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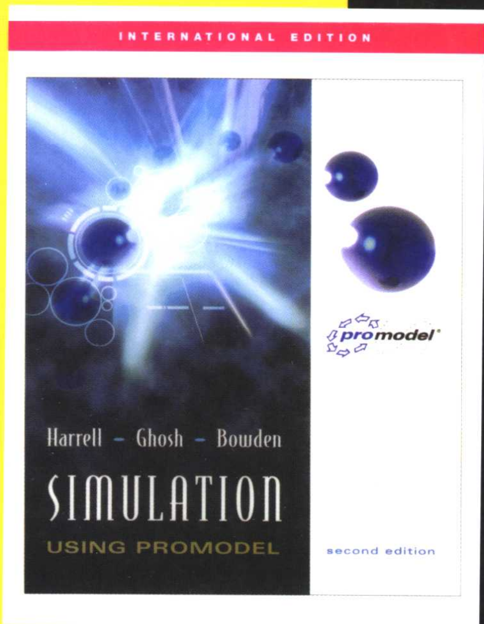
国外大学优秀教材——工业工程系列（影印版）

Charles Harrell, Biman K. Ghosh, Royce O. Bowden

系统仿真及ProModel软件应用（第2版）

Simulation Using ProModel (Second Edition)



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前　言

本教材系列的出版正值中国学术界工业工程学科经历巨大发展、实际工作中对工业工程的概念、方法和工具的使用兴趣日渐浓厚之时。在实际工作中有效地应用工业工程的手段将无疑会提高生产率、工作质量、合作的满意度和效果。

该系列中的书籍对工业工程的本科生、研究生和工业界中需要解决工程系统设计、运作和管理诸方面问题的人士最为适用。

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普渡大学工业工程学院（美国）
2002 年 4 月

BRIEF CONTENTS

PART I

STUDY CHAPTERS

PART II

LABS

PART III

CASE STUDY ASSIGNMENTS

P A R T

I STUDY CHAPTERS

Chapters

CHAPTER

1 Introduction to Simulation

"Man is a tool using animal. . . . Without tools he is nothing, with tools he is all."

—Thomas Carlyle

1.1 Introduction

On March 19, 1999, the following story appeared in *The Wall Street Journal:*

> Captain Chet Rivers knew that his 747-400 was loaded to the limit. The giant plane, weighing almost 450,000 pounds by itself, was carrying a full load of passengers and baggage, plus 400,000 pounds of fuel for the long flight from San Francisco to Australia. As he revved his four engines for takeoff, Capt. Rivers noticed that San Francisco's famous fog was creeping in, obscuring the hills to the north and west of the airport.
>
> At full throttle the plane began to roll ponderously down the runway, slowly at first but building up to flight speed well within normal limits. Capt. Rivers pulled the throttle back and the airplane took to the air, heading northwest across the San Francisco peninsula towards the ocean. It looked like the start of another routine flight. Suddenly the plane began to shudder violently. Several loud explosions shook the craft and smoke and flames, easily visible in the midnight sky, illuminated the right wing. Although the plane was shaking so violently that it was hard to read the instruments, Capt. Rivers was able to tell that the right inboard engine was malfunctioning, backfiring violently. He immediately shut down the engine, stopping the explosions and shaking.
>
> However this introduced a new problem. With two engines on the left wing at full power and only one on the right, the plane was pushed into a right turn, bringing it directly towards San Bruno Mountain, located a few miles northwest of the airport. Capt. Rivers instinctively turned his control wheel to the left to bring the plane back on course. That action extended the ailerons—control surfaces on the trailing edges of the wings—to tilt the plane back to the left. However, it also extended the

spoilers—panels on the tops of the wings—increasing drag and lowering lift. With the nose still pointed up, the heavy jet began to slow. As the plane neared stall speed, the control stick began to shake to warn the pilot to bring the nose down to gain air speed. Capt. Rivers immediately did so, removing that danger, but now San Bruno Mountain was directly ahead. Capt. Rivers was unable to see the mountain due to the thick fog that had rolled in, but the plane's ground proximity sensor sounded an automatic warning, calling "terrain, terrain, pull up, pull up." Rivers frantically pulled back on the stick to clear the peak, but with the spoilers up and the plane still in a skidding right turn, it was too late. The plane and its full load of 100 tons of fuel crashed with a sickening explosion into the hillside just above a densely populated housing area.

