SIMULATION METHODOLOGY -- A PRACTITIONER'S PERSPECTIVE

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In this paper we describe the steps one must follow in applying the simulation methodology to solve real problems. The paper highlights technical and non-technical issues a simulationist faces in applying the simulation methodology. Eight major phases are identified for the proper application of simulation; each phase is further broken into steps. The steps are designed to increase the successful use of simulation by new simulation modelers.

Significance: The successful application of simulation in industry requires a lot of up-front work prior to building a computer simulation model. The paper highlights the importance of conceptual design and its validation, teamwork, model life-cycle, and model documentation in addition to other factors for establishing simulation as a viable tool of analysis and design in a company.

Keywords: Simulation Methodology, Conceptual Model Design, Conceptual Validation, Verification, Operational Validation, Project Report, Model Life-Cycle, Project Functional Specification, Project Report.

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1. INTRODUCTION

Many papers have appeared in the past on the simulation methodology (the process of applying the simulation technique), the successful application of simulation and how to avoid the pitfalls of simulation (e.g., Law (1993), Musselman (1992), Sadowski (1989), Ulgen (1991)). In this paper, we attempt to combine all this information into a set of steps and guidelines such that first-time simulation modelers in industry have a high rate of success in applying the simulation methodology.

In this paper, we describe eight major phases for the proper application of simulation methodology, namely:

Phase 1. Define-the problem
Phase 2. Design the study
Phase 3. Design the conceptual model
Phase 4. Formulate inputs, assumptions, and process definition
Phase 5. Build, verify, and validate the simulation model
Phase 6. Experiment with the model and look for opportunities for design of experiments
Phase 7. Document and present the results
Phase 8. Define the model life cycle

Although these phases are generally applied in sequence, one may need to return to the previous phases due to changes in scope and objectives of the study. In particular, phases 3 through 6 of the process may be repeated for each major alternative studied as part of the project.

In the following sections of the paper, we discuss each phase in detail by identifying the steps to follow for its successful execution.

2. DEFINE THE PROBLEM

This phase of the simulation process has the most effect on the total simulation study since a wrong problem definition can waste a lot of time and money on the project. It is important that the problem definition should be explicit and documented as part of the Project Functional Specifications. This phase includes the following steps:

Step 1. Define the objectives of the study.
Step 2. List the specific issues to be addressed.
Step 3. Determine the boundary or domain of the study.
Step 4. Determine the level of detail or proper abstraction level.
Step 5. Determine if a simulation model is actually needed; will an analytical method work?
Step 6. Estimate the required resources needed to do the study.
Step 7. Perform a cost-benefit analysis.
Step 8. Create a planning chart of the proposed project.
Step 9. Write a formal proposal.

The information gathered at the end of this phase should suffice to estimate the total cost of the project. The simulation Group and the client generally meet once or twice to gather this information. A visit to observe the actual or a similar process during this phase is recommended too. A formal proposal is generally written at the end of this phase of the project. Continuing with the other phases is contingent on its acceptance.

2.1 Define the Objectives of the Study

The objectives of the study must be clearly specified by its clients. The clients of a project can be internal and/or external to the organization responsible for execution of the study. It is important to involve the highest level of management from the client's organization. Generally, an engineer and an engineering manager/supervisor from the client's organization is assigned to the simulation project team. It is desirable to incorporate the objectives of both(all) levels of client management for the study right from the beginning of the study. Due to the inherent nature of the objectives of different levels of management, one may decide to have two (or more) separate models to satisfy the objectives of all levels of management interested in the study. In most cases it is also desirable to have two levels of management from the simulation group involved with the study. A simulation engineer and a simulation project manager (leader) may be more effective in communicating with the multiple levels of the client organization.

The typical objectives of a simulation study can be to verify the throughput of a new manufacturing line, identify the bottleneck operations in a system, find the proper buffer capacities to attain certain levels of production, determine the best batch sizes and sequence for a multi-product manufacturing line, etc. It is typical to have multiple objectives that may be in conflict in a study, such as minimizing the buffer sizes while maximizing the throughput rates. One should remember that the objective of a simulation study can not be just to simulate the system.

