IENG 461
Systems Modeling and Simulation

A simulation is the imitation of the operation of a real-world process or system over time.
Whether done by hand or on a computer, it involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system.

The behavior of a system as it evolves over time is studied by developing a simulation model. This model usually takes the form of a set of assumptions concerning the operation of the system. These assumptions are expressed in mathematical, logical, and symbolic relationships between the entities, or objects of interest, of the system.
Once developed and validated, a model can be used to investigate a wide variety of "what if" questions about the real-world system. Potential changes to the system can first be simulated in order to predict their impact on system performance. Simulation can also be used to study systems in the design stage, before such systems are built.

Thus, simulation modeling can be used both as an analysis tool for predicting the effect of changes to existing systems, and as a design tool to predict the performance of new systems under varying sets of circumstances.

In some instances, a model can be developed which is simple enough to be "solved" by mathematical methods. The solution usually consists of one or more numerical parameters which are called measures of performance of the system. However, many real-world systems are so complex that models of these systems are virtually impossible to solve mathematically. In these instances, numerical, computer-based simulation can be used to imitate the behavior of the system over time. From the simulation, data are collected as if a real system were being observed. This simulation-generated data is used to estimate the measures of performance of the system.

In this course, it is intended to provide the students with an introductory treatment of the concepts and methods of one form of simulation modeling, the Discrete-Event Simulation Modeling.

1.1 When is simulation the Appropriate Tool?

The advance in simulation methodologies and the availability of special-purpose simulation languages, massive computing capabilities at a decreasing cost have made Simulation one of the most widely used and accepted tools in Operations Research and Systems Analysis.

Circumstances under which Simulation is the appropriate tool to use have been listed as follows, by Jerry BANKS et al.:

1. **Simulation enables the study of, and experimentation with, the internal interactions of a complex system, or of a subsystem within a complex system.**
2. **Informational, organizational and environmental changes can be simulated and the effect of these alterations on the model's behavior can be observed.**
3. **The knowledge gained in designing a simulation model may be of great value toward suggesting improvement in the system under investigation.**
4. **By changing simulation inputs and observing the resulting outputs, valuable insight may be obtained into which variables are most important and how variables interact.**
5. **Simulation can be used as a pedagogical device to reinforce analytic solution methodologies.**
6. **Simulation can be used to experiment with new designs or policies prior to implementation, so as to prepare for what may happen**
7. **Simulation can be used to verify analytic solutions.**

1.2 When simulation is not the Appropriate Tool?

a- Simulation should not be used when the problem can be solved using common sense.
b- Simulation should not be used if the problem can be solved analytically.
c- Simulation should not be used if it is easier to perform direct experiments.
d- Simulation should not be used if the costs exceed the savings.
e- Simulation should not be used if the resources or time are not available.
f- Simulation is not advised if no data is available, not even estimates.
g- If there is not enough time or the personnel are not available, simulation is not appropriate.
h- If managers have unreasonable expectations (say, too much too soon) or the power of simulation is overestimated, simulation may not be appropriate.
i- If system behavior is too complex or can't be defined, simulation is not appropriate. Human behavior is sometimes extremely complex to model.

1.3 Advantages and Disadvantages of Simulation

Simulation is intuitively appealing to a client because it mimics what happens in a real system or what is perceived for a system that is in the design stage. The output data from a simulation should directly correspond to the outputs that could be recorded from the real system. Additionally, it is possible to develop a simulation model of a system without dubious assumptions (such as the same statistical distribution for every random variable) of mathematically solvable models. For these and other reasons, simulation is frequently the technique of choice in problem solving.

As compared to optimization models, "Simulation models" are "run" rather than solved. Given a particular set of input and model characteristics, the model is run and the simulated behavior is observed. This process of changing inputs and model characteristics results in a set of scenarios that are evaluated. A good solution, either in the analysis of an existing system or the design of a new system, is then recommended for implementation.

