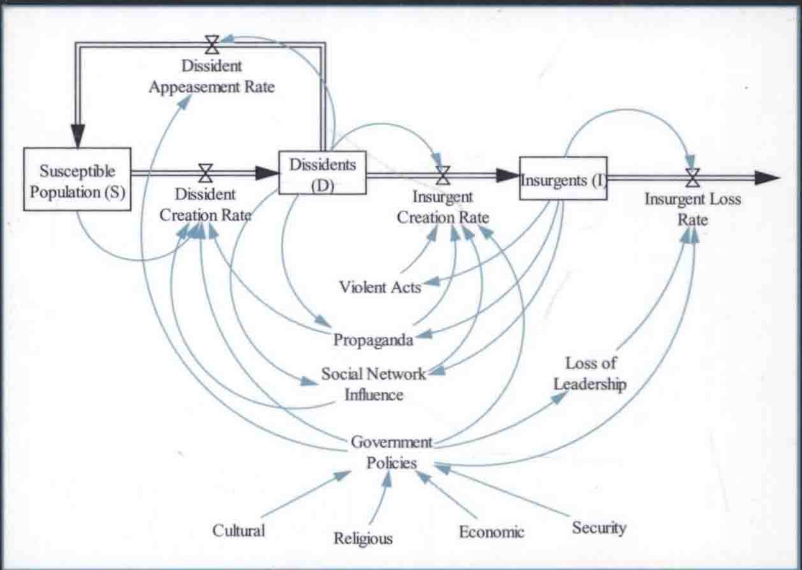
Principles of Modeling and Simulation

A Multidisciplinary Approach



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This book is dedicated to

Marsha, Amy, and Whitney

—John A. Sokolowski

Benjamin M. Mercury

—Catherine M. Banks

Preface

The impetus for this study is the realization that no textbook exists that provides an introduction to modeling and simulation suitable for multiple disciplines, especially those that are outside the science and engineering fields.

Many universities are realizing that modeling and simulation is becoming an important tool in solving and understanding numerous and diverse problems. They have begun to offer introductory courses in this field to acquaint their students with the foundational concepts that will help them apply modeling and simulation in many areas of research. This text serves to provide an orientation to the theory and applications of modeling and simulation from a multidisciplinary perspective.

To students who will be reading this text we offer a concise look at the key concepts making up the field of modeling and simulation. While modeling and simulation necessarily entails mathematical representations and computer programs, students need only be familiar with math at the college algebra level and the use of spreadsheets to understand the modeling and simulation concepts covered in this book.

The text is divided into three parts with nine chapters. Part One, *Principles of Modeling and Simulation: A Multidisciplinary Approach* introduces modeling and simulation and its role. Chapter 1 answers the question, "What Is Modeling and Simulation?" The chapter provides a brief history of modeling and simulation, lists the many uses or applications of modeling and simulation, and speaks to the advantages and disadvantages of using models in problem solving. Chapter 2 focuses on "The Role of Modeling and Simulation." It covers the two main reasons to employ modeling and simulation: solving a specific problem, and using modeling and simulation to gain insight into complex concepts.

Part Two, *Theoretical Underpinnings*, examines the most fundamental aspects of modeling and simulation. Chapter 3, "Simulation: Models That Vary over Time," provides a definition for simulation and introduces the reader to two main simulation concepts: discrete event simulation and simulation of continuous systems. Chapter 4, "Queue Modeling and Simulation" examines queuing models, sequential simulation, and parallel simulation. Chapter 5, "Human Interaction with Simulations," explains the two primary methods in which humans interface with simulations: simulation and data dependency and visual representation. Chapter 6, "Verification and Validation," answers two fundamental questions: What is verification and validation? and Why is verification and validation important?

Part Three, *Practical Domains*, affords the student an opportunity to consider the many uses of modeling and simulation as a tool in workforce development. Students will also review case studies and research conducted in various disciplines emphasizing the notion that models serve as approximations of real-world events.

Chapter 7 addresses the "Uses of Simulation." These uses are found in training, analysis, decision support, and acquisition. Chapter 8, "Modeling and Simulation: Real-World Examples," delves into specific applications of modeling and simulation in the Transportation, Business, Medical, and Social Sciences domains. Chapter 9 addresses "The Future of Simulation" by providing a basis for accepting modeling and simulation as a discipline with its own body of knowledge, research methods, and curriculum of study. It provides answers to the questions: Is modeling and simulation a tool or discipline? How should education, research, and training be conducted to support workforce development?

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Part One

Principles of Modeling and Simulation: A Multidisciplinary Approach

Chapter 1

What Is Modeling and Simulation?