Once the objectives of the simulation study are finalized, it is important to determine if one model can satisfy all the objectives of the study. For example, a model built to find the best number of AGVs in a material handling system may not be the right one to analyze the priority rules to be used in processing parts in the workcells of the same system. After the objectives of the study are finalized, they should be written and made part of the project document. Table 1 shows the contents of the Project Functional Specifications that should be written and agreed upon before starting to build the simulation model (Phase 5). It is important for the project team to remind itself of the original objectives of the project when processing the remaining steps and phases of the project. Freely changing the objectives of a simulation study throughout the project eventually will cause its failure. Therefore the project team should be reluctant to change the objectives unless they are discussed in detail and the consequences are identified and communicated to the customer.

Table 1. Contents of the Project Functional Specifications

1. Objectives of the Study
2. Issues to be addressed by the Study
3. Scope of Work
4. System (Process) Description
5. Model Assumptions
6. Model Input and Output
7. Project Planning Chart (Gantt Diagram)
8. Responsibilities of the Client

2.2 List the Specific Issues to be Addressed

Often the simulationist is not the engineer who is familiar with the design and operation of the system. By listing all issues the study should address and discussing them with all concerned parties, the simulationist will often gain further insight into the operation of the system. In addition, it is not uncommon for various groups within the client's organization to have different understandings of how the system functions. An early walk-through meeting with all interested parties to discuss the flow logic of the operations of the system will clarify the specific issues that the study should address. At this step, the client should specify the minimum and maximum values of the variables to be considered.

The itemized list of issues to be addressed by the study should be documented together with the objectives of the study as part of the Project Functional Specifications. For example, in a study to find the best number of AGVs in a material handling system, the issues to be addressed may include the AGV routing criteria, AGV speeds, idle AGV logic, AGV battery recharge policies. etc.

2.3 Determine the Boundary or Domain of the Study

The objectives of the study together with the specific issues to be addressed by the study identify the information required from the simulation model as well as the inputs and components needed by the model in order to generate the required output information. The task of determining which components of the real system to include and exclude from the simulation model requires both insight on how the real system operates and experience in simulation modeling. A good method is to make a list of all components in the real system and identify those needed for the simulation model. For example, for the AGV material handling study one may include the following components of the real system: stations to be visited by the AGVs in order to pick up or drop parts, AGV path, and AGV battery recharge stations.

Each component of the real system to be included as part of the model is identified in a manner such that the modeler and the project team agree that the component may have a significant direct or indirect effect on the simulation model output. Each component's effect on the other components of the system should be discussed before finalizing the list of components to be included in the model. Model boundary should be kept at a minimum in the beginning of the study and it should be extended later in the study only if crucial system behavior can not be exhibited by the model.

2.4 Determine the Level of Detail or Proper Abstraction Level

The model should include enough information to get confident answers for the specific questions asked from the study. In many cases, the availability of data and time, experience of the modeler, animation requirements, and expectations of the client are more dominant factors in determining the level of detail than the specific issues to be addressed by the study. The objective of the modeler should be to build the highest-level macro model that will satisfy the objectives of the study. For example, for the AGV material handling study, the manufacturing cells that request the AGVs to drop and pick up parts may be modeled as black boxes. Each manufacturing cell can be described with one interarrival distribution for AGV pickup requests and another interarrival distribution for AGV retrieval requests. On the other hand, in a more complex AGV study where there are synchronization issues among the manufacturing cells, one may need to describe in detail the schedule of operations at each cell.

The broad or macro-level assumptions of the model decided at this step of the process are influenced equally by the objectives of the study and by the availability of resources (time, personnel, and funds) for the project. In some cases, lack of time may force the modeler to build a macro level model that satisfies only a subset of the original objectives of the study.

2.5 Determine If a Simulation Model is Actually Needed; Will an Analytical Method Work?

The experience of the modeler with analytical techniques is very crucial for this step. In many cases, spreadsheet analysis, mathematical programming and optimization approaches such as linear programming and branch and bound technique, or statistical modeling techniques such as regression modeling may be more appropriate to use than simulation. For example, if the objective of the AGV study is to determine the number of AGVs in the system, a number of analytical models are available for this purpose and they work well for relatively simple systems (Wilhelm and Evans (1988), Maxwell and Muckstadt (1982), Ulgen and Kedia (1991)).

The appropriateness of an analytical model for the study may not be easy to identify at the first phase of the study but may become evident as late as at the fifth phase of the study while the simulation model is being developed. In many cases, the availability of analytical models for the simplified version of the system can be useful in validating the simulation model later in the study.

