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.
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> 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.
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> 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.
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> "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."
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> 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:

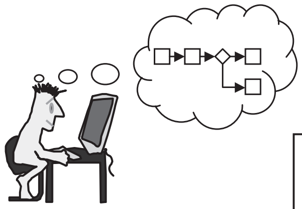
- What is simulation?
- Why is simulation used?
- How is simulation performed?
- When and where should simulation be used?

- 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.



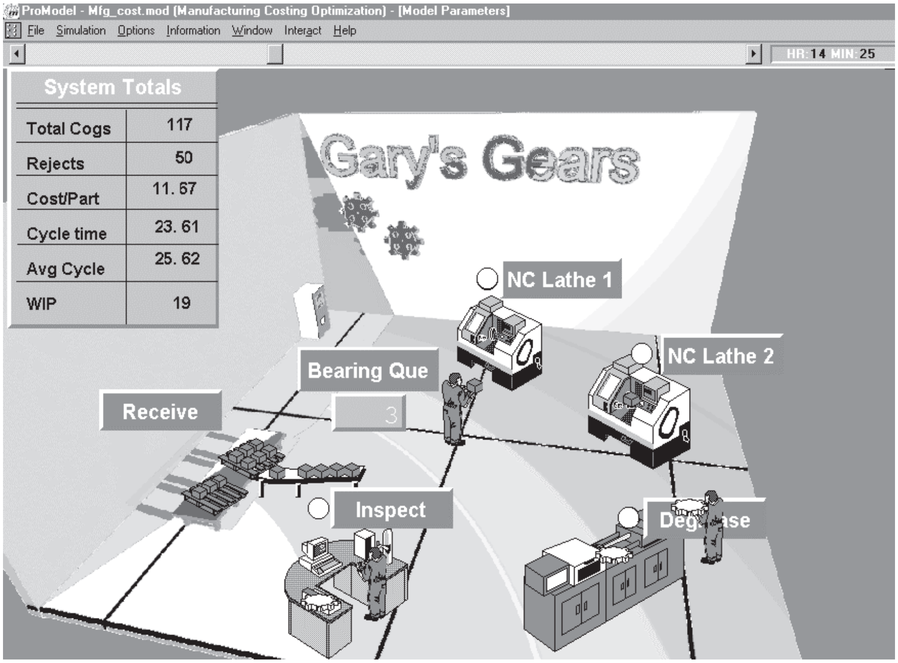
Simulation is the imitation of a dynamic system using a computer model in order to evaluate and improve system performance.

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 (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

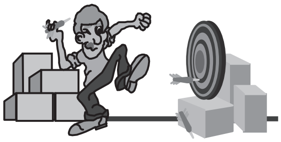
Simulation provides animation capability.



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.



Trial-and-error approaches are expensive, time consuming, and disruptive.

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. When we speak of *doing* simulation, we are talking about "the process of designing a model of a real system and conducting experiments with this model"

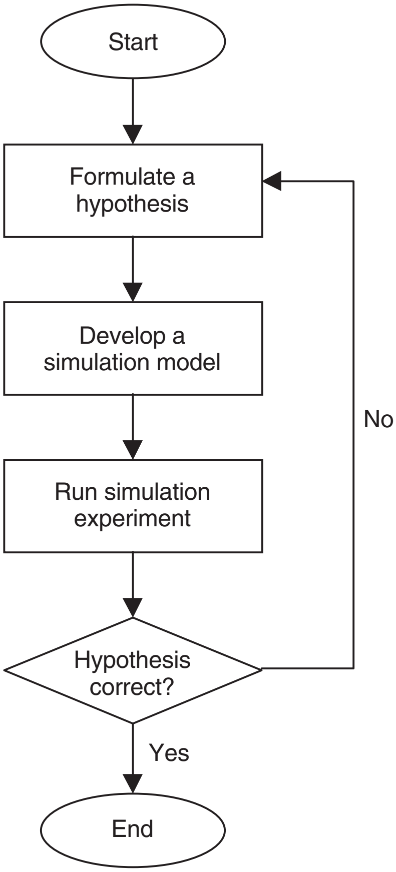
(Shannon 1998). Conducting experiments on a model reduces the time, cost, and disruption of experimenting on the actual system. In this respect, simulation can be thought of as a virtual prototyping tool for demonstrating proof of concept.

