global manufacturing of aircraft and automobiles or local health care delivery, value streams (or value networks) and work processes are central constructs in an overall conceptual model. Further, information and incentives are fundamental to value streams and work processes; understanding their roles is essential to understanding the enterprise and, hopefully, to using better information and incentives as a means to achieving increased value.

Conceptually, there are fundamental similarities between complex enterprise networks for delivering aircraft, automobiles, and health care. However, there is the substantial difference that aircraft and automobile providers are primarily product delivery systems, while health care providers are primarily service delivery systems. Products can be inventoried—services cannot. Products tend to be mass produced (perhaps with many variations) while health care services tend to be highly individualized.

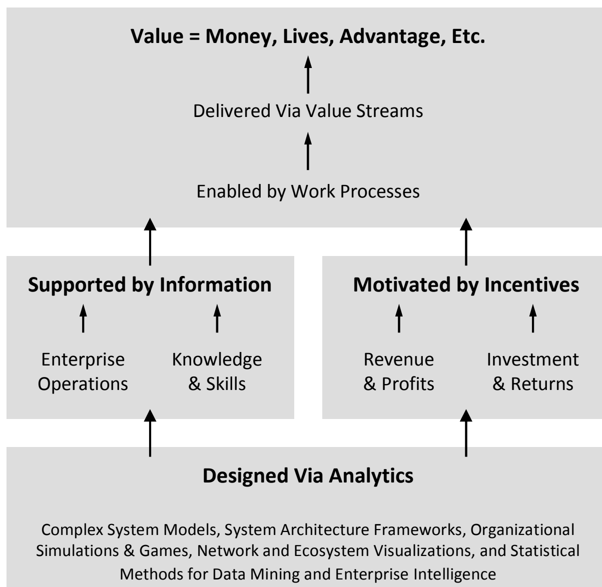

Figure 2. Value-Driven Nature of Enterprises

Aircraft and automobile manufacturing is an example of a complex product delivery system where many things have to come together into one smoothly functioning entity. In the case of an airplane, for example, companies collaborate and interact during the design process and form global supply relationships to provide and deliver major components, such as the wing, the fuselage or engine. In this type of domain, the physical products or "goods" are the center of this type of complex system.

Health care delivery, in contrast, is an example of a complex service delivery system where the complexity is due to the many organizational seams that hinder alignment of objectives and incentives, as well as information flow. There are many products that enable the services provided in such systems but, unlike complex product delivery systems, these products are not a primary source of the complexity of such systems. The socio-technical nature of the system is the primary source of complexity. In other words, people and organizations, rather than technology, are dominant (Rouse, 2007a).

The sharpness of this contrast blurs as we move up the hierarchy shown in Figure 1. People and organizational (socio-technical) issues dominate the upper two levels for both ecosystems. Further, as aircraft and automobile providers have come to realize the great economic opportunity surrounding the support and sustainment of their vehicles, the service aspects of this extended enterprise have become more attractive. Nevertheless, the level of integration required for aircraft and automobiles is inherently much greater than that required for health care. This can be illustrated by the simple fact that purchasers of aircraft and automobiles hopefully acquire one or more instance of every component of these systems while consumers of health care would never avail themselves of every service a provider offers.

The bottom element of Figure 2 address design via "analytics," including complex system models, system architecture frameworks, organizational simulations and games, network and ecosystem visualizations, and statistical methods for data mining and enterprise intelligence. Consideration of these models, methods, and tools begs the question of system representation.

2. Representation

An enterprise can be described in terms of *transformations* and *flows*, whether it produces a product or a service. In the case of product producing enterprises, the transformations convert purchased material (or components and assemblies) into a product ready for sale. Typically, there will be a large number of distinct transformations, and each of them may be viewed as a *node* in a *flow network*. A particular transformation node is involved in transactions related to the input and output of materials.

In a product oriented enterprise, there are two special categories of transformation nodes. *Customer-facing* nodes are a special case of transformation, as they transform ownership from the enterprise to the customer, and their transactions with customers will involve both an exchange of material and an exchange of payment. Likewise, *supplier-facing* nodes transform ownership from suppliers to the enterprise and involve payment. In general, transactions among the transformation nodes in the network that are not customer- or supplier-facing, do not involve an explicit payment.