2.6 Estimate the Required Resources Needed to Do the Study

Estimating how long a project will take and which resources will be used for the study is an important step. The detailed list of tasks to be performed in the study, the duration of each task, the resources to be used for each task and cost of each resource are needed in order to make a sound estimate of the resource requirements of the whole project. Level of detail and availability of data in the proper form are important factors in determining the time and type of resources required for the study. Availability of historical data from prior simulation projects can increase the confidence in the estimated resource levels, timing and cost of the project. A PERT analysis that gives the minimum, mode, and maximum duration for each task can be useful in estimating the total project time at different levels of confidence.

2.7 Perform a Cost-Benefit Analysis

This process need not be an extended formal process but it should be performed as a check-point in any study. A simple cost-benefit calculation for the study may also aid the modeler in determining the proper level of detail to include in the model. For example, for the AGV study, it would be wasteful to spend $20,000 of additional modeling time to decide if faster AGVs are better for the system when the total incremental cost of the faster AGVs is less than $20,000. The project team should consider the whole life-cycle of the system and all the relevant cost components in the cost-benefit analysis.
It is common to observe a cost-benefit ratio of one to one-hundred to one to one-thousand from a typical simulation study when one looks at the total benefits gained throughout the life of the system.

2.8 Create a Planning Chart of the Proposed Project

Simulation projects can easily get out of hand, especially if the rate of change in the scope of the project exceeds the rate at which the results are available to the clients of the project. A Gantt chart showing the tasks with milestone points can help control the project. Figure 1 shows a Gantt chart for the major phases of a simulation study. A detailed chart showing all the steps of the major phases of the study and the resources required at each of these steps increases the accuracy of the plan. A detailed Gantt chart with resource scheduling also identifies the contribution and importance of the client to the different steps of the project.

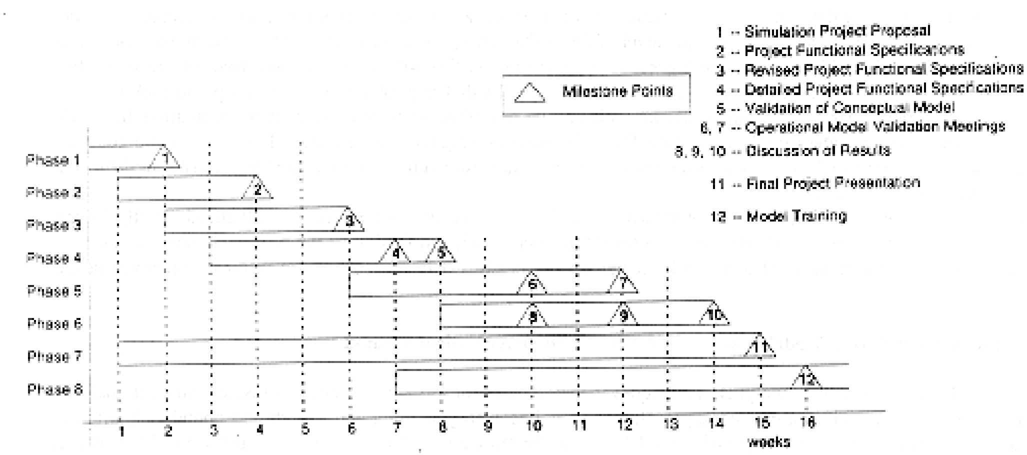

Figure 1. A Gantt Chart Showing the Major Phases of a Simulation Study

2.9 Write a Formal Proposal

The information gathered at the previous steps of this phase should be summarized in a formal proposal format to the client. If the proposal is for an outside client, it may also include sections on background of the simulation company, itemized cost and duration of the phases of the project, payment terms, and warranty. Table 2 shows the outline of a formal proposal written for an outside client of a simulation company.

Table 2. Contents of a Proposal for a Simulation Project

1. Introduction
2. Objectives and Scope of Work
3. Model Assumptions
4. Model Input and Output
5. Company Background
6. Role of Client Company
7. Project Timing
8. Project Cost
9. Payment Terms
10. Warranty

3. DESIGN THE STUDY

The design of the study is the second major phase of the simulation process. In this phase, some steps of the previous phase are investigated in more detail and the technical aspects of the problem are given more weight. One or two meetings for information gathering and observing the actual or similar process is generally conducted during this phase. The project team discusses issues in detail with the line engineers and operators in these meetings. This phase includes the following steps:

Step 1. Estimate the life cycle of the model.
Step 2. List broad assumptions.
Step 3. Estimate the number of models required.
Step 4. Determine the animation requirements.
Step 5. Select the tool.
Step 6. Determine the level of data available and what data is needed.
Step 7. Determine the human requirements and skill levels.
Step 8. Determine the audience (usually more than one level of management).
Step 9. Identify the deliverables.
Step 10. Determine the priority of this study in relationship to other studies. Step 11. Set milestone dates.
Step 12. Write the Project Functional Specifications.

