The Challenges of Modeling Enterprise Systems

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***Abstract*— Many of the pressing problems facing our society such as managing the delivery of health care to aging populations or making cities resilient against natural disasters are fundamentally defined by enterprise systems. The dilemma that enterprise systems pose to systems engineers is that the behavioral and social components of the system cannot be assumed away as it is the interactions among the behavioral, social, and technological components that determine outcomes. In this paper we consider two key challenges to modeling enterprise systems: overlapping representations and adaptive behavior. While it is unlikely that these challenges can ever be "solved", we believe that they can be addressed. To that end, we present a general methodology for modeling enterprise systems that aims to intelligently manage the difficulties imposed by the challenges.**

Keywords—Enterprise Systems, Complex Systems, Socio-technical Systems, Modeling and Simulation

I. Introduction

Many of the pressing problems facing our society such as managing the delivery of health care to aging populations or making cities resilient against natural disasters are fundamentally defined by enterprise systems. An enterprise system is, "a goal-directed organization of resources—human, information, financial, and physical—and activities, usually of significant operational scope, complication, risk, and duration." [11] The challenge that enterprise systems pose to systems engineers is that the behavioral and social components of the system cannot be assumed away as it is the interactions among the behavioral, social, and technological components that determine outcomes. Consequently, systems engineers working to improve outcomes for enterprise systems must find a way to expand their modeling repertoire to accommodate behavioral and social phenomena.

Unfortunately, modeling these systems poses two fundamental issues. First, enterprise systems are sufficiently complex that their structure and behaviors cannot be captured with a single representation or model. Second, enterprise systems contain people and organizations that are capable of adapting to changing circumstances. Consequently, modeling enterprise systems will often entail the composition of multiple, sometimes contradictory models from different domains that contain elements whose combined actions may be sensitive to small changes in inputs. While it is unlikely that these issues can ever be "solved", we believe that they can be addressed. To that end, we present a general methodology for modeling enterprise systems that aims to intelligently manage the associated difficulties. We will also discuss ongoing work to refine and support this methodology.

The remainder of this paper is organized as follows: Section 2 provides a brief history of attempts to combine models from multiple perspectives and describes the issues associated with incorporating behavioral and social science models into traditional engineering models. Section 3 highlights how these issues with multiple perspectives and adaptation arise in enterprise systems via four archetypal examples. Using these examples as motivation, Section 4 provides a discussion of the resulting modeling challenges. Section 5 provides an overview of a modeling methodology that attempts to address some of these challenges through intelligent scoping. Finally, Section 6 highlights ongoing work to further refine the methodology and mitigate the challenges of modeling enterprise systems.

II. Literature Review

As stated previously, this paper asserts that the two key challenges of modeling enterprise systems are the need to compose multiple, overlapping models from different perspectives and the adaptive effects of the human and organizational components of enterprise systems. We will deal with each of these in turn.

The idea of viewing a system from multiple perspectives has become a staple of systems engineering. Haimes was an early advocate for developing multiple models of a system, each from a different perspective. This approach was captured in the idea of hierarchical holographic modeling [4]. Viewing a system from multiple perspectives has even become institutionalized in the US government via the Department of Defense Architecture Framework (DoDAF) [3]. The importance of considering multiple perspectives is essentially unquestioned at this stage, but the challenge has been how to combine the perspectives as one moves beyond conceptual modeling.

The modeling and simulation community has taken up this challenge, but with limited success. Recognizing the difficulty of composing models, Tolk and Muguira [14] introduced the Levels of Conceptual Interoperability Model (LCIM). This

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model was subsequently updated by Wang, et. al. [15]. As with other types of interoperability model, the greater the number of layers over which two models are compatible, the lower the risk of error due to composition. The key contribution of LCIM is that it serves as a taxonomy of the types of misalignments that can cause model compositions to fail.

To that end, there has been a great deal of discussion regarding the use of ontologies as a means to improve model composition and interoperability [6-8,10,13]. Hoffman [7] notes two types of ontologies in the world of modeling and simulation: methodological and referential. A methodological ontology should capture techniques for modeling and a referential ontology should capture what objects and phenomena in the world are being modeled. Standardization in both types of ontologies can facilitate composition and interoperability.