In service oriented enterprises, the "flow" through the network is the customer, who visits one or more transformation nodes in order to receive the service they want. For example, in a doctor's office, the customer typically will interact with a scheduler (transforms the customer from unscheduled to scheduled), perhaps a physician assistant who collects information from the customer, the doctor who provides the service, and then an accounting function that insures payment is received.

The enterprise flow network is supported by a number of other associated networks. There is a *control network* that captures and archives information on the state of the enterprise and transactions that change the state. In addition, the control network makes decisions and communicates information necessary to coordinate flow and transformation activities.

There is a *financial network* that manages the flow of money through the enterprise. It not only connects to all the nodes in the transformation network, but also to suppliers of financing and to "inventories" of money. To an extent, the financial network can be viewed as an element of the control network for one particular class of resources – money.

There is a *social-organizational network* that may play a number of distinct roles. It may describe the organization of resources in the transformation or control networks. It may dictate general rules to which work processes or transactions must conform. There are usually formal and informal versions of this network. The informal version often plays a significant role is how work actually gets done.

There are also social forces that act more like force fields than networks, e.g., like gravity acts on masses. Cultural factors such as accountability, trust, risk attitudes, etc. have pervasive effects on how work is done, including how well it is done. Depending on the nature of changes being pursued (Rouse, 2006), the social network can either be an enabler or affordance or be an impedance – for the latter, it can act like an immune system and reject change.

The enterprise *work processes* may be specific to a particular node in one of the networks composing the enterprise, or may involve multiple nodes, perhaps spread across several networks. Value streams (actually, value *networks*) and work processes may extend beyond the boundary of the enterprise. For example, certain transformations may be outsourced, so that material (or a customer) is sent to a partner enterprise and then returns to the original enterprise. In fact, much of the innovation in manufacturing over the past twenty years has been in the form of "rationalizing" the transformation network, so that transformations are performed by enterprises that are most competent and cost effective at performing them.

If we look at a particular node in the transformation network, it must have an appropriate set of resources and practices, whereby it produces results that are evaluated with some set of metrics and criteria. Improving a given transformation node or network generally involves changing the resources committed, or changing the work practices, in order to produce a result that is better, faster, or cheaper. Feedback is essential in determining the performance of a transformation node or network. The further in time the assessment is removed from the performance, the more difficult to make improvements.

The enterprise also will have a number of functions that are not specifically focused on the transformations associated with products or services. For example, marketing attempts to create demand for the product or service produced, thereby transforming people into customers. Human resources attempts to maintain an appropriate inventory of people and skills, often transforming people into employees. Legal attempts to insure the work practices comply with all applicable laws and regulations, perhaps as part of the control network.

In summary, the enterprise creates value that is delivered by its value network executing its work processes. These work processes are enabled by knowledge—both about what has happened in the past (what were we able to do?) and knowledge about what may happen in the future (what do we think we can do?). They are motivated by success—both historical success (how was success measured and how were we rewarded for success?) and the anticipation of future success (how will success be measured and how successful do we think we can be?).

3. Modeling

There is a wide variety of approaches to mathematical and computational modeling of complex systems (Sage & Rouse, 2009). We will not attempt to catalog this wealth of approaches. Instead, we outline a modeling hierarchy based on the range of representations discussed in the last section.

- Transformation (within nodes): Milling machine, robot cell, MRI machine, dialysis machine

- Flow (between nodes): Materials, components, assemblies, products, patients, supplies

- Control (ΔTrans, ΔFlow): Production planning & control system, patient/clinician scheduling system

- Social/Organizational: Formal and informal interactions among workforce, suppliers, distributors, alliances

Note that we do not include specific "field" models for social and cultural forces such as accountability, trust, risk attitudes, etc. At this point, we see these phenomena being reflected in the parameters of the other classes of models, particularly the social/organizational models.

The modeling hierarchy is summarized in Figure 3. The columns of this hierarchy reflect the four types of representation listed above. The rows range from fundamental phenomena being represented, to types of representations, to micro-models of phenomena, to macro-models of the interactions of multiple instances of the same types of phenomena. The upper-most row on this hierarchy is labeled with off-the-shelf software tools commonly used to support the approach to modeling outline in their respective columns.

There are many problems that can be addressed by employing only one column in Figure 3. However, fully addressing complex enterprise issues requires moving across columns. Thus, we may need a modeling approach that embodies system dynamics, discrete events, and social interactions. So, for example, we might need to use a combination of Vensim, Arena, and REPAST.

