Chapter 28
Computational Modeling of Complex Enterprise Systems: A Multi-Level Approach

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28.1 Introduction

Enterprises are complex adaptive socio-technical systems (Dooley 1997; Rouse 2005). They exhibit nonlinear, dynamic characteristics, resulting in system behavior that often appears random or chaotic. Enterprises tend to consist of many independent agents, whose behavior can be described by social, psychological, and physical rules, rather than dictated by the dynamics of the entire system. The needs and desires of these agents are not homogenous; their goals and behaviors often conflict, requiring agents to dynamically adapt to each other's behavior. At the same time, agents are intelligent and learn. The overall enterprise system thus changes over time. This adaptation and learning often result in self-organizations in which patterns and behaviors emerge. Given that no single agent is in control, complex enterprise system behaviors are often unpredictable and uncontrollable. Successful transformation of such systems is consequently quite challenging. Traditional modeling and analyses approaches fail to consider these complex issues and are therefore inadequate for supporting enterprise transformation efforts. New methods and tools are therefore needed.

This chapter argues for the use of computational methods in pursuit of this engineering endeavor. Computational modeling augments and amplifies human decision making and facilitates exploration of a wide range of possibilities, thereby enabling the early discarding of bad ideas and refinement of good ones. This enables decision makers to "drive the future" before "writing the check" (Rouse 2013). Computational modeling of organizations has a rich history in terms of both

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research and practice (Prietula et al. 1998; Rouse and Boff 2005). This approach has achieved credibility in organization science (Burton 2003; Burton and Obel 2011), economics (Amman et al. 2006; Tesfatsion 2002), and the social sciences (Epstein 1996; Lazer et al. 2009). It is also commonly used by the military (Rouse and Boff 2005). Simulation of physics-based systems has long been in common use, but the simulation of behavioral and social phenomena has only matured in the past decade or so. It is of particular value for exploring alternative organizational concepts that do not yet exist and, hence, cannot be explored empirically.

28.2 Literature Review

It is not unique to conceptualize representations for complex systems such as enterprises using different levels of abstraction and aggregation. Using multiple levels of abstraction allows for modeling a wide range of phenomena that occur in such systems. Combining different levels of representation into a single model is one way to capture the different phenomena that exist in a large system such as an enterprise. Rouse and Bodner (2013) provide an extensive review of research in this field.

Mesarović et al. (1970) pioneered theories and representations for multilevel modeling, focusing on mathematical relationships between different elements in the overall model. They specify a two-level, hierarchical model where system elements operate in ways to optimize the overall objective of the system. They lay out relevant general principles for multilevel modeling, including the following:

- Selection or specification of levels depends on the modeler/analyst and his or her interests of study.
- Each level has its own principles or laws that govern behavior of system elements and relationships within that level.
- The behavior of a particular level generally depends on that of lower levels in the hierarchy.
- Each level has its own terms, concepts, and principles.
- Understanding of a system is gained by studying it across all levels. Detailed understanding comes from the lower levels, while understanding significance comes from higher levels.

In viewing a particular system for purposes of creating a multilevel model, it is important to frame and structure the problem so that the correct levels can be identified, and so that system elements and phenomena can be assigned to appropriate levels. Three particularly relevant approaches for this are the soft systems methodology (Checkland 1999), the viable systems model (Beer 1984), and critical systems heuristics (Ulrich 2003). These methodologies frame important questions that should be addressed prior to model specification. The viable systems methodology, in particular, provides guidance on organizing elements and relationships in an enterprise context.

While there are differences in phenomena and behavior in different levels of a multilevel model, three common elements found in each level are functions, structure and processes. Gharajedaghi (2011) advocates a method for utilizing these concepts in designing complex adaptive systems such as enterprises. While such building blocks are useful in modeling at multiple levels, it should be noted that interoperability across levels is a key issue. Tolk and Muguira (2003) describes a set of principles for achieving such interoperability with a focus on semantic interoperability.