"Hey Chet, that could ruin your whole day," said Capt. Rivers's supervisor, who was sitting beside him watching the whole thing. "Let's rewind the tape and see what you did wrong." "Sure Mel," replied Chet as the two men stood up and stepped outside the 747 cockpit simulator. "I think I know my mistake already. I should have used my rudder, not my wheel, to bring the plane back on course. Say, I need a breather after that experience. I'm just glad that this wasn't the real thing."

The incident above was never reported in the nation's newspapers, even though it would have been one of the most tragic disasters in aviation history, because it never really happened. It took place in a cockpit simulator, a device which uses computer technology to predict and recreate an airplane's behavior with gut-wrenching realism.

The relief you undoubtedly felt to discover that this disastrous incident was just a simulation gives you a sense of the impact that simulation can have in averting real-world catastrophes. This story illustrates just one of the many ways simulation is being used to help minimize the risk of making costly and sometimes fatal mistakes in real life. Simulation technology is finding its way into an increasing number of applications ranging from training for aircraft pilots to the testing of new product prototypes. The one thing that these applications have in common is that they all provide a virtual environment that helps prepare for real-life situations, resulting in significant savings in time, money, and even lives.

One area where simulation is finding increased application is in manufacturing and service system design and improvement. Its unique ability to accurately predict the performance of complex systems makes it ideally suited for systems planning. Just as a flight simulator reduces the risk of making costly errors in actual flight, system simulation reduces the risk of having systems that operate inefficiently or that fail to meet minimum performance requirements. While this may not be life-threatening to an individual, it certainly places a company (not to mention careers) in jeopardy.

In this chapter we introduce the topic of simulation and answer the following questions:

- What is simulation?
- Why is simulation used?
- How is simulation performed?
- When and where should simulation be used?

- What are the qualifications for doing simulation?
- How is simulation economically justified?

The purpose of this chapter is to create an awareness of how simulation is used to visualize, analyze, and improve the performance of manufacturing and service systems.

1.2 What Is Simulation?

The *Oxford American Dictionary* (1980) defines simulation as a way "to reproduce the conditions of a situation, as by means of a model, for study or testing or training, etc." For our purposes, we are interested in reproducing the operational behavior of dynamic systems. The model that we will be using is a computer model. Simulation in this context can be defined as the imitation of a dynamic system using a computer model in order to evaluate and improve system performance. According to Schriber (1987), simulation is "the modeling of a process or system in such a way that the model mimics the response of the actual system to events that take place over time." By studying the behavior of the model, we can gain insights about the behavior of the actual system.

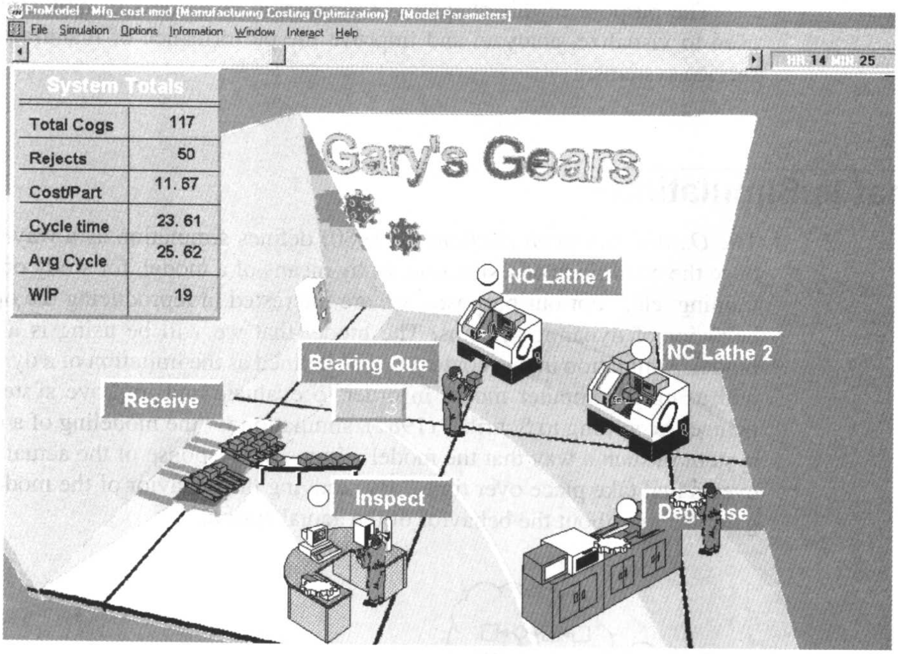
Simulation is the imitation of a dynamic system using a computer model in order to evaluate and improve system performance.