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 1.2, 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

FIGURE 1.2

The process of simulation experimentation.



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.

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. Much of the growth in the use of simulation is due to the increased availability and ease of use of simulation software that runs on standard PCs. 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 primary use of simulation continues to be in the area of manufacturing and logistics, which include warehousing and distribution systems. These areas 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. In the service sector, healthcare systems are also a prime candidate for simulation. 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 its operation can actually be demonstrated.

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 make improvements in many areas of both manufacturing and service industries. Typical applications of simulation include

- Work-flow planning.
- Capacity planning.
- Cycle time reduction.
- Staff and resource planning.
- Work prioritization.
- Bottleneck analysis.
- Quality improvement.
- Cost reduction.
- Inventory reduction.
- Throughput analysis.
- Productivity improvement.
- Layout analysis.
- Line balancing.
- Batch size optimization.
- Production scheduling.
- Resource scheduling.
- Maintenance scheduling.
- Control system design.

1.6 When Simulation Is Appropriate

Not all system problems that *could* be solved with the aid of simulation *should* be solved using simulation. It is important to select the right tool for the task. For some problems, simulation may be overkill—like using a shotgun to kill a fly. Simulation has certain limitations of which one should be aware before making a decision to apply it to a given situation. It is not a panacea for all system-related problems and should be used only if the shoe fits. As a general guideline, simulation is appropriate if the following criteria hold true:

- An operational (logical or quantitative) decision is being made.
- The process being analyzed is well defined and repetitive.
- Activities and events are interdependent and variable.
- The cost impact of the decision is greater than the cost of doing the simulation.
- The cost to experiment on the actual system is greater than the cost of simulation.

Decisions should be of an operational nature. Perhaps the most significant limitation of simulation is its restriction to the operational issues associated with systems planning in which a logical or quantitative solution is being sought. It is not very useful in solving qualitative problems such as those involving technical or sociological issues. For example, it can't tell you how to improve machine reliability or how to motivate workers to do a better job (although it can assess the impact that a given level of reliability or personal performance can have on overall system performance). Qualitative issues such as these are better addressed using other engineering and behavioral science techniques.

Processes should be well defined and repetitive. Simulation is useful only if the process being modeled is well structured and repetitive. If the process doesn't follow a logical sequence and adhere to defined rules, it may be difficult to model. Simulation applies only if you can describe how the process operates. This does not mean that there can be no uncertainty in the system. If random behavior can be described using probability expressions and distributions, they can be simulated. It is only when it isn't even possible to make reasonable assumptions of how a system operates (because either no information is available or behavior is totally erratic) that simulation (or any other analysis tool for that matter) becomes useless. Likewise, one-time projects or processes that are never repeated the same way twice are poor candidates for simulation. If the scenario you are modeling is likely never going to happen again, it is of little benefit to do a simulation.

Activities and events should be interdependent and variable. A system may have lots of activities, but if they never interfere with each other or are deterministic (that is, they have no variation), then using simulation is probably unnecessary. It isn't the number of activities that makes a system difficult to analyze. It is the number of interdependent, random activities. The effect of simple interdependencies is easy to predict if there is no variability in the activities. Determining the flow rate for a system consisting of 10 processing activities is very straightforward if all activity times are constant and activities are never interrupted. Likewise, random activities that operate independently of each other are usually easy to analyze. For example, 10 machines operating in isolation from each other can be expected to produce at a rate that is based on the average cycle time of each machine less any anticipated downtime. It is the combination of interdependencies and random behavior that really produces the unpredictable results. Simpler analytical methods such as mathematical calculations and spreadsheet software become less adequate as the number of activities that are both interdependent and random increases. For this reason, simulation is primarily suited to systems involving both interdependencies and variability.

The cost impact of the decision should be greater than the cost of doing the simulation. Sometimes the impact of the decision itself is so insignificant that it doesn't warrant the time and effort to conduct a simulation. Suppose, for example, you are trying to decide whether a worker should repair rejects as they occur or wait until four or five accumulate before making repairs. If you are certain that the next downstream activity is relatively insensitive to whether repairs are done sooner rather than later, the decision becomes inconsequential and simulation is a wasted effort.