It should be noted that a key technical issue in integrating different simulation models is that of time interoperability. This is an issue if two or more different models are used to represent different levels and then are integrated to form a multilevel model. Protocols such as the high-level architecture (HLA) have been developed to standardize how simulation models are integrated with respect to timing of state changes (DMSO 2001). State changes can be considered as continuous or discrete, and modeling paradigms have evolved that use one or the other representation. A multilevel model might combine these two representations. Zeigler et al. (2000) address the integration and coordination issues in combining differential equation, difference equation, and discrete event representations. One major focus is on rationalizing the different time scales associated with these different representations.

There is an emerging body of literature in multilevel modeling of enterprises, including enterprise networks (Basole et al. 2011), military communications (McDermott et al. 2013), and health care (Park et al. 2012; Rouse 2013).

28.3 A Multilevel Modeling Framework

The challenge of modeling enterprises and their transformations begins with the lack of a common understanding of what constitutes an enterprise. Although no single definition exists, it has been argued that an enterprise is a "goal-directed organization of resources—human, information, financial, and physical—and activities, usually of significant operational scope, complication, risk, and duration" (Rouse 2005). With this definition, enterprises can range from corporations to supply chains to markets to governments to economies.

Enterprises typically comprise a large number of organizations that contribute products and services to the enterprise, as well as other organizations that play important roles in the enterprise ecosystem (Basole and Rouse 2008). Thus, enterprises are complex socio-technical systems consisting of a highly interconnected and layered network of physical, economic, informational, and social relationships (Basole et al. 2011).

The architecture of an enterprise can be conceptually represented as a multilevel model consisting of four interdependent levels: people, processes, organizations, and ecosystem (Basole et al. 2011), as depicted in Fig. 28.1.

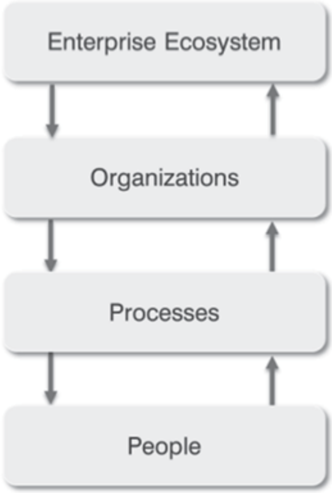

Fig. 28.1 Multilevel model of an enterprise

28.3.1 People

At the foundational level are people. People create value through work, for example, by assembling a product such as an aircraft or automobile; or providing services, such as medical care to patients. Social networks shape this level. People have many different characterizing attributes ranging from demographic characteristics to behaviors and incentives.

28.3.2 Processes

People conduct work in the context of business processes. These business 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. Processes are often depicted by network diagrams and characterize how and when work flows.

28.3.3 Organizations

Work practices and business processes occur in the context of organizations. Often, they occur within and across organizations. The realization of products, such as aircraft and automobiles, typically involves hundreds and perhaps thousands of organizations, not just in manufacturing and assembly, but also in design, development, and product life cycle support. Many health systems are federations of large numbers of small, independent organizations, perhaps having buildings, parking lots, and information systems in common. This fragmentation can make process design and operation difficult (Rouse 2008). Inter- and intra-organizational networks thus characterize the system structure level.

28.3.4 Ecosystem

All of these organizations as well as their business processes and people operate within the context of the entire enterprise ecosystem defined by society in terms of economic, social, political, and legal processes that incentivize or inhibit organizations in a range of ways. For instance, the "market maturity, economic conditions, and government regulations will affect the capacities (processes) that businesses (organizations) are willing to invest in to enable work practices (people), whether these people be employees, customers, or constituencies in general." (McDermott et al. 2013).

28.4 Case Studies

We illustrate our multilevel modeling framework using two domains of national importance and corresponding complexity: health-care delivery and global manufacturing. Both domains are complex public–public enterprises in which transformation is a necessary but incredibly challenging endeavor.

28.4.1 Health-Care Delivery

Health-care providers are facing fundamental changes to the way they get paid for their services—pay for outcome is replacing fee for service. As financial incentives change, providers must focus more on prevention and wellness to reduce risks of chronic diseases; providers of chronic care management will focus on population health issues such as keeping blood pressure (BP) and glycosylated hemoglobin (HgA1C) levels under control and avoiding hospitalizations and even office visits when e-visits will suffice; and providers of in-patient care will increase efforts to minimize readmissions. To achieve these results, providers must transform their delivery systems by focusing resources on processes and practices that create the desired health outcomes. Health-care payers want to avoid payment schemes that have negative or other unintended consequences.