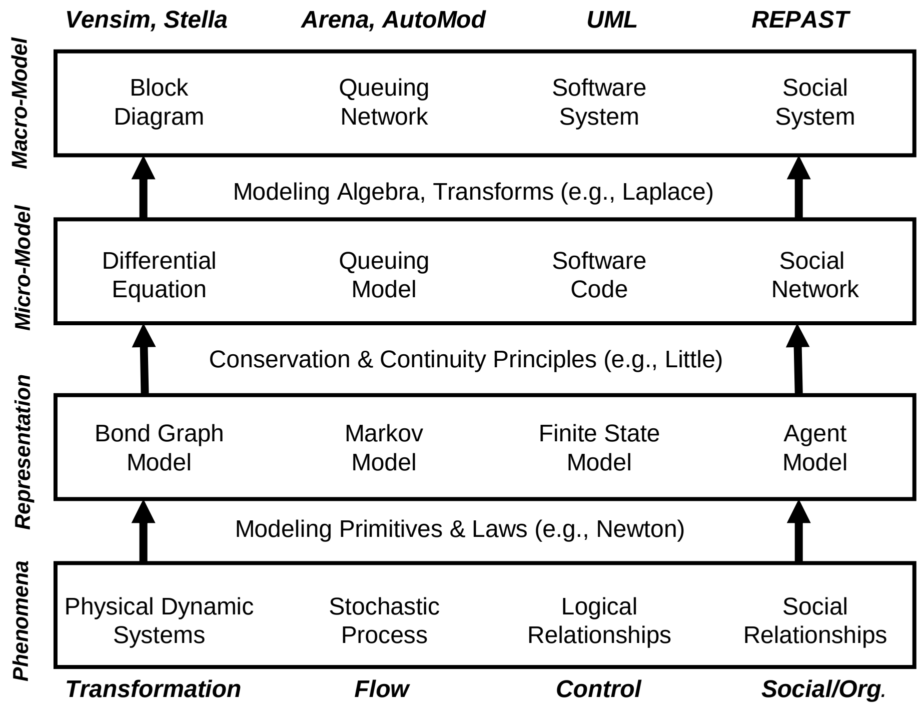

Figure 3. Modeling Hierarchy

Such an integrated modeling capability is needed to simulate organizational behavior and change over time. Traditional simulation approaches are limited by their focus on particular organizational aspects (i.e., the columns shown in Figure 3). Recent work is developing a framework that provides organizational simulation capability based on the concept of a reference model, or canonical description of a class of organizational systems, including architecture, components, inter-relations and behaviors (Bodner, 2009). This reference model is then linked to existing simulation tools that are then used to model specific organizational system elements (individual behavior, organizational processes, decision-making, etc.).

This work is being done in the context of the defense acquisition enterprise. This enterprise embodies both the process-focused nature of manufacturing (staged design, development and deployment processes for acquiring systems) and the diverse stakeholder nature of health care (contractors, military services, research and development labs, and government agencies).

Another concern that cuts across the columns of Figure 3 is alternative visual representations of such models, including the computational value of these representations. Basole and his colleagues (2008, 2009) are developing models and visualizations of complex value systems, using network analytic and information theoretic approaches, with a focus on dynamic and converging ecosystems, such as health care, manufacturing, biotech, and telecom markets. The objective of this work is to portray the numerous multi-level interactions between actors (e.g. individual, organizational, enterprise) and actor types (e.g. supplier, customer, enablers, etc.) as well as the interplay of different types of connections and flows (e.g. informational, contractual, financial, social, etc.) for purposes of risk identification, performance improvement, and innovation opportunity discovery.

Peak, et al (2008) have been exploring the use of SysML as a platform for both federating a number of product and enterprise models, as well as integrating the federated models with formal analysis methods.

Juxtaposing Figures 1 and 3, it is important to note that these two hierarchies are not meant to inherently align. Thus, for example, fundamental phenomena may occur at the organization or ecosystem level. The dynamics of international alliances for global manufacturing is a good example (Kapstein, 2009). In general, there are holistic phenomena that cannot be modeled by reducing the enterprise system to its basic constituent parts at the people and process levels. Consequently, fully understanding the enterprise requires a balance of holistic and reductionist views (Rouse & Basole, 2009).

4. Contrasts

How does this way of thinking about the enterprise help in understanding differences in manufacturing and health care delivery? How different are manufacturing and health care delivery?