Advantages and disadvantages have been summarized as follows, by Jerry BANKS et al.:

1. **New policies, operating procedures, decision rules, information flows, organizational procedures, and so on can be explored without disrupting ongoing operations of the real system.**
2. **New hardware designs, physical layouts, transportation systems, and so on, can be tested without committing resources for their acquisition.**
3. **Hypotheses about how or why certain phenomena occur can be tested for feasibility.**
4. **Time can be compressed or expanded allowing for a speed up or slow down of the phenomena under investigation.**
5. **Insight can be obtained about the interaction of variables.**
6. **Insight can be obtained about the importance of variables on the performance of the system.**
7. **Bottleneck analysis can be performed indicating where work in process, information, materials, and so on is being excessively delayed.**

8. **A simulation study can help in understanding how the system operates rather than how individuals think the system operates.**
9. **“What if” questions can be answered? This is particularly useful in the design of new systems.**

The disadvantages are:

1. **Model building requires special training. It is an art that is learned over time and through experience. Furthermore, if two models are constructed by two competent individuals, they may have similarities, but it is highly unlikely that they will be the same.**
2. **Simulation results may be difficult to interpret. Since most simulation outputs are essentially random variables (they are usually based on random inputs), it may be hard to determine whether an observation is a result of system interrelationships or randomness.**
3. **Simulation modeling and analysis can be time consuming and expensive. Skimping on resources for modeling and analysis may result in a simulation model or analysis that is not sufficient for the task.**
4. **Simulation is used in some cases when an analytical solution is possible, or even preferable. This particularly true in the simulation of some waiting lines where closed-form queuing models are available.**

In defense of simulation, these four disadvantages can be offset as follows (Jerry BANKS et al.):

1. **Vendors of simulation software have been actively developing packages that contain models that only need input data for their operation. Such models have the generic tag “simulators” or “templates.”**
2. **Many simulation software vendors have developed output analysis capabilities within their packages for performing very thorough analysis.**

3. **Simulation can be performed faster today than yesterday, and even faster tomorrow. This is attributable to the advances in hardware that permit rapid running of scenarios. It is also attributable to the advances in many simulation packages. For example, some simulation software contains constructs for modeling material handling using transporters such as fork lift trucks, conveyors, and automated guided vehicles.**
4. **Closed-form models are not able to analyze most of the complex systems that are encountered in practice. In nearly eight years of consulting practice by one of the authors, not one problem has been encountered that could have been solved by a closed form solution.**

1.4 Areas of Application:

- Manufacturing Applications
Design and evaluation, Lot sizing, Analysing storage retrieval strategies, Modeling facilities, etc…

- Construction Engineering

- Military Applications

- Logistics, Transportation, and Distribution Applications

- Business Process Simulation

- Human Systems

1.5 Systems and System Environment

To model a system, it is necessary to understand the concept of a system and the system boundary.
A "system" is defined as a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose.

e.g. A production system manufacturing automobiles.
The machines, component parts, and workers operate jointly along an assembly line to produce a high-quality vehicle.

A system is often affected by changes occurring outside the system. Such changes are said to occur in the system environment. In modeling systems, it is necessary to decide on the boundary between the system and its environment. This decision may depend on the purpose of the study.

1.6 Components of a system

In order to understand and analyze a system, a number of terms need to be defined.

An "entity" is an object of interest in the system.

An "attribute" is a property of an entity.

An "Activity" represents a time period of special length.

Example:
If a Bank is being studied, customers might be one of the entities, the balance in their checking accounts might be an attribute, and making deposits might be an activity.

The "state" of a system is defined to be that collection of variables necessary to describe the system at any time, relative to the objectives of the study.

Example:
In the Bank example, possible state variables are the number of busy tellers, the number of customers waiting in line or being served, and the arrival time of the next customer.

An "event" is defined as an instantaneous occurrence that might change the state of the system.

The term “endogenous” is used to describe activities and events occurring within a system, and the term “exogenous” is used to describe activities and events in the environment that affect the system.

