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Enhancing the Coverage of Simulation in the Introductory MS/OR Course: Needs, Problems, and Solution*

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The topic of simulation should be an important part of any business or engineering school's curriculum; but, several pedagogical problems currently limit the significant coverage of simulation in an introductory MS/OR (management science/operations research) course—an overview course where a variety of quantitative methods are introduced. In response to these needs and problems, this paper reports an innovative solution (software, text material, and presentation aids) that has been developed to effectively and efficiently provide a meaningful introduction to simulation in an overview course. The pedagogical support package facilitates the introduction of many pragmatic issues and concerns, thereby providing the student with a genuine appreciation for this powerful and popular modeling tool. It allows simulation to be covered at a level comparable to other important MS/OR topics, e.g. linear programming and regression.

INTRODUCTION

AN INTERESTING paradox exists in the topic coverage of most introductory management science/operations research (MS/OR) courses. This being that, in practice, simulation is applied to an extensive array of problems in a wide variety of areas; but, ironically in the curriculum of most engineering and management schools (and in most introductory textbooks) simulation receives very limited coverage. In order to eliminate this paradox, the author developed and implemented a comprehensive course module, referred to as $(SP)^2$ (Simulation Pedagogic Support Package). This package is designed to be used in an introductory (overview or survey) course where a variety of quantitative techniques are introduced.

This integrated package consists of three components. The first component, software, is designed specifically for use in the classroom, although it is powerful enough to handle many real-world problems. It facilitates the coverage of many practical concerns that must be addressed in the application of simulation. The output from the software is comprehensive, yet easy to understand—it provides both stand-alone summary reports and data files that can be read into any statistics or graphics package for further analysis. The second component, text material, documents and supports the software; but, more importantly, it addresses the many important simulation issues that are missing from introductory MS/OR textbooks. The final component of $(SP)^2$ is a set of classroom presentation aids that are designed to illustrate many of the important issues that must be considered when computer simulation is used as an analysis tool.

Before describing the module, the first section of this paper establishes the need for expanding the coverage of simulation in the introductory MS/OR course; this is followed by a discussion of the problems that have so far precluded a more comprehensive treatment of simulation in this type of course. The next three sections: (1) outline the topical coverage of the module, (2) describe the specially designed software, and (3) discuss the integration of the package into the classroom, through the use of case exercises and innovative presentation aids. The paper concludes with a list of benefits that result from expanding the coverage of simulation in the survey MS/OR course.

THE NEED FOR INCREASING THE EMPHASIS ON SIMULATION

There are three strong reasons why emphasis on simulation should be increased in the introductory MS/OR course—its widespread and diversified application base, attractive pedagogical attributes, and its relationship to the modeling process.

Widespread application

Simulation is one of the most powerful analysis tools available to designers and managers of complex systems. It is also one of the most widely used MS/OR techniques, as evidenced by several

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surveys in the literature. One survey, by Shannon, *et al.* [1], found that practitioners in academia, government, and business ranked simulation as the most useful MS/OR methodology. Another survey, by Forgionne [2], found that simulation was second only to general statistical analysis, in terms of the frequency of use of MS/OR techniques by large American corporations.

A third survey, that of nonacademic users of simulation by Christy and Watson [3], found simulation applications are common to most functional areas. They also found that simulation models are developed throughout the organization and many are created within the functional areas, as opposed to within centralized MS/OR departments. They reported the largest implementation problem to be the lack of quantitative education of top and middle managers and end users—precisely the problem to which this paper responds. Two other leading implementation problems were reported to be the lack of good data and insufficient time to perform the analysis (this should be helped greatly by new, easier-to-use software that is on the market today).

Given the widespread application of simulation, decision makers are more and more likely to utilize simulation-based information. Also, as computer software tools improve and become more accessible to a wider potential user base, these users must be better equipped to utilize them. Therefore, they must be exposed to more than simple manual examples. They must be aware of the many pragmatic issues that surround the *application* of simulation—precisely the issues that are addressed in the $(SP)^2$ module.

Pedagogical attributes

In addition to its widespread application, as evidenced by the surveys described above, statistically-based computer simulation can play an important pedagogical role in an engineering or management school's curriculum. From a pedagogical point of view, simulation: (1) provides a means of analysis for very complex systems that cannot be described or solved analytically; (2) demonstrates how analytic and simulation models differ and how they can be used to complement one another; (3) introduces the concept of stochastic systems; (4) acts as a laboratory environment where students can experiment with alternative system configurations and test assumptions; (5) reinforces and demonstrates an application area for many of the topics that were covered in introductory statistics courses (descriptive measures, graphs, sampling, probability distributions, estimation, and inference); and, (6) is a popular topic with students—it has been the author's experience that students find simulation intuitive, interesting, practical, and 'fun'.

Relationship to the 'Modeling' process

Simulation provides a clear illustration of the use of models, i.e. how a model is an abstraction and simplification of a real system. It illustrates how a decision maker can utilize a model to: study and gain an understanding of a real system, acquire information on the estimated performance of a real system, test the effect of alternative considerations, and perform sensitivity analyses on changes in the value of a system's parameters.