<u>Knowledge of the (Near Term) Future.</u> In manufacturing, tomorrow will be very much like today, at least if you are an OEM. The product does not change very often, even though there may be many variations. The production rate may fluctuate, but not dramatically, under normal circumstances. For primary health care delivery, tomorrow may be rather different from today—the set of patients seen tomorrow may have little (medically speaking) in common with those seen today. In contrast, specialists tend to see many patients with very similar problems, although patients are by no means as standardized as products. The implication is that it is much easier to achieve resource efficiency in the transformation process in manufacturing than it is in health care delivery, especially for primary health care.

<u>Work Process Variability.</u> In manufacturing, the goal is to minimize the variability in the work processes. Every unit of product should be treated the same. This allows the enterprise to learn and "perfect" the work process over the many instances of (very similar or identical) product units. In primary health care, there is so much variability from one customer to the next that it is very difficult to learn and "perfect" work processes that are customer specific, although it may be possible to perfect non-customer facing workflows, such as forms processing. For specialists and testing (e.g., MRIs), there is much less variability. Nevertheless, the customers may not want to be treated exactly the same.

<u>Expectations of Customers.</u> In manufacturing, customers have a very clear expectation regarding what they are purchasing, and what their experience will be in using the product. In health care delivery, often the customer has no clear expectation, other than a wish to be "made well." In manufacturing, customers generally have a range of

alternative suppliers, and a wealth of information to help them choose among the alternatives. In health care delivery, the customer may have only very limited options (e.g., PPO), and very little or no comparative information. Manufacturing tends to get very clear signals from customers regarding performance, whereas health care delivery tends to get a muted signal or no signal at all. The implication is that manufacturing has much better knowledge about what was done in the past and what can be done in the future, and is in a much better position to learn and improve. Recent emphasis on evidence-based medicine will likely enable health care to take advantage of lessons learned in manufacturing.

Ability to Buffer Against Variability. In manufacturing, it usually is possible to protect expensive resources from transient declines in their rate of application by providing inventory buffers. Products that are not needed immediately can be produced and stockpiled, or materials that will be needed in the future can be acquired now and stockpiled. In health care, the health care service cannot be stockpiled. A customer wants their service when they arrive. They do not want to be "stockpiled" to keep the doctor busy – although, this does tend to happen. The implication is that it is much more difficult to "optimize" resource utilization in health care than in manufacturing. The overarching issue is the inability to inventory time. Just as empty aircraft seats cannot be saved for later use, clinicians' capacities cannot be inventoried.

Cost to Produce. The cost to produce a unit of manufactured product is virtually the same from one unit to the next, because the work processes are so standardized and have so little variability. In fact, production learning typically results in unit costs decreasing. In health care, the cost of service from one customer to the next can be quite different—one customer requires only a simple consultation, whereas the next requires a battery of expensive tests. Greater variability in requirements naturally leads to less efficiency in the application of resources, **or** to less responsiveness to customer requirements (case in point, long lead times in Canada for certain kinds of procedures).

Traceability from Performance to Result. In manufacturing, usually it is fairly straightforward to trace back from the outcome (quality of the product) to the transformation process that produced a defect in the product. In health care, this kind of traceability is virtually impossible. The implication is that manufacturing has much more information to support learning and improvement than does health care delivery. A key issue here is health care's strict rules for what counts as evidence, i.e., randomized clinical trials. Evidence-based medicine initiatives are leading to more openness to other ways of learning, which will provide more credibility to operational traceability. Such traceability may include more than just the relationships between health care interventions and outcomes. For example, life style choices are likely to be strong determinants of outcomes.

Connection between Cost and Revenue. In manufacturing, price tends to be determined by market forces, a customer buys only one unit of product, and profit results from controlling costs. In health care, prices for many services are set by a government agency, and "profit" depends more upon maximizing the services rendered to a customer than on minimizing costs. The implication is that market forces drive manufacturing to achieve a better alignment between the goals of the producer and the goals of the consumer, whereas in health care delivery, the disconnect between the customer and the payer may lead producers to behave in ways that are not completely aligned with goals of their customers.

Duration of Production Process. In manufacturing, typically customers do not know and do not care how long it takes to produce the product, as long as it is available when they want it. In health care delivery, customers care a great deal about how long it takes to produce the service they need. Making them wait in order to improve the utilization of the expensive resources reduces the level of their satisfaction with the service received.