The cost to experiment on the actual system should be greater than the cost of simulation. While simulation avoids the time delay and cost associated with experimenting on the real system, in some situations it may actually be quicker and more economical to experiment on the real system. For example, the decision in a customer mailing process of whether to seal envelopes before or after they are addressed can easily be made by simply trying each method and comparing the results. The rule of thumb here is that if a question can be answered through direct experimentation quickly, inexpensively, and with minimal impact to the current operation, then don't use simulation. Experimenting on the actual system also eliminates some of the drawbacks associated with simulation, such as proving model validity.

There may be other situations where simulation is appropriate independent of the criteria just listed (see Banks and Gibson 1997). This is certainly true in the case of models built purely for visualization purposes. If you are trying to sell a system design or simply communicate how a system works, a realistic animation created using simulation can be very useful, even though nonbeneficial from an analysis point of view.

1.7 Qualifications for Doing Simulation

Many individuals are reluctant to use simulation because they feel unqualified. Certainly some training is required to use simulation, but it doesn't mean that only statisticians or operations research specialists can learn how to use it. Decision support tools are always more effective when they involve the decision maker, especially when the decision maker is also the domain expert or person who is most familiar with the design and operation of the system. The process owner or manager, for example, is usually intimately familiar with the intricacies and idiosyncrasies of the system and is in the best position to know what elements to include in the model and be able to recommend alternative design solutions. When performing a simulation, often improvements suggest themselves in the very activity of building the model that the decision maker might never discover if someone else is doing the modeling. This reinforces the argument that the decision maker should be heavily involved in, if not actually conducting, the simulation project.

To make simulation more accessible to non–simulation experts, products have been developed that can be used at a basic level with very little training. Unfortunately, there is always a potential danger that a tool will be used in a way that exceeds one's skill level. While simulation continues to become more user-friendly, this does not absolve the user from acquiring the needed skills to make intelligent use of it. Many aspects of simulation will continue to require some training. Hoover and Perry (1989) note, "The subtleties and nuances of model validation and output analysis have not yet been reduced to such a level of rote that they can be completely embodied in simulation software."

Modelers should be aware of their own inabilities in dealing with the statistical issues associated with simulation. Such awareness, however, should not prevent one from using simulation within the realm of one's expertise. There are both a basic as well as an advanced level at which simulation can be beneficially used. Rough-cut modeling to gain fundamental insights, for example, can be achieved with only a rudimentary understanding of simulation. One need not have extensive simulation training to go after the low-hanging fruit. Simulation follows the 80–20 rule, where 80 percent of the benefit can be obtained from knowing only 20 percent of the science involved (just make sure you know the right 20 percent). It isn't until more precise analysis is required that additional statistical training and knowledge of experimental design are needed.

To reap the greatest benefits from simulation, a certain degree of knowledge and skill in the following areas is useful:

- Project management.
- Communication.
- Systems engineering.
- Statistical analysis and design of experiments.
- Modeling principles and concepts.
- Basic programming and computer skills.
- Training on one or more simulation products.
- Familiarity with the system being investigated.

Experience has shown that some people learn simulation more rapidly and become more adept at it than others. People who are good abstract thinkers yet also pay close attention to detail seem to be the best suited for doing simulation. Such individuals are able to see the forest while still keeping an eye on the trees (these are people who tend to be good at putting together 1,000-piece puzzles). They are able to quickly scope a project, gather the pertinent data, and get a useful model up and running without lots of starts and stops. A good modeler is somewhat of a sleuth, eager yet methodical and discriminating in piecing together all of the evidence that will help put the model pieces together.

If short on time, talent, resources, or interest, the decision maker need not despair. Plenty of consultants who are professionally trained and experienced can provide simulation services. A competitive bid will help get the best price, but one should be sure that the individual assigned to the project has good credentials. If the use of simulation is only occasional, relying on a consultant may be the preferred approach.

1.8 Conducting a Simulation Study

Once a suitable application has been selected and appropriate tools and trained personnel are in place, the simulation study can begin. Simulation is much more than building and running a model of the process. Successful simulation projects are well planned and coordinated. While there are no strict rules on how to conduct a simulation project, the following steps are generally recommended:

Step 1: Define objective and plan the study. Define the purpose of the simulation project and what the scope of the project will be. A project plan needs to be developed to determine the resources, time, and budget requirements for carrying out the project.

Step 2: Collect and analyze system data. Identify, gather, and analyze the data defining the system to be modeled. This step results in a conceptual model and a data document on which all can agree.