Understanding and developing an appreciation for the modeling process is important to students regardless of whether they will be model 'producers' or model 'consumers'. Some students will pursue further work in MS/OR and mathematical modeling (and become model producers); therefore, this material provides a solid foundation for them to build upon. However, many students will not become modelers, but it is very likely that they will use models developed by others in order to make decisions (model consumer). Therefore, they must be at least sensitive to the modeling process, exposed to potential applications, and aware of some of the problems that can occur. An understanding of the modeling process also provides students with a framework for applying the techniques that are discussed in the course.

Most texts begin with a description of the modeling process (alternatively referred to as the scientific method). But, unfortunately, there is usually little mention of this process beyond the first chapter. The author feels that the modelling *process* is such an important component of the course that as each technique (not just simulation) is discussed in the course, it is discussed within the context shown in Fig. 1. The key components in Fig. 1 are the two processes—Model Production and Model Consumption—that link applications and techniques. Model production encompasses problem definition, model development, data preparation, and model solution. Model consumption includes: validation/verification, experimentation, consideration of alternatives, analysis, solution sensitivity, and implementation. The applications and techniques draw from previous knowledge, i.e. both from basic mathematics, probability, and statistics and from the functional areas of engineering and management. The material in this course then supports further discussion in more advanced MS/OR courses or in courses in the functional areas.

PROBLEMS CURRENTLY LIMITING THE EMPHASIS ON SIMULATION

Simulation, when covered in an introductory MS/OR course, is usually limited to a few superficial and cursory manual illustrations. This is mainly due to both limited textbook coverage and the lack of suitable software. The simulation text and software dilemma is in sharp contrast to other topics covered in the introductory course. For example, the textbook coverage of mathematical programming is abundant and the classroom-oriented software support (e.g. LINDO) is excellent.

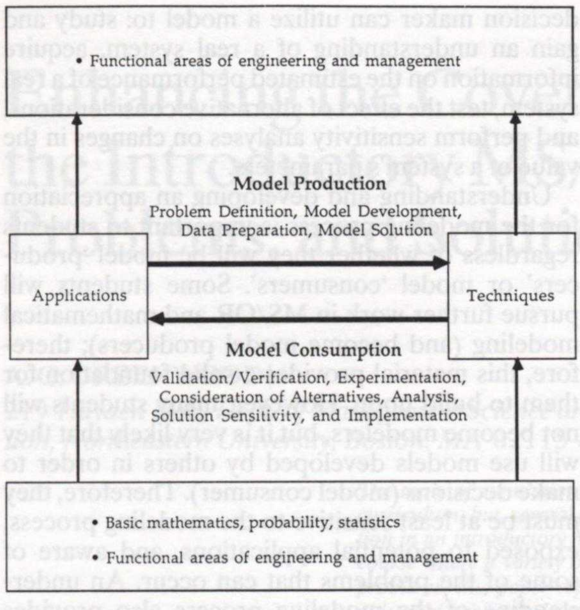

Fig. 1. Modeling process components link applications and techniques.

As a result of these problems, the key and practical issues that surround the application of simulation—e.g. notion of sampling, need for replication, selection of the appropriate input probability distributions, length of simulation, starting conditions, importance of statistical analysis, etc.—are not addressed. The notion of not going beyond simple manual examples is analogous to teaching only simple regression in a statistics course and teaching it only by means of formulas; i.e. without computer support to analyze larger, more meaningful data sets, consider multivariate models, and address model selection and diagnostics. It is also analogous to teaching only the graphical solution of LP models; i.e. without computer support to consider larger, more meaningful problems, illustrate more practical applications of LP, and address the important topic of sensitivity analysis.

More troubling than the limited textbook coverage, in terms of effectively teaching simulation, is the severe void of computer-based simulation tools suitable for classroom use. This is especially disturbing, since the computer is used exclusively in all real-world applications of simulation. One reason for the software problem is that usually statistically-based computer simulation models are constructed using a special-purpose language, e.g. GPSS, SLAM, SIMSCRIPT. Coverage of these languages are conducive only to courses devoted entirely to the topic of simulation; there is no time in an overview course to learn such a language.

The classroom use of computer software is essential for introductory modeling courses, since good software support removes the arduous computational tasks associated with many quantitative techniques. Good software support for a course helps to emphasize more sophisticated interpretation of results, rather than mechanical solutions. By exploring and experimenting with a modeling domain on the computer, students gain insight into the effects on output values rendered by the varying of key input values. They also obtain a better feel for how managers use models, once they have been developed and implemented.

SOLUTION: THE (SP)^2 MODULE

In response to the aforementioned needs and problems, the author has designed a module, to effectively and efficiently deliver a comprehensive introduction to simulation; i.e., to bring the level of coverage of simulation to a level near to that of regression or LP. The module is described below in terms of its three components: supplemented text (topical coverage), software, and teaching aids.