How can these entities and other health system stakeholders explore alternatives without having to invest the time and cost of implementing and evaluating each one? Because empirical redesign of health-care delivery is impractical, computational approaches hold enormous promise by enabling rapid and inexpensive exploration of alternative health-care delivery mechanisms and their impact on key economic and health outcomes (Basole et al. 2013).

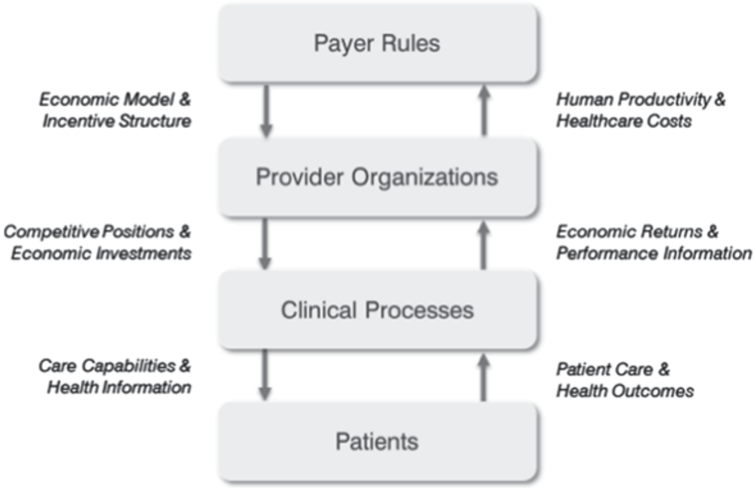

Fig. 28.2 Multilevel model of health-care delivery

A multilevel modeling approach in health care is dictated by the nature of the phenomena of interest, ranging from patient–clinician interactions to care-flow processes to organizational microeconomics to enterprise or national policy decisions. Multilevel modeling is also needed to enable simultaneous observation of computations by all stakeholders in evidence-based policy and practice, as well as to support interactive decision making.

Consider the architecture of the enterprise of health delivery shown in Fig. 28.2 (Grossmann et al. 2011; Rouse 2009; Rouse and Cortese 2010). The lowest level includes both patients and the health delivery workforce, whose availability affects system performance. Innovations at this level include, for example, practice control systems. However, the efficiencies that can be gained at the clinical practice level are limited by capabilities and information provided by the next level (delivery operations). For example, functionally organized practices are much less efficient than those where delivery is organized around care processes.

Similarly, the efficiencies that can be gained in operations are limited by the nature of the level above (system structure). Functional operations are driven by organizations structured around specialties (e.g., anesthesiology and radiology). When the different specialties are actually different businesses with independent economic objectives, process-oriented thinking becomes quite difficult. At an extreme, if a business (e.g., organization or functional unit) within the enterprise owns only an expensive magnetic resonance imaging (MRI) system, then their objective will be to employ it as often as possible to optimize individual business performance even if that increases overall costs of care. This is a good example of "suboptimization" within a system.

Moreover, efficiencies in system structure are limited by the health-care ecosystem in which organizations operate. The ecosystem sets the "rules of the game." For