Step 3: Build the model. Develop a simulation model of the system.

Step 4: Validate the model. Debug the model and make sure it is a credible representation of the real system.

Step 5: Conduct experiments. Run the simulation for each of the scenarios to be evaluated and analyze the results.

Step 6: Present the results. Present the findings and make recommendations so that an informed decision can be made.

Each step need not be completed in its entirety before moving to the next step. The procedure for doing a simulation is an iterative one in which activities are refined and sometimes redefined with each iteration. The decision to push toward further refinement should be dictated by the objectives and constraints of the study as well as by sensitivity analysis, which determines whether additional refinement will yield meaningful results. Even after the results are presented, there are often requests to conduct additional experiments.

Figure 1.3 illustrates this iterative process.

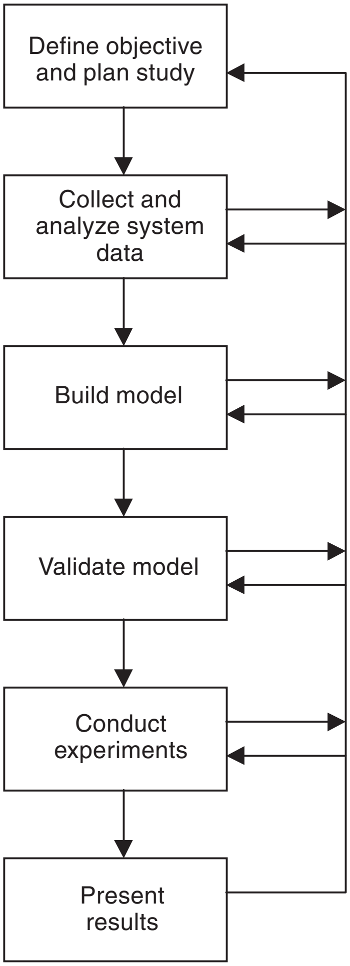
Here we will briefly look at defining the objective and planning the study, which is the first step in a simulation study. The remaining steps will be discussed at length in subsequent chapters.

1.8.1 Defining the Objective

The objective of a simulation defines the purpose or reason for conducting the simulation study. It should be realistic and achievable, given the time and resource constraints of the study. Simulation objectives can be grouped into the following general categories:

- *Performance analysis*—What is the all-around performance of the system in terms of resource utilization, flow time, output rate, and so on?
- *Capacity/constraint analysis*—When pushed to the maximum, what is the processing or production capacity of the system and where are the bottlenecks?
- *Configuration comparison*—How well does one system or operational configuration meet performance objectives compared to another?
- *Optimization*—What settings for particular decision variables best achieve desired performance goals?

Figure 1.3
Iterative nature of simulation.



- *Sensitivity analysis*—Which decision variables are the most influential on performance measures, and how influential are they?
- *Visualization*—How can the system operation be most effectively visualized?

Following is a list of sample design and operational questions that simulation can help answer. They are intended as examples of specific objectives that might be defined for a simulation study.

1. How many operating personnel are needed to meet required production or service levels?
2. What level of automation is the most cost-effective?
3. How many machines, tools, fixtures, or containers are needed to meet throughput requirements?

4. What is the least-cost method of material handling or transportation that meets processing requirements?
5. What are the optimum number and size of waiting areas, storage areas, queues, and buffers?
6. Where are the bottlenecks in the system, and how can they be eliminated?
7. What is the best way to route material, customers, or calls through the system?
8. What is the best way to allocate personnel to specific tasks?
9. How much raw material and work-in-process inventory should be maintained?
10. What is the best production control method (kanban, for example)?

When the goal is to analyze some aspect of system performance, the tendency is to think in terms of the mean or expected value of the performance metric. For example, we are frequently interested in the average contents of a queue or the average utilization of a resource. There are other metrics that may have equal or even greater meaning that can be obtained from a simulation study. For example, we might be interested in variation as a metric, such as the standard deviation in waiting times. Extreme values can also be informative, such as the minimum and maximum number of contents in a storage area. We might also be interested in a percentile such as the percentage of time that the utilization of a machine is less than a particular value, say, 80 percent. While frequently we speak of designing systems to be able to handle peak periods, it often makes more sense to design for a value above which values only occur less than 5 or 10 percent of the time. It is more economical, for example, to design a staging area on a shipping dock based on 90 percent of peak time usage rather than based on the highest usage during peak time. Sometimes a single measure is not as descriptive as a trend or pattern of performance. Perhaps a measure has increasing and decreasing periods such as the activity in a restaurant. In these situations, a detailed time series report would be the most meaningful.