The module was developed with funding support from the author's college and has successfully been implemented as an integral part of the introductory MS/OR course. This course, as is typical in business schools throughout the world, is a part of the college's core curriculum; i.e., it is required of all business majors, both at the undergraduate and graduate (MBA) levels. It follows the statistics sequence and precedes the operations management course. It includes such topics as mathematical programming (usually the dominant topic), forecasting, decision analysis, inventory, networks, queueing, simulation, etc. A similar course is often found in engineering schools, especially in industrial engineering and engineering management curricula. Typically the OR/MS course is preceded by a course(s) in probability and statistics and is followed by a variety of design and analysis courses that either apply the methodologies presented in the introductory course or explore those techniques in more detail.

Topical coverage (supplemental text)

The topics that are covered in the simulation module are outlined in Fig. 2. Presentation of these topics require about five to eight classroom hours, depending on the level of detail and the level of the course (undergraduate or graduate). The topics are divided into four main components. While several of the topics appear to follow a more traditional approach, they are discussed in the paper for completeness and to place the more unique topics into their proper context.

The (SP)^2 text is organized in the same manner as the topics in Fig. 2. While the text is often referred to as a supplemental text for the course, implying supplemental to the main text in the course (one of the many general introductory MS/OR texts on the market), for the purpose of teaching simulation, it becomes the primary source of information and the general introductory text becomes secondary. It is completely self contained and is comprehensive enough to stand alone or be used in conjunction

Section 1: Overview and introduction
- Simulation
- Queueing
- Case applications of queueing & simulation
- The modeling process

Section 2: Queueing systems
- Introduction
- NRC case example
- Characteristics of queueing systems
  - Arrival process
  - Service process
  - Service mechanism
  - Queue characteristics
  - Customer behavior
  - Other considerations
  - Measure's of performance
- Queueing analysis of the NRC case
  - Baseline case
  - Alternative systems
- Qualitative factors that affect queueing experiences
  - Social injustice
  - Environment
  - Feedback
- Exercises

Section 3: Manual simulation
- General concepts
- System definition
- Data analysis - arrival & service processes
  - Arrival process
  - Selecting the appropriate probability distribution
  - Service process
- Manual simulation of the NRC case
  - Setup for the manual simulation
  - Simulation logic
  - Simulation table
  - Simulation graph
- Results of the simulation
- Summary
- Exercises

Section 4: Computer simulation
- General description of the $(SP)^2$ package
- Access and input data
- Output: reports and files
- Analysis of simulation results - NRC case
  - Interpreting the basic $(SP)^2$ output
  - Confidence interval estimates
  - Further statistical analysis
  - Temporal view of the simulation
- Thrif-T Bank case
  - Problem definition
  - Analysis
- Computer Simulation Languages
  - Features of simulation languages

Fig. 2. Topical coverage in the simulation module.

with a general MS/OR text. Since it can stand alone and is not tied to any specific MS/OR text, it can be used at any college or university. The $(SP)^2$ text includes: all of the necessary technical material that is missing from the general MS/OR text, extensive examples and illustrations, specially designed exercises, instructions on the use of the accompanying software, and an integrated presentation of queueing, manual simulation and computer simulation.

The first main topic in the module, as outlined in Fig. 2, introduces simulation through a general discussion of modeling and the modeling process. It also contains a set of one-paragraph summaries of over a dozen published real-world applications of simulation and queueing (many from *IE* and *Interfaces*). This establishes the need for discussing the topic by illustrating the importance and widespread application of simulation. This is an application of the author's teaching philosophy to motivate by example, i.e. let theory follow application.

Since simulation is described in the context of queueing problems, the second portion of the module listed in Fig. 2 is a queueing primer. A simple case example is used to introduce the terminology and the basic concepts of queueing (e.g. arrival and service processes, service mechanism, queue characteristics, customer behavior, and measures of performance). Analytical models (M/M/s) are used to solve the case, illustrate the sensitivity of the various input parameters, and to introduce the notion of trading off the cost of service and the cost of waiting. The same example is carried throughout the entire module to provide continuity and to more clearly illustrate the similarities and differences between analytic and simulation models.

The third section, manual simulation, goes beyond providing the logic for simulating a simple queueing system by hand. One common violation of the assumptions inherent in analytic models is that the arrival and/or service processes in the real system are not Poisson (exponential). This poses an interesting question—how does one know if the analytic model is appropriate? If it is not appropriate, then what probability distribution should be used in the simulation? This section of the module includes a discussion on data collection and resurrects the concept of goodness-of-fit testing from an earlier statistics course. Manual simulation also resurrects from prior statistics work the concept of sampling and the characteristics of the different probability distributions. The same case example that was discussed in the queueing primer is used to illustrate the manual simulation concepts.

The fourth portion of the module outlined in Fig. 2, computer simulation, provides the major extension to what is normally taught in the introductory course. A detailed discussion of the pedagogical approach to this portion of the module is presented later in the paper (following a brief discussion of the $(SP)^2$ software below). The Computer Simulation section concludes with a brief introduction to computer simulation languages. This includes a discussion of the features and built-in capabilities of the simulation languages; also, a simple GPSS model and its corresponding output are used to illustrate these features.

One thing that becomes evident in the third and fourth sections of the module is that even though simulation provides a means to analyze systems where the assumptions of analytic models are violated, it is not a panacea and requires a significant amount of work to setup and analyze.