Many of the above contrasts reflect the fact that manufacturing focuses on engineered products while health care delivery focuses on natural systems. While they both are complex systems (Rouse, 2007b), there are significant differences:

- Patients have more variability than most products, at the very least in terms of size, age, race, etc., but also in terms of disease characteristics at particular points in time, as well as lifestyle choices and their evolving consequences.

- As a result, health care networks have more branching than manufacturing, especially unplanned branching due to evolving discovery of patient-specific patterns of symptoms.

- The nodes of specialists, tests, and treatments are somewhat standardized, but patients' paths are not, resulting in considerable variability of flows among transformation nodes.

- Primary care is intended to serve the role of managing the paths of patients, but the fragmentation of the enterprise severely limits the possibility for control to align time-varying demands and processing capacities.

Thus, health care delivery and manufacturing have significant differences. Nevertheless, many of the lessons learned in representation and modeling of manufacturing systems (Compton, 1988) can be fruitfully applied to health care delivery (Reid, et al, 2005.). A key element of the transfer of such lessons learned is recognizing the nature of the problem being addressed in terms of the constructs in Figure 3 and assuring that the specific approaches in one domain clearly map to the other domain.

5. Conclusions

This paper has summarized an ongoing comparative study of network models of complex enterprises. These networks were elaborated in terms of four characteristics: transformations, flows, controls, and social/organizational relationships. A model hierarchy was presented that related these four characteristics to phenomena, representations, micro-models, macro-models, and modeling tools. Examples of global manufacturing and health care delivery were woven through these discussions and a structured comparison of these two domains was provided.

We have pursued similar analyses in other domains such as retail and telecom. While space does not allow, our sense is that the constructs in Figures 1-3 are generally applicable across domains. Two overarching conclusions have resulted:

- Information and incentives are the factors that dominate an enterprise's abilities to fundamentally change the nature of the value provided and the ways in which this value is provided.

- Understanding the transformations, flows, controls, and social/organizational nature of the "as is" and "to be" enterprise are central to orchestrating the changes needed.

References

R.C. Basole, Visualization of Interfirm Relations in a Converging Mobile Ecosystem. *Journal of Information Technology*, Vol. 24, No. 2, 2009, 1-16.

R.C. Basole and W.B. Rouse, Complexity of Service Value Networks: Conceptualization and Empirical Investigation. *IBM Systems Journal*, Vol. 47, No. 1, 2008, 53-70.

D.A. Bodner, D.A., *A First-Generation Reference Model for Organizations to Support Organizational Simulation*. Working Paper, Tennenbaum Institute, Georgia Institute of Technology, Atlanta, GA, 2009.

W.D. Compton, Ed., *Design and Analysis of Integrated Manufacturing Systems*. National Academy Press, Washington, DC, 1988.

E.B. Kapstein, Governing Opportunism in International Armaments Collaboration: The Role of Trust. In W.B. Rouse, Ed., *The Economics of Human Systems Integration*. Wiley, New York, 2009

R. Peak, L. McGinnis, and C. Paredis, C. (2008) *Integrating System Design with Simulation and Analysis: Phase 1 Final Report*. Georgia Institute of Technology, Atlanta, GA, 2008.

P.P. Reid, W.D. Compton, J.H. Grossman,and G. Fanjiang, *Building a better delivery system: A new engineering/health care partnership*. National Academies Press, Washington, DC, 2005.

W.B. Rouse, (Ed.), *Enterprise Transformation: Understanding and Enabling Fundamental Change*. Wiley, New York, 2006.

W.B. Rouse, *People and Organizations: Explorations of Human-Centered Design*. Wiley, New York, 2007a.

W.B. Rouse, Complex Engineered, Organizational & Natural Systems: Issues Underlying the Complexity of Systems and Fundamental Research Needed to Address These Issues. *Systems Engineering*, 10 (3), 2007b, 260-271.

W.B. Rouse, Healthcare as a Complex Adaptive System. *The Bridge*, 38 (1), 2008, 17-25.

W.B. Rouse and R.C. Basole, Understanding Complex Product and Service Delivery Systems. In J. Spohrer, P. Maglio, and C. Kieliszewski, Eds., *Handbook of Service Science*. Springer-Verlag, Berlin, 2009.

W.B. Rouse, and K.R. Boff, *Organizational Simulation: From Modeling and Simulation to Games and Entertainment*. Wiley, New York, 2005.

A.P. Sage and W.B. Rouse, *Handbook of Systems Engineering and Management*. 2nd Edition, Wiley, New York, 2009.