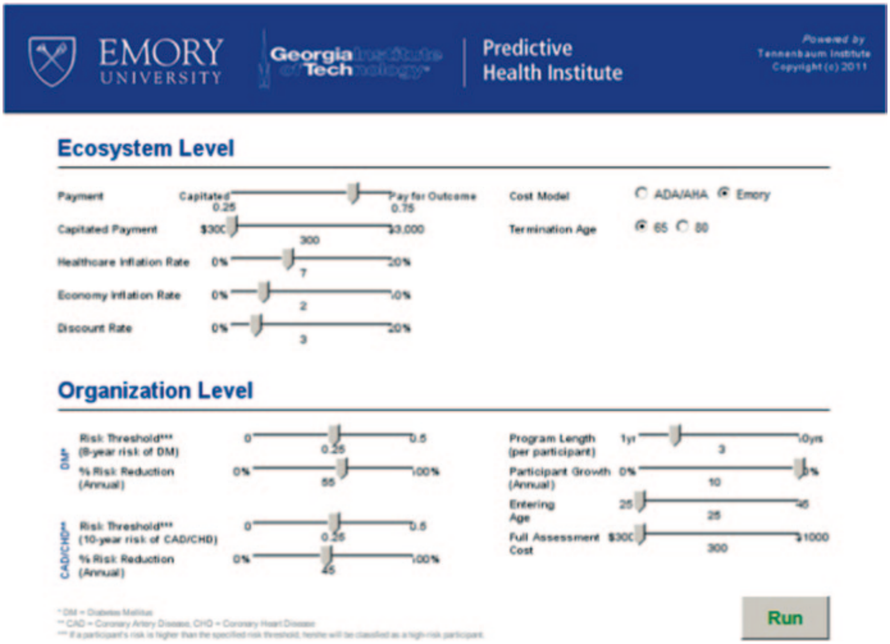

Fig. 28.3 Multilevel simulation dashboard

example, if the rules attach no value to healthy, productive people, then the focus will be on providing acceptable service over the short term at minimum cost. As "acceptable" is often difficult to agree upon, the greatest weight is usually placed on controlling the costs of the most expensive and profitable procedures. Differing experiences in other countries provide ample evidence of the range of impacts of the ecosystem.

We have piloted and successfully applied our multilevel modeling approach in several health-care delivery settings. Following, we present our computational modeling approach for an employer-based prevention and wellness program (Park et al. 2012). The decision of interest concerns the possibility of changing from a capitated system of payment to an outcomes-based payment system. The outcomes of interest are risk reductions in diabetes mellitus and coronary heart disease. More generally, decision makers were concerned with the design of prevention and wellness programs that are self-sustaining and provide a positive return on investment for the overall enterprise.

We implemented the four-level model and dashboard in AnyLogic[1], a commercially available simulation software tool that supports integrated modeling of discrete-event, agent-based and system dynamics simulations (see Fig. 28.3). Health-care stakeholders determined the key dashboard variables. Parameters for each of the model variables were driven by actual or national datasets. The dashboard

[1] www.anylogic.com.

allows a wide range of users (e.g., decision makers, policy analysts, organizational designers) to change model parameters and view the simulation outcomes in real time.

However, model parameters have many complex interdependencies that may lead to nonintuitive outcomes. Consequently, we ran some experimental simulations using a parameter variation approach, resulting in a large number of result surfaces, shown in Fig. 28.4. Our results showed that financial objectives between different stakeholders should not be independently optimized, since if any stakeholder loses significantly, the system becomes dysfunctional. Our results also showed that in order for the wellness and prevention provider to stay in business, it would have to change its business model, stratifying the population by risk levels and tailoring processes to each stratum. Our approach enabled exploring "what if," comparing it to "what is," and tailoring the delivery system to the nature of the population served as well as the priorities of the participating organizations. All of this is done in an interactive, inspectable environment open to participation of all stakeholders.

28.4.2 Global Manufacturing

Global manufacturing is increasingly characterized by complex supply chains, which provide components and subsystems that are eventually combined to form final systems products for customers. Consider an aircraft such as the Boeing 787. Aircraft traditionally have been designed and manufactured within a command-and-control enterprise, whereby a lead firm performs most tasks and contracts out relatively simple components and subsystems to suppliers. In recent years, though, these lead firms have evolved to be true systems integrators that work with partner firms, who are given increased responsibility for design and manufacturing of complex components and subsystems (Kessler et al. 2012; Tang et al. 2009). This trend creates complexity that must be managed in the supply chain, which often spans many different countries.

One type of emerging risk in these types of ecosystems is the possibility of counterfeit parts. Clearly, counterfeit parts can have important implications for the reliability, safety, and life cycle cost of products. Counterfeit parts fall into two major categories—parts designed with malicious intent and those designed with intent to defraud. In the private sector, the latter is typically the concern; while in the defense sector, the former arises as a concern due to potential enemies who may influence the supply chain. The global nature of today's supply chains clearly increases the risk for malicious counterfeits in the defense sector.

As counterfeit parts become a threat, it is desirable to have a method of developing strategies to counteract them, and to understand the effectiveness and cost of such strategies before they are adopted. Supply chains are well suited to a multilevel modeling approach for studying this problem. In this section, we focus on multilevel modeling for a defense sector supply chain, as shown in Fig. 28.5.