Approaches for achieving compatibility among standard methodological ontologies such as discrete event, discrete time, and differential equation based simulations have been covered exhaustively by Zeigler, Praehoefer, and Kim [16]. The compatibility issue arises when we consider referential ontologies, particularly when humans come into play. Hoffman [7] notes that, "…it might be difficult, if not impossible, to capture many purposeful human actions in formal systems – including referential ontologies." He goes on further to state that, "…in many socio-technical and most social domains the specification of such 'well defined' domain ontologies (referential ontologies) will be impossible…Hence, in these cases, there is no easy mapping possible between referential and methodological ontologies…This mapping, if possible at all…would not be a technical matter, but a challenging and subjective task of selection." Consequently, it is unlikely that there is a universal solution for combining multiple representations for enterprise systems. Instead, we need to determine how to best approach the "subjective task of selection."

This selection problem begs the question of what types of behavioral and social models we should select to properly capture the effects of adaptation by and interaction among humans and organizations. Harvey and Reed [5] provide an extensive analysis of the types of models used in social science such as statistical modeling, structural modeling, and historical narratives. They propose a hierarchy of ontological complexity in social systems and align those classes of models with the levels of the hierarchy. The core issue from an engineering standpoint is that Harvey and Reed's analysis seems to operate on the tacit assumption that all human systems are deterministic machines. However, from an engineering standpoint, we have to assume agency on the part of decision makers in order for us to introduce decision variables into models. It appears that most models from the social sciences are descriptive of the phenomena of interest rather than prescriptive in the sense of supporting one or more decision makers in affecting or controlling the phenomena.

To complicate matters, there are difficulties with accommodating the effects of adaptation within the models themselves. For many enterprise problems, we are concerned with economic issues such as effects of market forces on organizational behavior. Unfortunately, in many circumstances of interest such as technology selection and investor behavior, neo-classical economic models falter. The economist W. Brian Arthur has investigated cases where neoclassical economic models can lead to inaccurate predictions due to increasing returns coupled with agent behavior [2]. The result is that outcomes can be intrinsically unpredictable because they become sensitive to small changes in inputs.

For example, Arthur found that in circumstances with increasing returns, technology selection becomes path dependent and inferior technologies can actually be "locked-in" by incidental events [1]. Another study that employed an agent based model of the stock market found deviations from the standard rational expectations hypothesis and was able to replicate bubbles and crashes similar to what is seen in the real stock market [9]. The conclusion we can draw is that blindly incorporating standard models from behavioral and social sciences into engineering may actually lead to extremely misleading guidance for decision makers. However, we may not be able to model our way out of these situations, and another approach is required.

III. Archetypal Examples

The modeling difficulties just described are fairly abstract. In order to motivate subsequent discussion, context is required. The following examples of complex enterprise systems provide a basis for identifying levels of phenomena of interest in a range of problem areas. These examples will allow us to refine our understanding of the modeling challenges.

A. Deterring or Identifying Counterfeit Parts

Thousands of suppliers provide millions of parts that flow through supply chains to subsystem assembly and then final assembly of the overall system. Performance and reliability of these parts determines performance and availability of the overall system to serve its intended purpose (e.g., transportation, defense, etc). Downward pressures on suppliers' pricing of parts potentially undermine suppliers' profit margins, motivating them to cut costs somewhere. Leaning of materials and production costs reaches diminishing returns for one or more suppliers, which causes them to intentionally decrease quality of parts. Counterfeit parts are detected by increased and tightened inspection and/or inhibited by economic incentives for suppliers, both of which exacerbate cost problems.

B. Traffic Control via Congestion Pricing

Congestion in particular urban areas causes increased transit times in these areas. Time-varying time-unit pricing is adopted for use of these roads. Government likes the revenue. Business in these areas may be concerned about loss of traffic. Motorists respond by avoiding these areas and using other roads or modes of transportation. Increasing demands for alternatives affects congestion in these areas. Motorists communicate with each other in search of shortcuts and avoiding tolls. Thus, flows affect pricing, and pricing affects flows, with no guarantee of an equilibrium.

