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Research Challenges in Modeling and Simulation for Engineering Complex Systems

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Chapter 1
Introduction

Richard Fujimoto and Margaret Loper

Computer-based models and simulations are vital technologies needed in advanced economies to guide the design of complex systems. M&S technologies are essential to address the critical challenges facing society today such as the creation of smart, sustainable cities, development of advanced aircraft and manufacturing systems, and creating more secure and resilient societies and effective health care systems, to mention a few.

However, the development and use of reliable computer models and simulations is today time consuming and expensive, and results produced by the models may not be sufficiently reliable for their intended purpose. M&S faces unprecedented new challenges. Engineered systems are continually increasing in complexity and scale. Advances in M&S are essential to keep up with this growing complexity and to maximize the effectiveness of new and emerging computational technologies to engineer the increasingly complex systems that are needed in the future.

1.1 Why Now?

Computer-based models and simulations have been in use as long as there have been computers. For example, one application of the ENIAC, the first electronic digital computer, was to compute trajectories of artillery shells to create firing tables used in World War II. There is no question that computer simulations have had major impacts on society in the past and will continue to do so in the future.

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simulation program is an acceptable representation of the conceptual model. Verification is to a large extent a software development activity. Validation is concerned with ensuring the simulation program is an acceptable representation of the system under investigation for the questions posed in the study. This is often accomplished by comparing results produced by the simulation program with data measured from the system under investigation or, in the absence of an implemented system that can be measured, other models of the system. Once the simulation model has been validated to an acceptable degree of certainty, it is applied to answer the questions posed in the first step of the life cycle. The model will be executed many times, e.g., using different random number streams for stochastic simulation models, or to explore various parameter settings; the experiment design defines the simulation runs that are to be completed. Output analysis concerns characterization and quantification of model results, e.g., to determine confidence intervals and variance of output values. Simulation models often must be modified and evolve during the life cycle, e.g., to improve the validity of its results or to incorporate new capabilities or to answer new questions not recognized in the initial design. Configuration control refers to the processes necessary to manage these changes. Finally, once the necessary results have been produced, they must be documented and presented to the individuals or decision makers to illustrate key behaviors and outcomes predicted by the simulation model.

The boxes in blue in Fig. 1.1 represent model development activities and the orange boxes represent simulation development activities. These boxes do not represent an absolute separation between modeling and simulation—the “develop simulation model and program” box bridges between the modeling and simulation

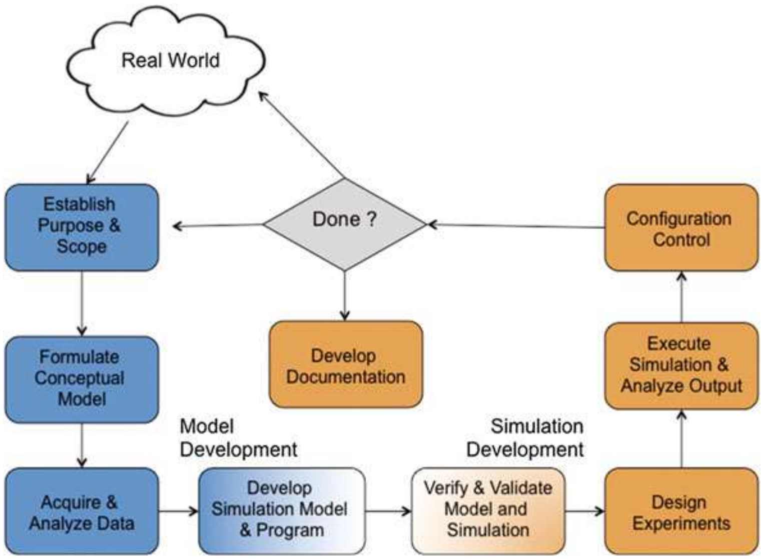

Fig. 1.1 M&S life cycle process (Loper 2015)

1.3.1 Applications

Engineered systems continue to grow in complexity and scale. Existing modeling and simulation capabilities have not kept pace with the need to design and manage new emerging systems. Although the focus here is on modeling and simulation per se, distinct from the domain in which the technology is applied, the requirements of modeling and simulation technologies are ultimately derived from the application. In this context, the new emerging developments in specific applications of societal importance are relevant in order to assess the needs and impacts that advances in modeling and simulation will have within those domains.