The $(SP)^2$ software

The $(SP)^2$ software provides an easy-to-use, yet comprehensive, vehicle for students to experiment with realistic queueing simulation models. It enhances their practical understanding of the significant issues that surround the use of simulation as an analysis tool in the business environment. This section describes the software; its role in the module is discussed in the following section.

A list of the key features that are incorporated into the $(SP)^2$ software package is provided in Fig. 3—no other package provides both the ease of use and the range of capabilities and features that the $(SP)^2$ package provides. The software allows students to focus on some of the broader issues of simulation and gain insight into the effects on output values rendered by the varying of key input values. Because the package removes many of the arduous tasks associated with simulation, it emphasizes sophisticated interpretation of results, rather than mechanical solutions.

Users of the $(SP)^2$ software do not have to know any computer languages. All of the input requirements for the simulation are requested through a menu of self-explanatory prompts and the details of the execution process are transparent to the user. Typical inputs include: type of model (single- or

- Menu selection of a variety of probability distributions: deterministic, empirical, exponential, normal, triangular, and uniform. The mean value of the distribution is automatically calculated whenever it is not directly specified.
- Two types of waiting line arrangements: single-queue and multi-queue.
- Optional consideration of balking.
- Number of customers in the system at the start of the simulation is a variable.
- Other user-specified input parameters:
  - number of parallel servers
  - length of simulation and simulation time unit
  - choice of random number seeds
- Customized output: easy-to-read and understand, primary measures of performance for queueing systems, presentation of input values as well as output statistics.
- Experiment is replicated a specified number of times; statistics for each replication and summary values are automatically provided.
- Replication data from the output summary is also stored in an ASCII file for use with other software.
- "Snapshots" of system performance, throughout the first replication of the simulation, are stored in an ASCII file for use with other software.
- For comparison purposes, the output report provides the measures of performance for the system assuming it is represented by a M/M/s model.
- Automatically reports the percentage of customers that waited longer than a specified period of time (referred to as the wait-time threshold value); also, reports the percentage of customers that do not wait at all.

Fig. 3. Feature of the $(SP)^2$ software package.

multi-queue), number of parallel servers, whether balking is to be considered, initial number of customers in the system when the simulation begins, number of times the model is to be replicated, and choice of arrival and service processes from a wide variety of probability distributions. The system also allows the user to specify a wait-time threshold value; i.e. the simulation automatically records the percentage of customers that waited longer than a specified threshold value.

The program is written entirely in GPSS/H (except a few support routines are written in FORTRAN and linked with the GPSS/H compiler), as shown in Fig. 4. GPSS is a widely used simulation programming language that has been in existence for more than twenty years. The H-version (developed and marketed by Wolverine Software of Arlington, VA) is extremely powerful, especially in terms of developing specialized I/O (input/output); i.e., user interfaces (friendly prompts for input and customized output report formats) can be developed *within* GPSS/H, thereby eliminating the need for multi-language interfaces and ties to specific hardware. As shown in Fig. 4, the queueing models form the kernel of the package. These basic models are enveloped in a program manager that controls: the entry of the necessary parameter values supplied by the user, the running of the simulations themselves, and the formatting of the output reports.

An example of the primary output from the (SP)² software, entitled 'Simulation Summary Report', is provided in Fig. 5. It is a specially designed and edited version of the standard GPSS output. The standard GPSS output contains more information than is needed in the course and does not conveniently display or summarize the replication data. As shown in Fig. 4, the report is also written to an ASCII-formatted file (replication data only, no headings, totals, etc.) so that it can be easily read into other software packages for more extensive analysis (additional descriptive statistics, plots, etc.).

The top portion of the report contains a description of the simulated system; the bottom portion contains a summary of the results. As can be seen from the example, in Fig. 5, a single-server queueing model is considered with exponentially distributed interarrival and service times. The simulation begins 'empty and idle' (no one in the system) and runs for eight hours (480 minutes) of simulated time. The simulation is replicated 10 times, i.e. the system is studied over ten separate and independent eight-hour periods. This example is from the same case that has been discussed throughout the module (analytic queueing model, manual simulation, and now computer simulation). The bottom portion of Fig. 5 provides a variety of measures of the system's simulated performance; these measures are provided both for each replication and overall (combined).

The detailed data in Fig. 5 illustrates the importance of replicating the simulation experiment. It becomes evident, when one examines the difference in the results from replication to replication, that the decision maker would not want to