Example:

In the Bank example, the arrival of a customer is an exogenous event, and the completion of service of a customer is an endogenous event.

Examples of Systems and Components:

Bank System

- **Entities: Customers.**
- **Attributes: Checking account balance.**
- **Activities: Making deposits.**
- **Events: Arrival; departure.**
- **State Variables: Number of busy tellers; number of customers Waiting.**

Rapid rail System

- **Entities: Riders.**
- **Attributes: Origination; destination.**
- **Activities: Traveling.**
- **Events: Arrival at station; arrival at destination**
- **State Variables: Number of riders waiting at each station; number of riders in transit.**

Production System

- **Entities: Machines.**
- **Attributes: Speed; capacity; breakdown rate.**
- **Activities: Welding; stamping.**
- **Events: Breakdown.**
- **State Variables: Status of machines (busy, idle, or down).**

Communications System

- **Entities: Messages.**
- **Attributes: Length; destination.**
- **Activities: Transmitting.**
- **Events: Arrival at destination.**
- **State Variables: Number waiting to be transmitted.**

Inventory System

Entities: Warehouse.
Attributes: Capacity.
Activities: Withdrawing.
Events: Demand.
State Variables: Levels of inventory; backlogged demands.

Note: In the above examples, only a partial listing of the system components is shown. A complete list cannot be developed unless the purpose of the study is known.

1.7 Discrete and Continuous Systems:

Systems can be categorized as discrete or continuous. Few systems in practice are wholly discrete or continuous, but since one type of change predominates for most systems, it will usually be possible to classify a system as being either discrete or continuous [Jerry BANKS et al.].

A "discrete system" is one in which the state variable(s) change only at a discrete set of points in time.
e.g. Bank system
The state variable: the number of customers in the bank

A "Continuous system" is one in which the state variable(s) change continuously over time.
e.g. The dam system
The state variable: The head of water behind a dam.

1.8 Model of a System

Sometimes it is of interest to study a system to understand the relationships between its components or to predict how the system will operate under a new policy. Sometimes it is possible to experiment with the system itself, but not always. A new system may not yet exist; it may be only in hypothetical form or at the design stage. Even if the system exists, it may be impractical to experiment with it. For example, it may not be wise or possible to double the unemployment rate to determine the effect of employment on inflation. In the case of a bank, reducing the numbers of tellers to study the effect on the length of waiting lines

may infuriate the customers so greatly that they move their accounts to a competitor.

Consequently, studies of systems are often accomplished with a model of a system.

A model is defined as a representation of a system for the purpose of studying the system. For most studies, it is necessary to consider only those aspects of the systems that affect the problem under investigation. The model is a simplification of the system.

Different models of the same system may be required as the purpose of investigation changes.

Just as the components of a system were entities, attributes, and activities, models are represented similarly. However, the model contains only those components that are relevant to the study.

1.9 Types of Models

Models can be classified as being mathematical or physical.

A mathematical model uses symbolic notation and mathematical equations to represent a system.

A simulation model is a particular type of mathematical model of a system.

Simulation models may be further classified as being static or dynamic, deterministic or stochastic, and discrete or continuous.

A static simulation model, sometimes called a Monte Carlo simulation, represents a system at a particular point in time.

Dynamic simulation models, represent systems as they change over time (e.g. The simulation of a bank from 9:00 A.M. to 4:00 P.M.)

Deterministic simulation models, are simulation models that contain no random variables. They have a known set of inputs that will result in a unique set of outputs (e.g. Deterministic arrivals would occur at a dentist).

A stochastic simulation model has one or more random variables as input. Random inputs lead to random outputs. Since the outputs are random, they can be considered only as estimates of the true characteristics of a model (e.g. Simulation of a bank would involve random interarrival times and random services times. Thus, the output measures; the average number of people waiting, the average waiting time of a customer, must be treated as statistical estimates of the true characteristics of the system).