Specific application domains discussed later include the following:

- Aerospace
- Health care and medicine
- Manufacturing
- Security and defense
- Sustainability, urban growth, and infrastructures

1.3.2 Conceptual Modeling

Although one of the first steps in the development of a model is the development of its conceptual model, such conceptual models have traditionally been informal, document-based. As the complexity of simulation models increases and the number of domain experts contributing to a single model grows, there is an increasing need to create formal, descriptive models of the system under investigation and its environment. This is particularly important for the engineering of complex systems where multiple system alternatives are explored, compared, and gradually refined over time. The descriptive model of each system alternative—describing the system of interest, the environment, and interactions between them—can serve as a conceptual model for a corresponding analysis or simulation model. Formal modeling of these descriptive, conceptual models poses significant research challenges:

- How can models expressed by different experts in different modeling languages be combined in a consistent fashion?
- What level of formality is suitable for efficient and effective communication?
- What characteristics should a modeling environment have to support conceptual modeling in an organizational context—a distributed cognitive system?
- What transformations of conceptual models to other representations are possible and useful? What are the major impediments to realizing such transformations?

1.3.3 Computational Methods

The main reason for modeling is to extend human cognition. By expressing our knowledge in a mathematical formalism, the rules of mathematical inference implemented in computer algorithms can be used to draw systematic conclusion that are well beyond the natural cognitive ability of humans. For instance, simulation allows us to project how the state of a system will change over time for complex systems with millions of state variables and relationships. Advancing the algorithms for such inference so that ever larger models can be processed more quickly is likely to remain a crucial capability for engineering and science. Besides simulation, there is an increasing role for model checking, especially for engineered systems that are affected by high-impact low-probability events.

This raises questions such as the following:

- What are current trends in computing affecting modeling and simulation and how can they best be exploited?
- How will these trends change the nature of simulation and reasoning algorithms?
- What are the major gaps in computational methods for modeling and simulation, and what are the most important research problems?
- How can one best exploit the vast amounts of data now becoming available to synergistically advance M&S for engineering complex systems?

1.3.4 Model Uncertainty

The goal of modeling and simulation often is to make predictions, either to support decisions in an engineering, business, policymaking context or to gain understanding and test hypotheses in a scientific context. It is impossible to prove a model is correct—the predictions are always uncertain. Yet, many models and simulations have been proven to be useful, and their results are routinely used for many purposes. To further improve the usefulness of models, it is important that we develop a rigorous theoretical foundation for characterizing the uncertainty of the predictions. Within the modeling and simulation community, there is still a lack of agreement on how best to characterize this uncertainty. A variety of frameworks have been proposed around concepts of validation and verification, and a variety of uncertainty representations have been proposed.

This leads to the following questions:

- What is the most appropriate approach to consistently represent and reason about uncertainty in complex systems?
- What is the best approach to characterizing the uncertainty associated with a simulation model in order to enable and facilitate reuse?

and the pace of change is accelerating. While M&S has served society well in the past, new innovations and advances are now required to enable it to continue to be an indispensable tool to enable deep understandings and effective design of new and emerging complex engineered systems.

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Chapter 2
Applications

William Rouse and Philomena Zimmerman

2.1 Introduction

Modeling and simulation provide a powerful means to understand problems, gain insights into key trade-offs, and inform decisions at all echelons of the domain. Applications of modeling and simulation should be driven by the nature of the problems of interest and the appropriateness of the model or simulation for the problem and domain in which this approach is being considered or applied.

This chapter begins by reviewing five important areas to understand the nature of the problems addressed rather than the approaches to modeling and simulation employed in these instances. This leads to consideration of crosscutting challenges associated with these examples. This chapter concludes with a discussion of specific modeling and simulation challenges identified.

2.2 Five Examples

Five exemplar application areas where modeling and simulation can provide the means to understand problems, gain insights into key trade-offs, and inform decisions include the following:

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