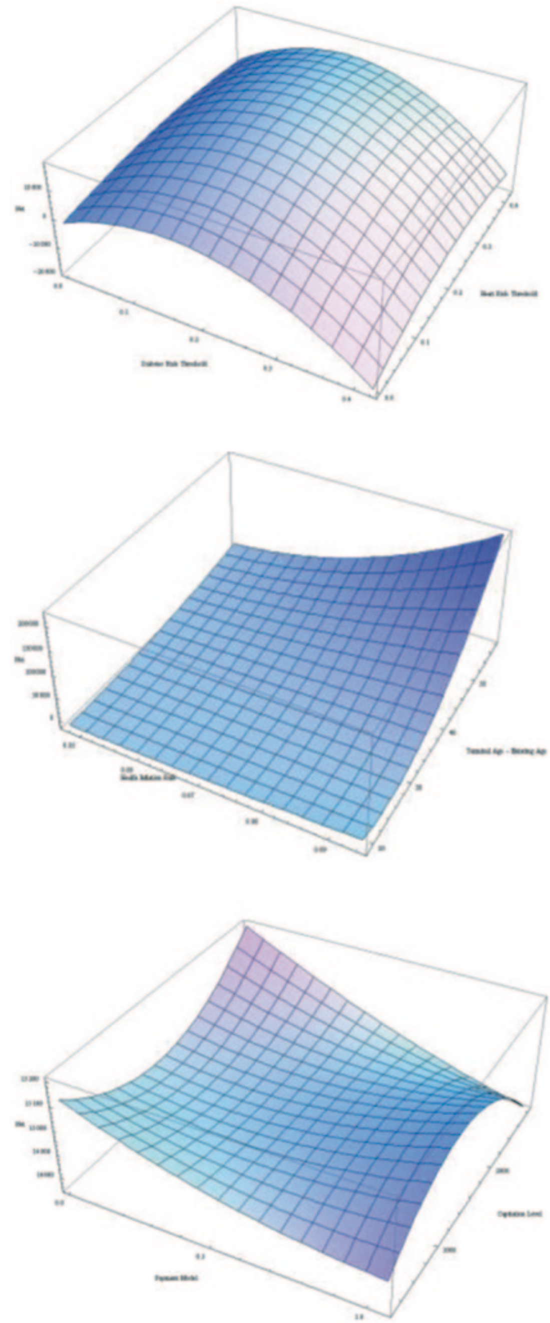

Fig. 28.4 Experimental simulation results. (Source: Park et al. 2012)

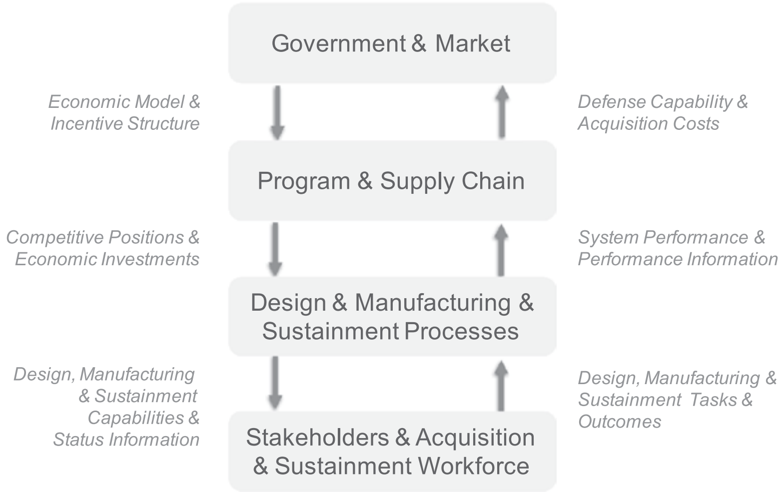

Fig. 28.5 Multilevel model of global manufacturing

The focus of this model is on a particular aircraft program, which is responsible for designing, manufacturing and then sustaining a new military aircraft, and the supply chain associated with the program. The program structure, then, consists of the government program office that provides oversight, a lead systems integrator (LSI) firm that performs and oversees design and manufacturing, a supply network containing firms that perform specific design and manufacturing tasks, and a sustainment network that performs sustainment of deployed aircraft (e.g., maintenance and repair). In the supply network, firms are organized in a tiered network, whereby the LSI contracts with firms in the first tier, which in turn contract with firms in the second tier, and so on. The supply network eventually becomes the sustainment network as aircraft are deployed, and suppliers move from providing components and subsystems for new aircraft to providing replacement parts. Note that the sustainment network also includes government facilities in addition to private firms.