In practice, simulation is usually performed using commercial simulation software like ProModel that has modeling constructs specifically designed for capturing the dynamic behavior of systems. Performance statistics are gathered during the simulation and automatically summarized for analysis. Modern simulation software provides a realistic, graphical animation of the system being modeled (see Figure 1.1). During the simulation, the user can interactively adjust the animation speed and change model parameter values to do "what if" analysis on the fly. State-of-the-art simulation technology even provides optimization capability—not that simulation itself optimizes, but scenarios that satisfy defined feasibility constraints can be automatically run and analyzed using special goal-seeking algorithms.

This book focuses primarily on discrete-event simulation, which models the effects of the events in a system as they occur over time. Discrete-event simulation employs statistical methods for generating random behavior and estimating

FIGURE 1.1

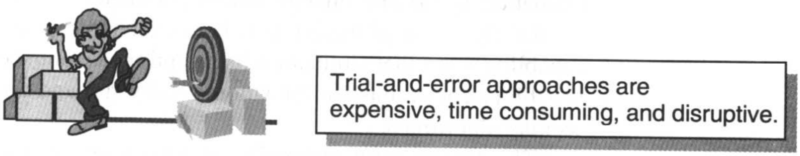
Simulation provides animation capability.



model performance. These methods are sometimes referred to as Monte Carlo methods because of their similarity to the probabilistic outcomes found in games of chance, and because Monte Carlo, a tourist resort in Monaco, was such a popular center for gambling.

1.3 Why Simulate?

Rather than leave design decisions to chance, simulation provides a way to validate whether or not the best decisions are being made. Simulation avoids the expensive, time-consuming, and disruptive nature of traditional trial-and-error techniques.



With the emphasis today on time-based competition, traditional trial-and-error methods of decision making are no longer adequate. Regarding the shortcoming of trial-and-error approaches in designing manufacturing systems, Solberg (1988) notes,

> The ability to apply trial-and-error learning to tune the performance of manufacturing systems becomes almost useless in an environment in which changes occur faster than the lessons can be learned. There is now a greater need for formal predictive methodology based on understanding of cause and effect.

The power of simulation lies in the fact that it provides a method of analysis that is not only formal and predictive, but is capable of accurately predicting the performance of even the most complex systems. Deming (1989) states, "Management of a system is action based on prediction. Rational prediction requires systematic learning and comparisons of predictions of short-term and long-term results from possible alternative courses of action." The key to sound management decisions lies in the ability to accurately predict the outcomes of alternative courses of action. Simulation provides precisely that kind of foresight. By simulating alternative production schedules, operating policies, staffing levels, job priorities, decision rules, and the like, a manager can more accurately predict outcomes and therefore make more informed and effective management decisions. With the importance in today's competitive market of "getting it right the first time," the lesson is becoming clear: if at first you don't succeed, you probably should have simulated it.

By using a computer to model a system before it is built or to test operating policies before they are actually implemented, many of the pitfalls that are often encountered in the start-up of a new system or the modification of an existing system can be avoided. Improvements that traditionally took months and even years of fine-tuning to achieve can be attained in a matter of days or even hours. Because simulation runs in compressed time, weeks of system operation can be simulated in only a few minutes or even seconds. The characteristics of simulation that make it such a powerful planning and decision-making tool can be summarized as follows:

- Captures system interdependencies.
- Accounts for variability in the system.
- Is versatile enough to model any system.
- Shows behavior over time.
- Is less costly, time consuming, and disruptive than experimenting on the actual system.
- Provides information on multiple performance measures.
- Is visually appealing and engages people's interest.
- Provides results that are easy to understand and communicate.
- Runs in compressed, real, or even delayed time.
- Forces attention to detail in a design.

Because simulation accounts for interdependencies and variation, it provides insights into the complex dynamics of a system that cannot be obtained using other analysis techniques. Simulation gives systems planners unlimited freedom to try out different ideas for improvement, risk free—with virtually no cost, no waste of time, and no disruption to the current system. Furthermore, the results are both visual and quantitative with performance statistics automatically reported on all measures of interest.