While well-defined and clearly stated objectives are important to guide the simulation effort, they should not restrict the simulation or inhibit creativity. Michael Schrage (1999) observes that "the real value of a model or simulation may stem less from its ability to test a hypothesis than from its power to generate useful surprise. Louis Pasteur once remarked that 'chance favors the prepared mind.' It holds equally true that chance favors the prepared prototype: models and simulations can and should be media to create and capture surprise and serendipity. . . . The challenge is to devise transparent models that also make people shake their heads and say 'Wow!'" The right "experts" can be "hypervulnerable to surprise but well situated to turn surprise to their advantage. That's why Alexander Fleming recognized the importance of a mold on an agar plate and discovered penicillin." Finally, he says, "A prototype should be an invitation to play. You know you have a successful prototype when people who see it make useful suggestions about how it can be improved."

1.8.2 Planning the Study

With a realistic, meaningful, and well-defined objective established, a scope of work and schedule can be developed for achieving the stated objective. The scope of work is important for guiding the study as well as providing a specification of the work to be done upon which all can agree. The scope is essentially a project specification that helps set expectations by clarifying to others exactly what the simulation will include and exclude. Such a specification is especially important if an outside consultant is performing the simulation so that there is mutual understanding of the deliverables required.

An important part of the scope is a specification of the models that will be built. When evaluating improvements to an existing system, it is often desirable to model the current system first. This is called an "as-is" model. Results from the as-is model are statistically compared with outputs of the real-world system to validate the simulation model. This as-is model can then be used as a benchmark or baseline to compare the results of "to-be" models. For reengineering or process improvement studies, this two-phase modeling approach is recommended. For entirely new facilities or processes, there will be no as-is model. There may, however, be several to-be models to compare.

To ensure that the scope is complete and the schedule is realistic, a determination should be made of

- The models to be built and experiments to be made.
- The software tools and personnel that will be used to build the models.
- Who will be responsible for gathering the data for building the models.
- How the models will be verified and validated.
- How the results will be presented.

Once these issues have been settled, a project schedule can be developed showing each of the tasks to be performed and the time to complete each task. Remember to include sufficient time for documenting the model and adding any final touches to the animation for presentation purposes. Any additional resources, activities (travel, etc.) and their associated costs should also be identified for budgeting purposes.

1.9 Economic Justification of Simulation

Cost is always an important issue when considering the use of any software tool, and simulation is no exception. Simulation should not be used if the cost exceeds the expected benefits. This means that both the costs and the benefits should be carefully assessed. The use of simulation is often prematurely dismissed due to the failure to recognize the potential benefits and savings it can produce. Much of the reluctance in using simulation stems from the mistaken notion that simulation is costly and very time consuming. This perception is shortsighted and ignores the fact that in the long run simulation usually saves much more time and cost than it consumes. It is true that the initial investment, including training and start-up costs, may be between \$10,000 and \$30,000 (simulation products themselves generally range between \$1,000 and \$20,000). However, this cost is often recovered after the first one or two projects. The ongoing expense of using simulation for individual projects is estimated to be between 1 and 3 percent of the total project cost (Glenney and Mackulak 1985). With respect to the time commitment involved in doing simulation, much of the effort that goes into building the model is in arriving at a clear definition of how the system operates, which needs to be done anyway. With the advanced modeling tools that are now available, the actual model development and running of simulations take only a small fraction (often less than 5 percent) of the overall system design time.

Savings from simulation are realized by identifying and eliminating problems and inefficiencies that would have gone unnoticed until system implementation. Cost is also reduced by eliminating overdesign and removing excessive safety factors that are added when performance projections are uncertain. By identifying and eliminating unnecessary capital investments, and discovering and correcting operating inefficiencies, it is not uncommon for companies to report hundreds of thousands of dollars in savings on a single project through the use of simulation. The return on investment (ROI) for simulation often exceeds 1,000 percent, with payback periods frequently being only a few months or the time it takes to complete a simulation project.