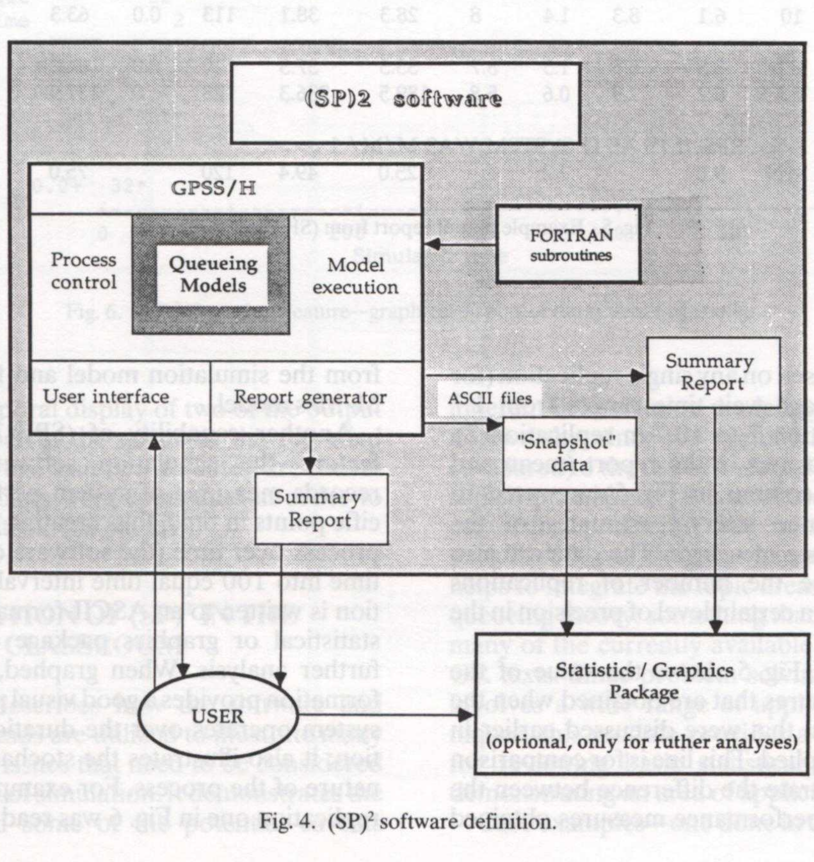

Fig. 4. (SP)² software definition.

S I M U L A T I O N   S U M M A R Y   R E P O R T

(SP)2 SIMULATION PEDAGOGICAL SUPPORT PACKAGE V.4 (11/88)

This simulation, using GPSS, was performed by: USER'S NAME

++++++ SYSTEM DESCRIPTION ++++++

Number of phases: SINGLE — Queue type: SINGLE-QUEUE
Number of parallel servers (channels): 1 — Queue discipline: FIFO
Reniging: NO — Jockeying: NO
Balking: NO
Initial number of customers in the system: 0

Arrival time distribution: EXPONENTIAL
Mean time betw'n arrivals (1 / [arrival rate]) = 4.0 MIN

Service time distribution: EXPONENTIAL
Mean service time (1 / [service rate]) = 3.0 MIN

Number of replications: 10 — Random-no. seed: 1
Each replication was simulated for 480 MIN .

++++++ SUMMARY of RESULTS ++++++

Rep	Customer <-Wait Time-> Mean	StD	Waiting <-Line Lth-> Mean	Max	% Cust with NO wait	% Cust waiting > 5	No. Arvl	% Cust (Arvls) Balked	Serv Util
1	5.6	6.1	1.4	9	29.2	45.0	119	0.0	68.5
2	10.7	8.4	3.0	11	12.0	67.4	131	0.0	86.8
3	7.0	7.8	2.0	12	27.3	40.9	136	0.0	70.9
4	6.8	8.4	1.9	11	33.6	42.5	134	0.0	70.2
5	6.4	6.6	1.8	10	32.8	46.2	129	0.0	65.2
6	4.2	5.5	1.0	7	42.0	33.0	112	0.0	59.0
7	1.7	3.4	0.4	4	64.8	11.4	104	0.0	45.1
8	3.6	5.8	0.8	7	44.1	22.7	109	0.0	50.9
9	3.4	4.9	0.9	8	39.2	25.4	117	0.0	61.8
10	6.1	8.3	1.4	8	28.3	38.1	113	0.0	63.3
MN	5.5	6.5	1.5	8.7	35.3	37.3	120	0.0	64.2
VAR	6.2	2.9	0.6	5.8	189.5	236.3	128	0	131.9

<<< RESULTS AS IF SYSTEM WAS M/M/ 1 >>>

MN	9.0		2.2		25.0	49.4	120		75.0

Fig. 5. Example output report from $(SP)^2$ software.

make a decision based on any single replication (for example, the average wait time ranges from 1.7 minutes in replication 7 to 10.7 in replication 2). The summary measures in the report (mean and variance of each column in Fig. 5) are used to construct confidence interval estimates of the various performance measures. The data are also used to determine the number of replications necessary to attain a certain level of precision in the estimate.

The last line in Fig. 5 shows the value of the performance measures that are obtained when the queueing formulas, that were discussed earlier in the module, are applied. This line is for comparison purposes—to illustrate the difference between the estimated system performance measures obtained from the simulation model and from the analytic M/M/s model.