TABLE I COMPARISON OF ARCHETYPAL EXAMPLES

Levels of Phenomena	Counterfeit Parts	Congestion Pricing	Healthcare Delivery	Urban Resilience
Historical Narrative	Evolution of defense ecosystem in terms of decision processes	Evolution of transportation ecosystem in terms of technologies & expectations	Evolution of healthcare ecosystem in terms of ends supported and means provided	Evolution of urban ecosystem in terms of social development
Ecosystem Characteristics	Defense ecosystem – norms, values and supplier economics	Transportation ecosystem – norms, values & expectations of convenience	Healthcare ecosystem – norms, values and resource competition	Urban ecosystem – norms, values and social resilience
Organizations & Processes	System assembly and deployment networks and controls	Transportation infrastructure networks and flows, and control systems	Provider, payer and supplier organizations – investments, capacities, flows, outcomes	Urban infrastructure networks and flows -- water, energy, people
People or Basic Elements	Flow of parts in supply chain to assembly and deployment	Individual vehicles and driver decision making in response to flows and controls	People's health and disease incidence, progression and treatment	Peoples' evolving perceptions, expectations and decisions

C. *Impacts of Investments in Healthcare Delivery*

Demand for services (e.g., chronic disease care) and payment models (e.g., by Medicare) drive investments in capacities by healthcare providers to provide services. Capacities in the form of people, equipment, and facilities are scheduled to meet demands. Use of capacities as scheduled results in outcomes, costs, and revenue. Quality of outcomes drives increased (or decreased) demands for services. More subtly, decreased capacities to care for diseases with low payments can cause increased prevalence of other diseases. For example, poor care for early diabetes mellitus leads to increases in coronary heart disease.

D. *Human Responses and Urban Resilience*

A projected storm surge leads to predictions of flooding within a specific urban topography. Projected flooding leads to anticipated deterioration of infrastructure for transportation, energy, etc. Projections are communicated to inhabitants and subsequently communicated among inhabitants, resulting in altered perceptions. Perceptions (and later experiences) of impending deterioration lead people to adapt by planning to move to higher ground or to leave the area. Plans are shared among inhabitants, resulting in altered intentions. Intentions to move or leave enable projections of demands on urban infrastructure. Projections result in altered communications to inhabitants as well as among inhabitants. The results can range from resilient responses to complete gridlock.

E. *Comparison of Examples*

Table I compares the four examples in terms of levels of phenomena that are of interest for addressing the problems just described. These phenomena include organizational decision making, flows and outcomes, and human responses, all within the context of ecosystem characteristics and historical precedents.

The four examples differ along a continuum from a system that is centrally designed (i.e., DoD acquisition), to two systems designed in a very decentralized manner (i.e., healthcare delivery and urban systems), to natural systems of disease, weather, oceans, rivers, etc. Thus, the nature and extent of uncertainties vary substantially among these four examples. These differences also result in very different modeling paradigms (e.g., partial differential equations versus agent-based models), which contribute to the modeling challenges for enterprise systems.

However, these examples also exhibit two common features. First, each has phenomena of interest that emerge within each layer of abstraction. This would suggest that a different representation of the enterprise system would be relevant for each layer. Second, each exhibits feedback loops that cut across two or more layers. For example, the incentive to counterfeit increases with declining supplier profit margins. High-level policies designed to combat counterfeiting could raise costs at the lower levels. This could further erode profit margins and actually increase the incentive to counterfeit. Thus, the counterfeiting problem cannot be addressed without considering the relationships between the different layers of the enterprise system.

In short, the examples highlight the modeling challenges that we will take up in the next section: Understanding enterprise systems requires understanding a diversity of overlapping phenomena that interact through the adaptive behavior of the human and organizational participants.

IV. MODELING CHALLENGES

After having considered the four archetypal examples, we can now circle back and revisit our enterprise modeling challenges: overlapping representations and adaptive participants.

A. *Overlapping Representations*

First, we shall consider the issues with overlapping representations. To facilitate the discussion, let us consider one very useful type of model, the venerable map. Maps support many different functions including: visualization, analysis, coordination, communication, data storage, and control just to name a few. Consequently, there are many types of maps such as political, topographic, population, vegetation, tactical, etc. It is a fairly obvious assertion that no one map can be made to satisfy all possible applications. Yet, people attempt this feat with mathematical models and simulations all the time!