One of the difficulties in developing an economic justification for simulation is the fact that it is usually not known in advance how much savings will be realized until it is actually used. Most applications in which simulation has been used have resulted in savings that, had the savings been known in advance, would have looked very good in an ROI or payback analysis.

One way to assess in advance the economic benefit of simulation is to assess the risk of making poor design and operational decisions. One need only ask what the potential cost would be if a misjudgment in systems planning were to occur. Suppose, for example, that a decision is made to add another machine to solve a capacity problem in a production or service system. What are the cost and probability associated with this being the wrong decision? If the cost associated with a wrong decision is \$100,000 and the decision maker is only 70 percent confident that the decision is correct, then there is a 30 percent chance of incurring a cost of \$100,000. This results in a probable cost of \$30,000 ($.3 \times \$100,000$). Using this approach, many decision makers recognize that they can't afford *not* to use simulation because the risk associated with making the wrong decision is too high.

Tying the benefits of simulation to management and organizational goals also provides justification for its use. For example, a company committed to continuous improvement or, more specifically, to lead time or cost reduction can be sold on simulation if it can be shown to be historically effective in these areas. Simulation has gained the reputation as a best practice for helping companies achieve organizational goals. Companies that profess to be serious about performance improvement will invest in simulation if they believe it can help them achieve their goals.

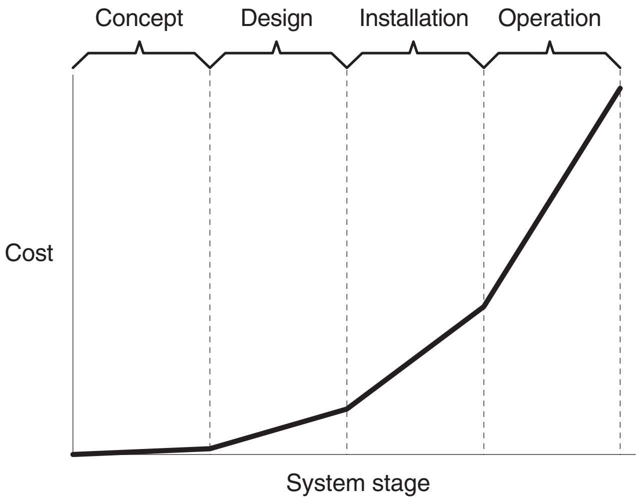


FIGURE 1.4
Cost of making changes at subsequent stages of system development.

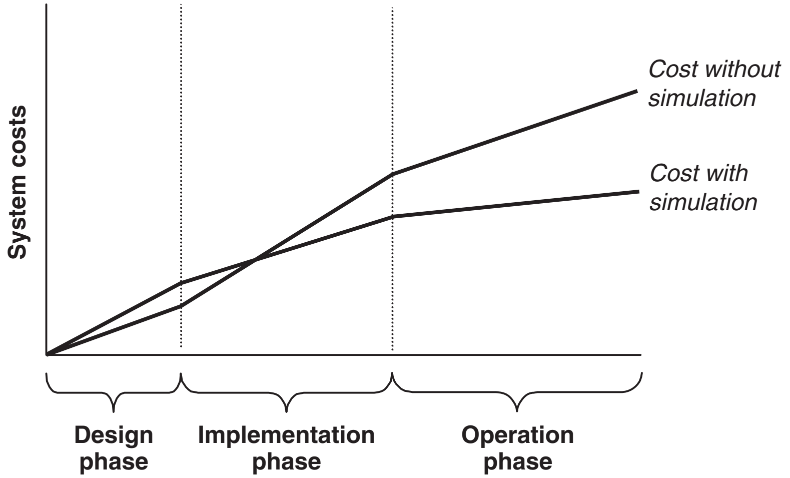


FIGURE 1.5
Comparison of cumulative system costs with and without simulation.

The real savings from simulation come from allowing designers to make mistakes and work out design errors on the model rather than on the actual system. The concept of reducing costs through working out problems in the design phase rather than after a system has been implemented is best illustrated by the *rule of tens*. This principle states that the cost to correct a problem increases by a factor of 10 for every design stage through which it passes without being detected (see Figure 1.4).