Another capability of $(SP)^2$ is the 'snapshot' feature—the simulation software automatically records measures of system performance at specific points in time, thus creating 'snapshots' of the process over time (the software divides simulated time into 100 equal time intervals). This information is written to an ASCII-formatted file so that a statistical or graphics package can be used for further analysis. When graphed, this type of information provides a good visual picture of how the system operates over the duration of the simulation; it also illustrates the stochastic and dynamic nature of the process. For example, the data from replication one in Fig. 6 was read into Minitab and

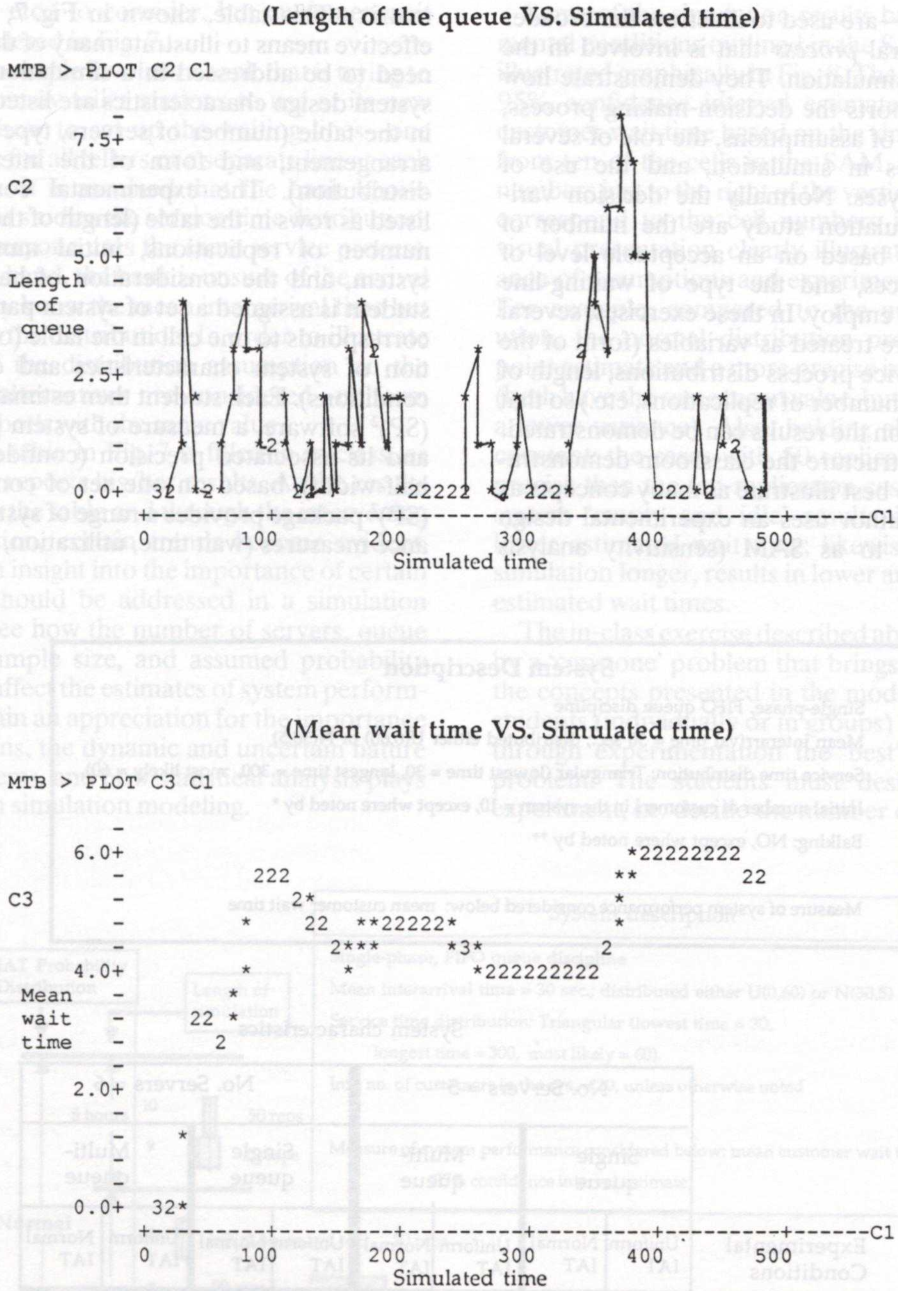

Fig. 6. (SP)² 'Snapshot' feature—graphical display of the system's operation.

plotted—the temporal display of two of the output measures—number in the queue at the recorded time and the average wait time to date—are shown in Fig. 6 (data points were connected in order to more clearly illustrate the pattern).

UTILIZATION OF (SP)² IN THE CLASSROOM

This section describes how the software and other classroom aids are utilized to illustrate many of the pragmatic issues that need to be considered in the application of simulation. It demonstrates the complexities and some of the potential caveats inherent in simulation modeling. This is especially noteworthy, since the use of simulation has been compared to the use of a scalpel—'in the hands of a skilled practitioner, it is a fabulous instrument for correcting problems, but in the hands of the unskilled, it can do great harm' [4, p. 19]. It also helps to integrate the topic areas of simulation and queueing theory; something that is not done well in many of the currently available introductory MS/OR texts. Since problem solving using simulation involves a wide range of applied statistical techniques, this module provides a very good vehicle for reviewing basic statistical concepts and for demonstrating an area of application.