For many real world problems, we need to take advantage of more than one map to solve a single problem. This is relatively straightforward when we can partition the problem space and obtain a clean divide between applicable maps. For example, imagine that we are planning a trip from New York to Washington, DC in the era before Google Maps. We would most likely use a low resolution map to plan our highway route between the cities and a higher resolution street map to plan our route to the hotel once we enter DC. There is no conflict between the maps because we are able to partition our problem in time and space such that there is no need to overlap the high-resolution map with the low resolution map

The difficulties arise when we cannot find a clean partition. Imagine that we are concerned with the possibility of climate change instigating genocide between ethnic groups. To consider this problem, we would want maps showing possible sea level rise, changes in rainfall patterns, agriculture, population densities and ethnicities, political boundaries, and even placement of military forces to name just a few. All of these viewpoints interrelate, and it is unlikely that a single partition will be found that will allow a clean separation between them. When we cannot find a clean partition, we are trying to simultaneously employ conflicting representations of the same underlying reality just as we saw in the archetypal examples (e.g., viewing traffic as both a flow and as individual drivers). Simultaneous representations can be problematic because each could, in principle, affect the state of the other, leading to vicious cycles

The challenge of overlapping representations is exacerbated with enterprise systems because as we move up the layers of abstraction from physical systems to humans to organizations to enterprises, the number of potentially valid, relevant, overlapping representations increases. This is directly in line with the referential ontology problem described in section 2. It is important to note that these overlaps are only a problem with our models, not the real world. Consequently, when we consider enterprise systems we are faced with daunting model selection and composition problems, which is, of course, an issue to be addressed via an appropriate modeling methodology.

B. *Impact of adaptive behavior*

Enterprises are made up of people and organizations that are capable of prediction and adaptation. This can lead to positive feedback loops that can exaggerate tiny changes in the system state. The precise impact of these feedback loops can be difficult if not impossible to predict [2].

Consider the case of bubbles in financial markets. They are the result of investors getting caught in a positive feedback loop. In this loop, many investors think that market is going to go up and make investments accordingly, which causes the market to go up. This, in turn, causes investors to think the market will continue to go up. You can know that you are in a bubble market but have no way to know how high it will go or when it will burst. Classical economic models are built on negative feedback loops that push investors toward an equilibrium, and thus are poor predictors under such circumstances.

For example, consider a case where a country is transitioning from an agriculture based economy to an industrial economy. People are beginning to leave their farms and move to cities. You may be able to predict that a few cities will get extremely large, a few more will be medium sized, and a large number will remain small. This is opposed to a set of equally sized cities. The problem is that it will be almost impossible to predict which cities will become extremely large. Consequently, when modeling enterprise systems to inform policy makers and decision makers, it may be impossible in many circumstances to make any sort of specific predictions. Given this intrinsic lack of predictability, it is again necessary to address this issue through an overarching approach to modeling enterprise systems as opposed to a particular modeling technique.

V. Modeling Methodology[1]

Given this greater understanding of the enterprise modeling challenges, we can consider how those challenges may be addressed methodologically. We cannot expect to construct a single model (even through composition) that will address all aspects of an enterprise problem. Instead, modeling becomes a process through which we selectively model subsets of the enterprise with an informed understanding of how these subsets interrelate both with each other and the portions of the enterprise we chose not to model.

Experience has shown that models should be developed with a clear intent, with defined scope and givens. Initial emphasis should be on alternative views of phenomena important to addressing the questions of interest. Selected views can then be more formally modeled and simulated. The following ten-step methodology provides a structure to support this approach to modeling.

Step 1: Decide on the Central Questions of Interest

The history of modeling and simulation is littered with failures of attempts to develop models without clear intentions in mind. Models provide means to answer questions. Efforts to model enterprise systems are often motivated by decision makers' questions about the feasibility and efficacy of decisions on policy, strategy, operations, etc. The first step is to discuss the questions of interest with the decision maker(s), define what they need to know to feel that the questions are answered, and agree on key variables of interest.

Step 2: Define Key Phenomena Underlying These Questions

The next step involves defining the key phenomena that underlie the variables associated with the questions of interest. Phenomena can range from physical or organizational, to economic or political. Broad classes of phenomena across these four domains include continuous and discrete flows, manual and automatic control, resource allocation, and individual and collective choice. Mature domains often have developed standard descriptions of relevant phenomena.

Step 3: Develop One or More Visualizations of Relationships among Phenomena

Phenomena can often be described in terms of inputs, processes, and outputs. Often the inputs of one phenomenon are the outputs of other phenomena. Common variables among phenomena provide a basis for visualization of the set of key

[1] An earlier version of this methodology can be found in Rouse and Pennock [12]

phenomena. Common visualization methods include block diagrams, IDEF, influence diagrams, and systemigrams.