Discrete and continuous systems were defined previously. Discrete and continuous models are defined in an analogous manner.

The choice of whether to use a discrete or continuous simulation model is a function of the characteristics of the system and the objective of the study.

Note: the models considered in this course are discrete, dynamic, and stochastic.

1.10 Discrete-Event System Simulation

The state variable changes only at a discrete set of points in time.

The simulation models are analyzed by numerical rather than by analytical methods.

Analytical methods employ the deductive reasoning of mathematics to solve the model (e.g. Differential calculus can be used to determine minimum-cost policy for some inventory models).

Numerical methods employ computational procedures to solve mathematical models.

In case of simulation models, models are "run" rather than solved; that is, an artificial history of the system is generated based on the model

assumptions, and observations are collected to be analyzed and to estimate the true system performance measures.

Real world simulation models are rather large, and since the amount of data stored and manipulated is so vast, the runs are usually conducted with the aid of a computer. However, much insight can be obtained by simulating small models manually.

In summary, this course (IE-362) is about discrete-event system simulation in which the models of interest are analyzed numerically, usually with the aid of a computer.

1.11 Steps in a simulation study

- **a- Problem formulation: Every study should begin with a statement of the problem. The analyst must ensure that the problem being described is clearly understood.**
- **b- Setting of objectives and overall project plan: The objective indicate the questions to be answered by simulation. At this point a determination should be made concerning whether simulation is the appropriate methodology for the problem as formulated and objectives as stated. If it is decided that simulation is appropriate, the overall project plan should include a statement of the alternative systems to be considered, and a method for evaluating the effectiveness of these alternatives. It should also include the plans for the study in terms of the number of people involved, the cost of the study, and the number of days required to accomplish each phase of the work with the anticipated results at the end of each stage.**
- **c- Model conceptualization: The construction of a model of a system is probably as much art as science. The art of modeling is enhanced by an ability to abstract the essential features of a problem, to select and modify basic assumptions that characterize the system, and then to enrich and elaborate the model until a useful approximation results. Thus, it is best to start with a simple model and build toward greater complexity. However, the model complexity need not exceed that required to accomplish the purposes for which the model is intended.**

It is not necessary to have a one-to-one mapping between the model and the real system. Only the essence of the real system is needed. It is advisable to involve the model user in model conceptualization. This will both enhance the quality of the resulting model and increase the confidence of the model user in the application of the model.

- **d- Data collection: There is a constant interplay between the construction of the model and the collection of the needed input data. Data collection takes a large portion of the total time required to perform a simulation therefore, it is necessary to begin it as early as possible at the early stages of model building.**
- **e- Model translation: The model must be entered into a computer-recognizable format (program).**
- **f- Verification pertains to the computer program prepared for the simulation model. Is the computer program performing properly? If the input parameters and logical structure of the model are correctly represented in the computer, verification has been completed.**
- **g- Validation is the determination that a model is an accurate representation of the real system. It is usually achieved through the calibration of the model, an iterative process of comparing the model to actual system behavior and using the discrepancies between the two, and the insights gained to improve the model. This process is repeated until model accuracy is judged acceptable.**
- **h- Experimental design: For each system design that is simulated, decisions need to be made concerning the length of the initialization period, the length of simulation runs, and the number of replications to be made of each run.**
- **i- Production runs and analysis: are used to estimate measures of performance for the system designs that are being simulated.**
- **j- More runs? The analyst determines if additional runs are needed and what design those additional experiments should follow.**
- **k- Documentation and reporting: There are two types of documents; program and progress. Project reports give a chronology of work done and decisions made. The result of**

all the analysis should be reported clearly and concisely in a final report. This will enable the model users (the decision makers) to review the final formulation, the alternative systems that were addressed, the criterion by which the alternatives were compared, the results of the experiments, and the recommended solution to the problem.

l- Implementation: The success of the implementation phase depends on how well the previous eleven steps have been performed and on the continual involvement of the model user.