Case examples—one done in class, another done outside of class—are used to illustrate the broader and more general *process* that is involved in the application of simulation. They demonstrate how simulation supports the decision-making process, the importance of assumptions, the role of several statistical issues in simulation, and the use of sensitivity analyses. Normally the decision variables in a simulation study are the number of servers to use, based on an acceptable level of customer services, and the type of waiting-line arrangement to employ. In these exercises, several other factors are treated as variables (form of the arrival and service process distributions, length of the simulation, number of replications, etc.) so that their influence on the results can be demonstrated.

In order to structure the classroom demonstration in a way to best illustrate as many concepts as possible, the author uses an experimental design table, referred to as SAM (sensitivity analysis matrix). This table, shown in Fig. 7, provides an effective means to illustrate many of the issues that need to be addressed in a simulation study. The system design characteristics are listed as columns in the table (number of servers, type of queueing arrangement, and form of the interarrival-time distribution). The experimental conditions are listed as rows in the table (length of the simulation, number of replications, initial number in the system, and the consideration of balking). Each student is assigned a set of system parameters that corresponds to one cell in the table (one combination of system characteristics and experimental conditions). Each student then estimates, using the $(SP)^2$ software, a measure of system performance and its associated precision (confidence interval half-width), based on one set of conditions. The $(SP)^2$ package provides a range of system performance measures (wait time, utilization, length of the

System Description

Single-phase, FIFO queue discipline

Mean interarrival time = 30 sec.; distributed either U(0,60) or N(30,5)

Service time distribution: Triangular (lowest time = 30, longest time = 300, most likely = 60).

Initial number of customers in the system = 10, except where noted by *

Balking: NO, except where noted by **

Measure of system performance considered below: mean customer wait time

System characteristics

Experimental Conditions		No. Servers = 5				No. Servers = 6			
		Single queue		Multi-queue		Single queue		Multi-queue	
		Uniform IAT	Normal IAT	Uniform IAT	Normal IAT	Uniform IAT	Normal IAT	Uniform IAT	Normal IAT
Simulate 1 hour	10 reps	1 104.0 (46.7)	6						
	50 reps	2	7						
	50 reps * Init. no. in sys. = 0	3	8						
	50 reps ** Balk, 5 or more								
Simulate 8 hours	10 reps	4	9						
	50 reps	5	10						

Fig. 7. SAM (Sensitivity Analysis Matrix)—experimental design structure for classroom demonstration of simulation.

waiting line, etc.) to consider, but customer wait time is considered in Fig. 7.

The case example involves a bank that is trying to decide how many teller stations to use at its new facility and how to set up the waiting lines—one common line for all tellers or a separate line at each teller station. It is assumed that the bank knows from previous studies the service-time distribution; therefore, everyone uses the same service process. On the other hand, the bank is unsure of the arrival process—they know the mean interarrival time but do not know the distribution. In order to illustrate the effect of the distribution assumption on the results, two alternatives are considered—uniform and normal, both with the same value.

The entire table in Fig. 7 is filled-in in class, as each student reports his/her results. As the results are posted to the table and through the intervening class discussion, certain trends become evident. Students gain insight into the importance of certain issues that should be addressed in a simulation study; they see how the number of servers, queue discipline, sample size, and assumed probability distribution affect the estimates of system performance. They gain an appreciation for the importance of assumptions, the dynamic and uncertain nature of many systems, and how statistical analysis plays a large role in simulation modeling.

Some of the simulation results based on experimental conditions outlined in the SAM (Fig. 7) are illustrated graphically in Fig. 8. The plots represent 95% confidence interval estimates of the mean customer wait time based on the simulation results from ten of the cells in the SAM. (The reference numbers just to the right of the vertical axis in Fig. 8 correspond to the cell numbers in Fig. 7.) This visual presentation clearly illustrates the importance of assumptions and experimental conditions. For example, compared to the uniform distribution, the normal distribution provides a lower point estimate and a more precise interval estimate (both have the same mean value, but the normal has a lower variance). Also, holding all other factors constant: the cases with 50 replications are more precise than the ten-replication cases; starting the system 'empty and idle' results in significantly lower estimated wait time; likewise, running the simulation longer, results in lower and less variable estimated wait times.

The in-class exercise described above is followed by a 'capstone' problem that brings together all of the concepts presented in the module. It requires students (individually or in groups) to recommend through experimentation the 'best' solution to a problem. The students must design their own experiment, i.e. decide the number of replications,