Step 4: Determine Key Tradeoffs That Appear to Warrant Deeper Exploration

The visualizations resulting from Step 3 often provide the basis for in-depth discussions and debates among members of the modeling team as well as the sponsors of the effort, which hopefully includes the decision makers who intend to use the results of the modeling effort to inform their decisions. Lines of reasoning, perhaps only qualitative, are often verbalized that provide the means for immediate resolution of some issues, as well as dismissal of some issues that no longer seem to matter. New issues may, of course, also arise.

Step 5: Identify Alternative Representations of These Phenomena

Computational representations are needed for those phenomena that will be explored in more depth. These representations include equations, curves, surfaces, process models, agent models, etc. – in general, instantiations of standard representations. Boundary conditions can affect choices of representations. This requires deciding on fixed and variable boundary conditions such as GDP growth, inflation, carbon emissions, etc. Fixed conditions can be embedded in representations while variable conditions require controls such as slider bars to accommodate – see Step 9.

Step 6: Assess the Ability to Connect Alternative Representations

Representations of phenomena associated with tradeoffs to be addressed in more depth usually require inputs from other representations and produce outputs required by other representations. Representations may differ in terms of dichotomies such as linear vs. nonlinear, static vs. dynamic, deterministic vs. stochastic, continuous vs. discrete, and so on. They may also differ in terms of basic assumptions of Markov vs. Non-Markovian processes. This step involves determining what can be meaningfully connected together.

Step 7: Determine a Consistent Set of Assumptions

The set of assumptions associated with the representations that are to be computationally connected need to be consistent for the results of these computations to be meaningful. At the very least, this involves synchronizing time across representations, standardizing variable definitions and units of measures, and agreeing on a common coordinate system or appropriate transformations among differing coordinate systems. It also involves dealing consistently with continuity, conservation, and independence assumptions.

Step 8: Identify Data Sets to Support Parameterization

The set of representations chosen and refined in Steps 5-7 will have parameters such as transition probabilities, time constants, and decay rates that have to be estimated using data from the domain(s) in which the questions of interest are to be addressed. Data sources need to be identified and conditions under which these data were collected determined. Estimation methods need to be chosen, and in some cases developed, to provide unbiased estimates of model parameters.

Step 9: Program and Verify Computational Instantiations

To the extent possible, this step is best accomplished with commercially available software tools. The prototyping and debugging capabilities of such tools are often well worth the price. A variant of this proposal is to use commercial tools to prototype and refine the overall model. Once the design of the model is fixed, one can then develop custom software for production runs. The versions in the commercial tools can then be used to verify the custom code. This step also involves instantiating interactive visualizations with graphs, charts, sliders, radio buttons, etc.

Step 10: Validate Model Predictions, at Least Against Baseline Data

The last step involves validating the resulting model. This can be difficult when the model has been designed to explore policies, strategies, etc. for which there is no empirical data. A weak form of validation is possible by using the model to predict current performance with the "as is" policies, strategies, etc. In general, models used to explore "what if" possibilities are best employed to gain insights that can be used to frame propositions for subsequent empirical study.

Not all problems require full use of this ten-step methodology. Often visual portrayals of phenomena and relationships are sufficient to provide the insights of interest. For example, an exploration of the visualization may reveal that the key determinant of outcomes is a market exhibiting increasing returns. In that case, it is unlikely that any model will provide an accurate prediction, and the decision maker would be better off pursuing an option-based strategy.

Visualizations are also valuable for determining which aspects of the problem should be explored more deeply. For those aspects that should be modeled mathematically, the process of walking through the methodology should aid modelers in selecting the appropriate models based on the context. It should also aid in the identification of partitions when the composition of multiple models is required. In those areas where a complete partition cannot be achieved, heuristics for composition may be employed but often at the of cost accuracy.[2] The ten-step methodology is intended to make these trades explicit to facilitate informed choices.

VI. Conclusions and Future Work

Many of the major challenges that humanity faces today entail managing or at least influencing enterprise systems. Of course managing involves making decisions, and we need models to support informed decision-making. In this paper we have discussed two of the key challenges to modeling enterprise systems: overlapping representations and adaptive participants. We also presented a modeling methodology that will help guide engineers and analysts through the process of mitigating these challenges.