Simulation helps avoid many of the downstream costs associated with poor decisions that are made up front. Figure 1.5 illustrates how the cumulative cost resulting from systems designed using simulation can compare with the cost of designing and operating systems without the use of simulation. Note that while the short-term cost may be slightly higher due to the added labor and software costs associated with simulation, the long-term costs associated with capital investments and system operation are considerably lower due to better efficiencies realized through simulation. Dismissing the use of simulation on the basis of sticker price is myopic and shows a lack of understanding of the long-term savings that come from having well-designed, efficiently operating systems.

Many examples can be cited to show how simulation has been used to avoid costly errors in the start-up of a new system. Simulation prevented an unnecessary expenditure when a *Fortune* 500 company was designing a facility for producing and storing subassemblies and needed to determine the number of containers required for holding the subassemblies. It was initially felt that 3,000 containers were needed until a simulation study showed that throughput did not improve significantly when the number of containers was increased from 2,250 to 3,000. By purchasing 2,250 containers instead of 3,000, a savings of $528,375 was expected in the first year, with annual savings thereafter of over $200,000 due to the savings in floor space and storage resulting from having 750 fewer containers (Law and McComas 1988).

Even if dramatic savings are not realized each time a model is built, simulation at least inspires confidence that a particular system design is capable of meeting required performance objectives and thus minimizes the risk often associated with new start-ups. The economic benefit associated with instilling confidence was evidenced when an entrepreneur, who was attempting to secure bank financing to start a blanket factory, used a simulation model to show the feasibility of the proposed factory. Based on the processing times and equipment lists supplied by industry experts, the model showed that the output projections in the business plan were well within the capability of the proposed facility. Although unfamiliar with the blanket business, bank officials felt more secure in agreeing to support the venture (Bateman et al. 1997).

Often simulation can help improve productivity by exposing ways of making better use of existing assets. By looking at a system holistically, long-standing problems such as bottlenecks, redundancies, and inefficiencies that previously went unnoticed start to become more apparent and can be eliminated. "The trick is to find waste, or *muda,*" advises Shingo; "after all, the most damaging kind of waste is the waste we don't recognize" (Shingo 1992). Consider the following actual examples where simulation helped uncover and eliminate wasteful practices:

- GE Nuclear Energy was seeking ways to improve productivity without investing large amounts of capital. Through the use of simulation, the company was able to increase the output of highly specialized reactor parts by 80 percent. The cycle time required for production of each part was reduced by an average of 50 percent. These results were obtained by running a series of models, each one solving production problems highlighted by the previous model (Bateman et al. 1997).
- A large manufacturing company with stamping plants located throughout the world produced stamped aluminum and brass parts on order according

to customer specifications. Each plant had from 20 to 50 stamping presses that were utilized anywhere from 20 to 85 percent. A simulation study was conducted to experiment with possible ways of increasing capacity utilization. As a result of the study, machine utilization improved from an average of 37 to 60 percent (Hancock, Dissen, and Merten 1977).

- A diagnostic radiology department in a community hospital was modeled to evaluate patient and staff scheduling, and to assist in expansion planning over the next five years. Analysis using the simulation model enabled improvements to be discovered in operating procedures that precluded the necessity for any major expansions in department size (Perry and Baum 1976).

In each of these examples, significant productivity improvements were realized without the need for making major investments. The improvements came through finding ways to operate more efficiently and utilize existing resources more effectively. These capacity improvement opportunities were brought to light through the use of simulation.

1.10 Sources of Information on Simulation

Simulation is a rapidly growing technology. While the basic science and theory remain the same, new and better software is continually being developed to make simulation more powerful and easier to use. It will require ongoing education for those using simulation to stay abreast of these new developments. There are many sources of information to which one can turn to learn the latest developments in simulation technology. Some of the sources that are available include

- Conferences and workshops sponsored by vendors and professional societies (such as, Winter Simulation Conference and the IIE Conference).
- Professional magazines and journals (*IIE Solutions, International Journal of Modeling and Simulation,* and the like).
- Websites of vendors and professional societies (www.promodel.com, www.scs.org, and so on).
- Demonstrations and tutorials provided by vendors.
- Textbooks (like this one).

1.11 How to Use This Book

This book is divided into two parts. Part I contains chapters describing the science and practice of simulation. The emphasis is deliberately oriented more toward the practice than the science. Simulation is a powerful decision support tool that has a broad range of applications. While a fundamental understanding of how simulation works is presented, the aim has been to focus more on how to use simulation