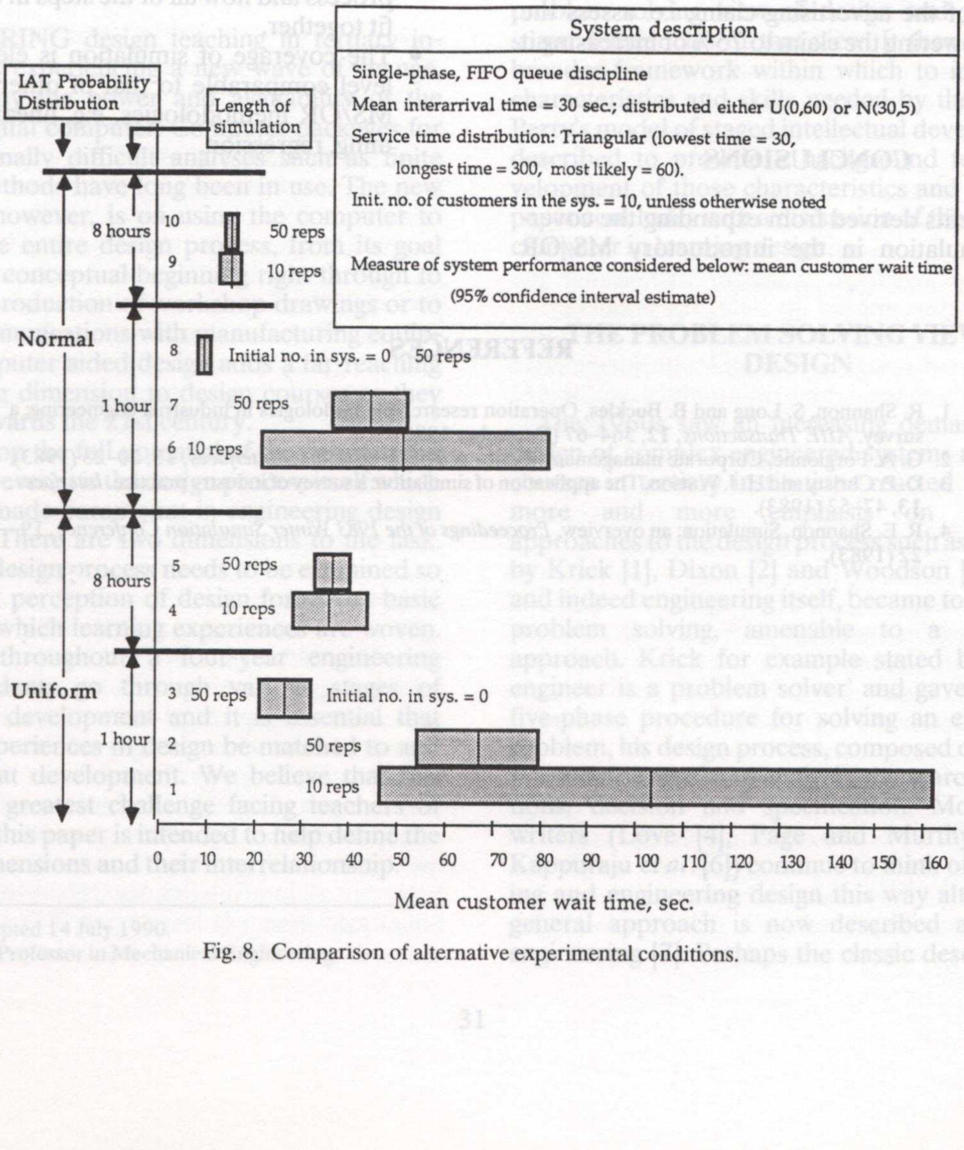

Fig. 8. Comparison of alternative experimental conditions.

initial conditions, length of the simulation, etc. In some cases only a sample from the service/or arrival processes are given; i.e., the students must select the appropriate distribution. Their assumptions, analyses, and recommendations are documented in a written report and are discussed in class. The written report is composed of two parts—a short management summary and a more detailed technical report.

One example application that has been used involves facilities planning for manufacturing plant expansion. Students find the best setup for the department; i.e., they recommend both the number of new machines and the number of spaces to allow for parts awaiting processing. The case considers one step in a production process where parts arrive from an oven. Some of the factors that are addressed are: investment and operating costs of the machines and building space, labor costs, breakage costs (if there is no space to wait when a part arrives, it falls off the conveyor and breaks), additional processing costs (if a part waits too long to be processed, it requires additional work at a later step in the production process). Another example application involves a large retail catalog company. The students find the 'best' number of telephone operators to use in order to meet the company's advertising claim—on the average, 80% of the customer's calls are answered by an operator in one minute or less. They also examine the sensitivity of the advertising claim; i.e. assess the impact of lowering the claim to 75% or increasing it to 90%.

CONCLUSIONS

The benefits derived from expanding the coverage of simulation in the introductory MS/OR course through the use of $(SP)^2$ package are summarized below:

- Since the module goes well beyond simple manual illustrations and introduces many pragmatic issues and concerns, students gain a genuine appreciation of the powerful and popular modeling tool. The comprehensive introduction provided by the pedagogic support package lays a solid foundation for future work.
- The importance of assumptions and the role of sensitivity analysis are clearly demonstrated. This is greatly facilitated by the use of the innovative design matrix—SAM.
- The topics of queueing, manual simulation, and computer simulation are well integrated.
- Many of the topics discussed in earlier statistics courses are resurrected—it not only provides a review, but demonstrates an important application area.
- The cases and exercises, in conjunction with the $(SP)^2$ software, provide students with the opportunity to explore 'real world' problems. They also get a chance to practice communicating their findings and recommendations through class discussion and written reports.
- Simulation, especially computer simulation, provides a great illustration of the modeling process and how all of the steps in the process fit together.
- The coverage of simulation is elevated to a level comparable to that of other important MS/OR methodologies, e.g. linear programming, regression.

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