However, our work in this domain is only just beginning. Our long-term vision is to support the aforementioned modeling methodology with additional tools. First, we would

[2] A more detailed discussion of the approaches to model composition and associated heuristics can be found in Rouse and Pennock [12]

like to create a catalog of visualization techniques that support model scoping and selection as well as decision making for enterprise systems. Second, we would like to develop guidance for model selection contingent on both the type of enterprise system and the nature of the question under consideration. Third, we intend to create a set of justified heuristics for composing different types of models. There are many heuristics already in use by modelers today. The issue is that there is no theoretical basis for where and how they can be applied. Finally, we would like develop criteria that would indicate to modelers and decision makers when the adaptive behavior of enterprise participants is likely to enable unpredictable outcomes. This would allow decision makers to alter their strategy accordingly.

REFERENCES

[1] W. B. Arthur, "Competing technologies, increasing returns, and lock-in by historical events," The Economic Journal, Vol. 99, No 394, pp. 116-131, 1989.

[2] W. B. Arthur, "Complexity and the economy," Science, Vol. 284, No. 5411, pp. 107-109, 1999.

[3] Department of Defense, DoD Architecture Framework Version 2.02, United States Department of Defense, http://dodcio.defense.gov/dodaf20.aspx (last accessed 2/13/14).

[4] Y. Y. Haimes, "Hierarchical holographic modeling," IEEE Transactions on Systems, Man, and Cybernetics, Vol. 11, No. 9, pp. 606-616, 1981.

[5] D. L. Harvey and M. Reed, "Social science as the study of complex systems," in Chaos Theory in the Social Sciences: Foundations and Applications, L. D. Kiel and E. Elliot, Eds, Ann Arbor: The University of Michigan Press, 1997, pp. 295-323.

[6] M. Hoffman, M., "Epistemic and normative aspects of ontologies in modelling and simulation," Journal of Simulation, Vol. 5, No. 3, pp. 135-146, 2011.

[7] M. Hoffman, M., "Ontology in modeling and simulation: An epistemological perspective," in Ontology, Epistemology, and Teleology for Modeling and Simulation, A. Tolk, Ed, Heidelberg: Springer, 2013, pp. 59-87.

[8] L. McGinnis, E. Huang, K. S. Kwon, and V. Ustun, "Ontologies and simulation: A practical approach," Journal of Simulation, Vol. 5, No. 3, pp. 190-201, 2011.

[9] R. Palmer, W. B. Arthur, J. H. Holland, B. LeBaron, and P. Tayler, "Artificial economic life: A simple model of a stockmarket," Physica D: Nonlinear Phenomena, Vol. 75, No. 1, pp. 264-274, 1994.

[10] C. Partridge, A. Mitchell, and S. de Cesare, "Guidelines for developing ontological architectures in modeling and simulation," in Ontology, Epistemology, and Teleology for Modeling and Simulation, A. Tolk, Ed, Heidelberg: Springer, 2013, pp. 22-57.

[11] W. B. Rouse, "Enterprises as systems: Essential challenges and approaches to transformation," Systems Engineering, Vol. 8, No. 2, pp. 138-150, 2005.

[12] W. B. Rouse and M. J. Pennock, Multi-Level Modeling of Complex Socio-Technical Systems, Center for Complex Systems and Enterprises, Technical Report: CCSE-2013-02, December 2, 2013.

[13] A. Tolk, "Enhancing simulation composability and interoperability using conceptual/semantic/ontological models," Journal of Simulation, Vol. 5, No. 3, pp. 133-134, 2011.

[14] A. Tolk and J. A. Muguira, "The levels of conceptual interoperability model," Fall Simulation Interoperability Workshop, Orlando, FL: Simulation Interoperability Standards Organization, 2003.

[15] W. G. Wang, A. Tolk, and W. P. Wang, "The levels of conceptual interoperability model: Applying systems engineering principles to M&S," Proceedings of the Spring Simulation Multiconference, Spring Sim 2009, San Diego, CA, 2009.

[16] B. P. Zeigler, H. Praehofer, and T. G. Kim, Theory of Modeling and Simulation, 2nd ed, Amsterdam: Academic press, 2000.