Catherine M. Banks

INTRODUCTION

Modeling and Simulation, or M&S as it is commonly referred, is becoming one of the academic programs of choice for students in all disciplines. M&S is a discipline with its own body of knowledge, theory, and research methodology. At the core of the discipline is the fundamental notion that *models are approximations for the real-world.* To engage M&S, students must first create a model approximating an event. The model is then followed by *simulation*, which allows for the repeated observation of the model. After one or many simulations of the model, a third step takes place and that is *analysis*. Analysis aids in the ability to draw conclusions, verify and validate the research, and make recommendations based on various iterations or simulations of the model. These basic precepts coupled with *visualization*, the ability to represent data as a way to interface with the model, make M&S a problem-based discipline that allows for repeated testing of a hypothesis. Teaching these precepts and providing research and development opportunities are core to M&S education. M&S also serves as a tool or application that expands the ability to analyze and communicate new research or findings.

There has been much attention paid to M&S by the National Science Foundation (NSF). In 1999, then Director Dr. Rita R. Colwell declared simulation as the *third branch* of science at the fall meeting of the American Geophysical Union [1]. In a more recent report entitled, "Simulation-based Engineering Science: Revolutionizing Engineering Science through Simulation," the NSF drew on the expertise of an esteemed cadre of scientists to discuss the challenges facing the United States as a technological world leader. The group made four recommendations that they

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believed would help restore the United States to its leadership role in this strategically critical technology (simulation). One recommendation went straight to the study of M&S:

> *"The Panel recommends that NSF underwrite an effort to explore the possibility of initiating a sweeping overhaul of our engineering educational system to reflect the multidisciplinary nature of modern engineering and to help students acquire the necessary modeling and simulation skills."* [2]
>
> Simulation-Based Engineering Science: Final Report, May 2006

The intent of this text is to introduce you to M&S education and research from a multidisciplinary approach so that you can acquire the skills necessary to this critical technology.

Fundamental to a formal engineering M&S program of study is its curriculum built upon four precepts—modeling, simulation, visualization, and analysis. Students study the basics of **modeling** as a way to understand the various modeling paradigms appropriate for conducting digital computer simulations. They must understand **simulation** and the methodology, development, verification and validation, and design of simulation experiments. Students who are able to engage **visualization** are able to provide an overview of interactive, real-time 3D computer graphics and visual simulations using high-level development tools. Important to any student research is the **analysis** of the findings; and included in any good analysis is an observation of the constraints and requirements of applying M&S. In other words, analysis also includes making known the limitations of the research.

It was political scientist Herbert A. Simon (1916–2001) who introduced the notion of *learning by doing* (also known as experiential learning).[1] M&S can be just that. It is the simulation of a model that allows for the imitation of the operation of a real-world process or system over time. To imitate an operation over time one must generate a history, real or artificial, to draw inferences concerning the operating characteristics of the real system that is represented [3]. The art and science of M&S has evolved very rapidly since the mid-1980s, so much so that it easily parallels the technological advances of mainframe and desktop computers and the ever-increasing emergence of the internet and World Wide Web (www).

[1] **Herbert A. Simon** was a political scientist who conducted research in a variety of disciplines including cognitive psychology, computer science, public administration, economics, management, and philosophy of science. Dr. Simon was among the founding fathers of several of today's most important scientific domains, including artificial intelligence, information processing, decision-making, problem-solving, attention economics, organization theory, complex systems, and computer simulation of scientific discovery. He was the first to analyze the architecture of complexity and to propose a preferential attachment mechanism to explain power law distributions. He introduced the notion of *experiential learning, bounded rationality*, and *satisficing*. Dr. Simon's research at Carnegie Mellon University resulted in numerous cited publications. He remains one of the most influential social scientists of the 20th century.

MODELS: APPROXIMATIONS OF REAL-WORLD EVENTS

A *model* is a representation of an event and/or things that is real (a case study) or contrived (a use-case). It can be a representation of an actual system. It can be something used in lieu of the real thing to better understand a certain aspect about that thing. To produce a model you must abstract from reality a description of a vibrant system. The model can depict the system at some point of abstraction or at multiple levels of the abstraction with the goal of representing the system in a mathematically reliable fashion. A *simulation* is an applied methodology that can describe the behavior of that system using either a mathematical model or a symbolic model [4]. Simply, simulation is the imitation of the operation of a real-world process or system over a period of time [3]. As you will see there are many uses of M&S. M&S can be used to determine the ordering policies of Wal-Mart's extensive inventory system, or it can be used to analyze the prospects and rate of rehabilitation of a patient who just underwent knee-replacement surgery, or it can be used to evaluate ocean currents and waves to better understand weather patterns.

M&S begins with 1) developing computer simulation or a design based on a model of an actual or theoretical physical system, then 2) executing that model on a digital computer, and 3) analyzing the output. Models and the ability to act out with those models is a credible way of understanding the complexity and particulars of a real entity [4]. From these three steps you can see that M&S facilitates the simulation of a system and then a testing of the hypothesis about that system. For example, if you wanted to determine how many cashiers are needed to process a certain number of customers during rush hour with the assurance that the store's high level of quality service was not compromised, you must first research the current system of processing customers.