Even if no problems are found when analyzing the output of simulation, the exercise of developing a model is, in itself, beneficial in that it forces one to think through the operational details of the process. Simulation can work with inaccurate information, but it can't work with incomplete information. Often solutions present themselves as the model is built—before any simulation run is made. It is a human tendency to ignore the operational details of a design or plan until the implementation phase, when it is too late for decisions to have a significant impact. As the philosopher Alfred North Whitehead observed, "We think in generalities; we live detail" (Audon 1964). System planners often gloss over the details of how a system will operate and then get tripped up during implementation by all of the loose ends. The expression "the devil is in the details" has definite application to systems planning. Simulation forces decisions on critical details so they are not left to chance or to the last minute, when it may be too late.

Simulation promotes a try-it-and-see attitude that stimulates innovation and encourages thinking "outside the box." It helps one get into the system with sticks and beat the bushes to flush out problems and find solutions. It also puts an end to fruitless debates over what solution will work best and by how much. Simulation takes the emotion out of the decision-making process by providing objective evidence that is difficult to refute.

1.4 Doing Simulation

Simulation is nearly always performed as part of a larger process of system design or process improvement. A design problem presents itself or a need for improvement exists. Alternative solutions are generated and evaluated, and the best solution is selected and implemented. Simulation comes into play during the evaluation phase. First, a model is developed for an alternative solution. As the model is *run,* it is put into operation for the period of interest. Performance statistics (utilization, processing time, and so on) are gathered and reported at the end of the run. Usually several *replications* (independent runs) of the simulation are made. Averages and variances across the replications are calculated to provide statistical estimates of model performance. Through an iterative process of modeling, simulation, and analysis, alternative configurations and operating policies can be tested to determine which solution works the best.

Simulation is essentially an experimentation tool in which a computer model of a new or existing system is created for the purpose of conducting experiments. The model acts as a surrogate for the actual or real-world system. Knowledge gained from experimenting on the model can be transferred to the real system (see Figure 1.2). When we speak of *doing* simulation, we are talking about "the

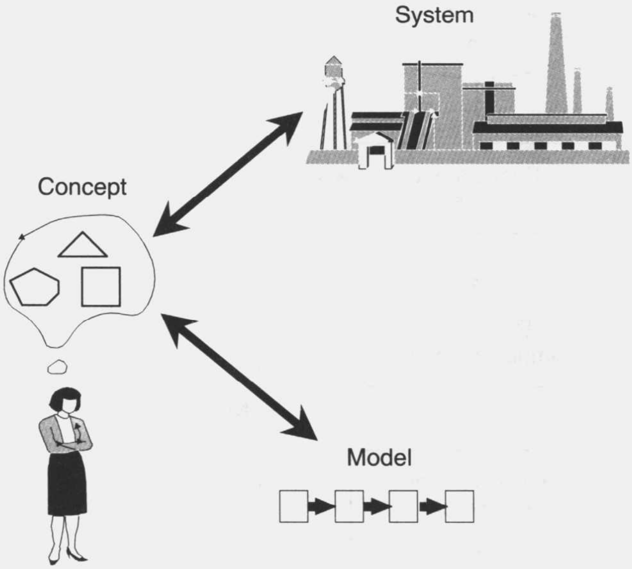


FIGURE 1.2

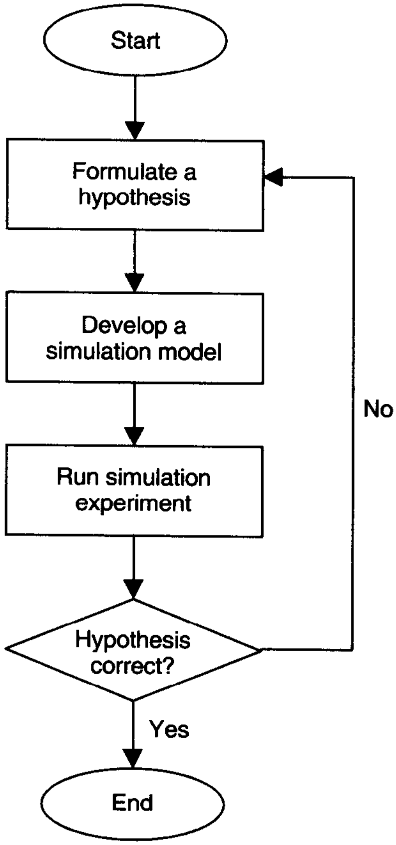
Simulation provides a virtual method for doing system experimentation.

process of designing a model of a real system and conducting experiments with this model" (Shannon 1998). Conducting experiments on a model reduces the time, cost, and disruption of experimenting on the actual system. In this respect, simulation can be thought of as a virtual prototyping tool for demonstrating proof of concept.