At the ecosystem level, the government and market provide the incentive structure via competition and contractual vehicles for firms involved in the program. The program and these firms incur costs covered by these contracts and eventually produce an aircraft fleet for purchase by the government that meets the requirements specified by the government customer. This process is enabled by the design and manufacturing processes regulated by the government and performed by the firms in the program. The acquisition workforce employed by these firms and the government performs tasks associated with the design and manufacturing process, and stakeholders eventually receive the deployed aircraft resulting from the program. The sustainment workforce performs maintenance, repair, and upgrade tasks.

The types of questions for which the model can be used are the following:

- Should the government make investments in its research and development that could aid in counterfeit part identification or mitigation? For instance, advances

in trusted system development could allow identification of counterfeit parts prior to their usage. Advances in robust system development could enable a deployed aircraft to operate even with a critical component that is counterfeit.
- Should the government use a trusted supplier program that restricts supplier participation in a program to those that have passed quality tests? How restrictive should this program be? Should it be relaxed as the aircraft life cycle advances (and suppliers typically become fewer in number for its replacement parts)?
- Which components and subsystems should be classified as critical, thus necessitating monitoring for replacement by potential counterfeit parts?
- Should replacement parts be inspected to determine whether they are counterfeit? Which parts should be inspected, and what parameters should be used for the inspection program (e.g., frequency, inspection lot size, etc.)?

These questions should be evaluated according to trade-offs between multiple criteria, including cost, system performance, and system availability in deployment. In particular, cost is likely to involve trade-offs among investments made upstream, for instance, versus downstream cost savings. The model is currently under development using AnyLogic.

28.4.3 Data and Modeling Approaches

The two case study descriptions present the problems and the approaches used to study and address these multilevel enterprise problems. However, it is instructive to see which particular data and modeling approaches apply to each level in each model. These are summarized in Table 28.1.

28.5 Conclusions

This chapter has presented a multilevel computational modeling approach to understanding complex enterprise systems and supporting their transformation. We illustrate our approach using two case studies in manufacturing and health care. Our approach enables rapid exploration of alternative and entirely novel organizational designs, allowing us to gain insights into why many intuitively appealing ideas could be flawed with unacceptable higher-order and unexpected consequences. Multilevel simulation of enterprises provides a powerful means to portray the vision, experience it, and redesign it to better achieve the collective stakeholders' goals and objectives.

Table 28.1 Data and modeling approaches for case studies

	Global manufacturing		Health-care	
	Data	Modeling approaches	Data	Modeling approaches
Ecosystem	Threats, defense industrial base health, contractual vehicles, DoD acquisition, and counterfeiting policies	Economic projections, policy-based constraints and incentive parameters, and counterfeiting propensity parameters	Economic and social requirements and constraints	Economic projections, policy and regulation and rules of the game using macroeconomic models
Organizations	Government and private firm decision variables, supplier performance capabilities, counterfeiting capabilities, and motives	Microeconomic firm models, principal–agent models, and networked agented-based simulations	Organizational decision variables, performance, and outcome criteria	Organizational objectives, incentives and requirements using microeconomic models
Processes	Acquisition stage durations, production capacities, transport models, inventory models, maintenance and replacement schedules, and upgrade cycles	Defense acquisition and sustainment process workflow models and material flow models in supply chains	Patient, information, and financial workflow and clinical capacity data	Health care flow processes using discrete event and/or continuous workflow models
People	Number of personnel, skills and skills levels, reposting relationships, and social networks	Engineers, program managers, logisticians, and counterfeiters using agent-based models	Patient characteristics, clinical data, schedule data, adherence data, etc.	Individual patients, their characteristics, and behavior using agent-based models

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