You will no doubt review the work schedule and note that the manager has scheduled more cashiers during peak times. You will then assess how many customers are processed during peak times based on the cashier tapes. Also, you might want to see how long it takes to process a customer at slow periods and at heavy traffic periods—you might be surprised to find that customers are processed in shorter exchanges at busy times. Do the customers feel rushed? How many errors are made? Do the customer lines flow smoothly? Are the cash registers placed in good locations? All of this is part of the initial research you will do to develop your model. Once you have sufficient data you can create your model. It is important to note that *models are driven by data* and so your data collection must be done with great accuracy.

Once the model is created you can craft a fairly well-thought-out and credible hypothesis such as, *if the store manager does this, this will be his result.* But are you certain? There may be unexpected changes to the model—a cashier is out sick, a cash register breaks, the power goes out and stops all transactions. What can the manager do to accommodate these unforeseen occurrences? You can assist the manager by creating a number of simulations or iterations of the model to ascertain the "what if." Upon reviewing the output of your simulations, you can provide that data to the store manager so that he or she can make well-informed decisions about the scheduling of cashiers and distribution of registers to meet the goal of high-quality service. As you can see from the example, M&S gives you many opportunities to repeat a simulation of the hypothesis. In essence, you have the ability to repeat the testing of the hypothesis through various simulations. Let's take a closer look at simulation.

First, we must appreciate that defining simulation is not as clear-cut as defining model. Definitions of simulation range from:

- a method for implementing a model over time
- a technique for testing, analysis, or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model
- an unobtrusive scientific method of inquiry involving experiments with a model rather than with the portion of reality that the model represents
- a methodology for extracting information from a model by observing the behavior of the model as it is executed
- a nontechnical term meaning not real, imitation (the correct word here is the adjective simulated)[2]

Simulation is used when the real system cannot be engaged. The real system may not be engaged because 1) it may not be accessible, 2) it may be dangerous to engage the system, 3) it may be unacceptable to engage the system, or 4) the system may simply not exist. So to counter these objections a computer will "imitate" operations of these various real-world facilities or processes. Modeling depends on computational science for the visualization and simulation of complex, large-scale phenomena. These models may be used to replicate complex systems that exhibit chaotic behavior and so simulation must be used to provide a more detailed view of the system. Simulation also allows for virtual reality research whereby the analyst is immersed within the simulated world through the use of devices such as head-mounted display, data gloves, freedom sensors, and forced-feedback elements [4]. *Artificial Life* and *Computer Animation* are offshoots of computational science that allow for additional variations in modeling.[3]

Now that we know what comprises a model and what constitutes a simulation, we then couple these steps with visualization. M&S coupled with visualization refers to the process of developing a model of a system, extracting information from the

[2] Additional information and definitions can be found at the U.S. Department of Defense, Defense Modeling and Simulation Office (DMSO) online glossary at http://www.dtic.mil/whs/directives/corres/pdf/500059m.pdf.

[3] *Artificial life* enables the analysts to challenge the experiment by allowing the computer program to simulate artificial life forms. *Computer animation* is emphasized within computer graphics and it allows the modeler to create a more cohesive model by basing the animation on more complex model types. With the increased use of system modeling there has been an increased use of computer animation, also called physically based modeling [4].

model (simulation), and using visualization to enhance our ability to understand or interpret that information. We have mentioned "system" a number of times. Let's take a look at what constitutes a system.

An accepted definition of "system" was developed by the International Council of Systems Engineering (INCOSE). A **system** is a *construct or collection of different elements that together produce results not obtainable by the elements alone.*[4] The elements can include people, hardware, software, facilities, policies, documents—all things required to produce system-level qualities, properties, characteristics, functions, behavior, and performance. Importantly, the value of the system as a whole is the relationship among the parts. There are two types of systems: 1) *discrete* in which the variables change instantaneously at separate points in time and, 2) *continuous* where the state variables change continuously with respect to time. There are a number of ways to study a system:

- the actual system versus a model of the system
- a physical versus mathematical representation
- analytical solution versus simulation solution (which exercises the simulation for inputs in question to see how they affect the output measures of performance) [5]

As you will learn, M&S holds a significant place in research and development due to its inherent properties of modeling, simulating, analyzing, and visualizing (communicating). It is becoming the training apparatus of choice. In fact, M&S is considered a new tool of choice in the fields of health services, education, social sciences, business and industry. Many folks in the M&S community (researchers, academicians, industry, and military) were introduced to M&S as a tool that evolved with the modern military of the 20th century. But its origins can be traced to an ancient military whose use of wargames made it one of the most efficient armies in military history.

A BRIEF HISTORY OF MODELING AND SIMULATION

The act of wargames and challenging or outwitting an opponent on the battlefield is centuries old. In ancient Rome, the then world's largest empire was secured by the world's largest military. The Roman Army conducted live training between two contingents of its military (red team versus blue team). Their training battlefield reflected an environment the troops would encounter somewhere within the expansive Roman Empire that spanned the Scottish border in northern Europe throughout North Africa into the Near East (Afghanistan). The Roman Army had to learn how to fight in unknown regions against armies with diverse warring techniques. Although their training exercises were not intended to draw blood, their training honed a mili-

[4] Additional information and definitions can be found at the INCOSE online glossary at http://www.incose.org/mediarelations/glossaryofseterms.aspx.