The procedure for doing simulation follows the scientific method of (1) formulating a hypothesis, (2) setting up an experiment, (3) testing the hypothesis through experimentation, and (4) drawing conclusions about the validity of the hypothesis. In simulation, we formulate a hypothesis about what design or operating policies work best. We then set up an experiment in the form of a simulation model to test the hypothesis. With the model, we conduct multiple replications of the experiment or simulation. Finally, we analyze the simulation results and draw conclusions about our hypothesis. If our hypothesis was correct, we can confidently move ahead in making the design or operational changes (assuming time and other implementation constraints are satisfied). As shown in Figure 1.3, this process is repeated until we are satisfied with the results.

By now it should be obvious that simulation itself is not a solution tool but rather an evaluation tool. It describes how a defined system will behave; it does not prescribe how it should be designed. Simulation doesn't compensate for one's ignorance of how a system is supposed to operate. Neither does it excuse one from being careful and responsible in the handling of input data and the interpretation of output results. Rather than being perceived as a substitute for thinking, simulation should be viewed as an extension of the mind that enables one to understand the complex dynamics of a system.

FIGURE 1.3
The process of simulation experimentation.



1.5 Use of Simulation

Simulation began to be used in commercial applications in the 1960s. Initial models were usually programmed in FORTRAN and often consisted of thousands of lines of code. Not only was model building an arduous task, but extensive debugging was required before models ran correctly. Models frequently took a year or more to build and debug so that, unfortunately, useful results were not obtained until after a decision and monetary commitment had already been made. Lengthy simulations were run in batch mode on expensive mainframe computers where CPU time was at a premium. Long development cycles prohibited major changes from being made once a model was built.

Only in the last couple of decades has simulation gained popularity as a decision-making tool in manufacturing and service industries. For many companies, simulation has become a standard practice when a new facility is being planned or a process change is being evaluated. It is fast becoming to systems planners what spreadsheet software has become to financial planners.

The surge in popularity of computer simulation can be attributed to the following:

- Increased awareness and understanding of simulation technology.
- Increased availability, capability, and ease of use of simulation software.
- Increased computer memory and processing speeds, especially of PCs.
- Declining computer hardware and software costs.

Simulation is no longer considered a method of "last resort," nor is it a technique reserved only for simulation "experts." The availability of easy-to-use simulation software and the ubiquity of powerful desktop computers have made simulation not only more accessible, but also more appealing to planners and managers who tend to avoid any kind of solution that appears too complicated. A solution tool is not of much use if it is more complicated than the problem that it is intended to solve. With simple data entry tables and automatic output reporting and graphing, simulation is becoming much easier to use and the reluctance to use it is disappearing.

The primary use of simulation continues to be in the area of manufacturing. Manufacturing systems, which include warehousing and distribution systems, tend to have clearly defined relationships and formalized procedures that are well suited to simulation modeling. They are also the systems that stand to benefit the most from such an analysis tool since capital investments are so high and changes are so disruptive. Recent trends to standardize and systematize other business processes such as order processing, invoicing, and customer support are boosting the application of simulation in these areas as well. It has been observed that 80 percent of all business processes are repetitive and can benefit from the same analysis techniques used to improve manufacturing systems (Harrington 1991). With this being the case, the use of simulation in designing and improving business processes of every kind will likely continue to grow.

While the primary use of simulation is in decision support, it is by no means limited to applications requiring a decision. An increasing use of simulation is in the area of communication and visualization. Modern simulation software incorporates visual animation that stimulates interest in the model and effectively communicates complex system dynamics. A proposal for a new system design can be sold much easier if it can actually be shown how it will operate.

On a smaller scale, simulation is being used to provide interactive, computer-based training in which a management trainee is given the opportunity to practice decision-making skills by interacting with the model during the simulation. It is also being used in real-time control applications where the model interacts with the real system to monitor progress and provide master control. The power of simulation to capture system dynamics both visually and functionally opens up numerous opportunities for its use in an integrated environment.

Since the primary use of simulation is in decision support, most of our discussion will focus on the use of simulation to make system design and operational decisions. As a decision support tool, simulation has been used to help plan and