The information gathered at the end of this phase of the project is documented in the Project Functional Specifications. The project team may change the project timing and resource requirements based on the new information available at the end of this phase of the project.

3.1 Estimate the Life Cycle of the Model

The simulation model can be used just to gather the necessary information to solve a problem, as a training tool, both as a training tool and for solving a problem, or as an on-going scheduling tool, etc. Each of these uses will affect how the model should be created. For example, for the AGV study, a simple animation may be sufficient if the model is not going to be used for training purposes too.

3.2 List Broad Assumptions

The broad or macro level assumptions are finalized at this step. Which components of the real system will be excluded, included as a black box, included in moderate detail, or included in fine detail is decided at this step. It is important to keep a formal list of broad assumptions throughout the study, starting at the design phase, since the scope of work and the micro level assumptions to be made in model building will depend on them. These assumptions should be kept in mind all through the process and included in the Final Report. A trap which many modelers may fall into is waiting until the end of the study to record

record their assumptions: by then, they may have forgotten many of them and wasted a lot of time in inadvertently changing the scope of work throughout the process.

3.3 Estimate the Number of Models Required

The models in a study are developed in stages, each model representing an alternate solution for the problem. The first model developed is generally labeled as the Base Model, followed by Alternate Model 1, Alternate Model 2, etc. Each model may be tested under different variations of its parameters. For example, for the AGV study, the Base Model may be an AGV system that serves four manufacturing cells while Alternate Model 1 may be the one where AGVs serve six manufacturing cells. Each model may be tested under different number of AGVs, AGV speeds, and AGV dispatching rules. For the same example, Alternate Models 2 and 3 may be a system where conveyors are used instead of AGVs for material handling among the four and six manufacturing cell configurations.

In some studies the number of models may be well-defined at the beginning of the study including the number of variations of their parameters to be tested while in others the alternate models are considered only if the previous models do perform unsatisfactorily. If the latter, the project team should assume a certain number of models for the project and proceed with the process.

3.4 Determine the Animation Requirements

Animation is an important tool in the simulation process and is utilized during model verification and validation, in selling of the simulation results to management, in generating new ideas for the design and operation of a system, and for training. Different detail levels of animation may be required for different purposes. 3-D detailed animation may be required in a detailed engineering verification simulation study for the conveyor systems of a paint shop or the layout of a robot cell. On the other hand, a simple (or no) animation may suffice in a simulation study for identifying the number of AGVs required to serve four stations in a cellular manufacturing plant.

3.5 Select the Tool

Selecting the best simulation tool for the study depends on many factors including the life-cycle of the project, tools the client currently owns, tools the simulation group has experience with, the animation requirements of the study, the detail level of the study, and the system considered in the study. Sometimes trying to force a simulation tool to perform beyond its designed intentions may add more time and cost to the process and slow down the execution of the model considerably. The project team should weigh all these factors before selecting the simulation tool for the study.

3.6 Determine the Level of Data Available and What Data is Needed

Data collection activities may take a lot of time in a study and it is important that the modeler get involved early in setting up the data collection plans for the study. The modeler should examine all the data available and learn how and when it was collected. The modeler should check if macro or summary level data is available on all stochastic processes in the system. Before deciding whether to collect any more data, the modeler should assess how crucial the missing data may be for the study. Based on experience, if it is decided to collect data on some process, the actual data collection should be started only if there is no macro data available or experts disagree on estimates for the process. Even in such a case, the data collection should be at a macro level initially. Detailed data collection should be made only after the simulation model has been used to verify that the data is crucial for the study (Phase 6).

3.7 Determine the Human Requirements and Skill Levels

The human requirements in a simulation study are due to (1) interaction with people familiar in management of the system, (2) interaction with people familiar with the engineering details of the system, (3) modeler(s) familiar with the simulation tool to be used as well as experience with modeling similar type of systems, and (4) data collection required by the study. It is best to have an engineer and an engineering manager from the client's company be part of the simulation project team. In some studies, due to time limitations of the project, one may need to divide the modeling tasks among several modelers. It is important for a simulation manager to understand the limitations and strengths of the modelers in the project team. Data collection for a study may be done directly by the modeler(s), engineers familiar with the system, or by a third party. It is important that the modeler and data collection people meet and plan for the procedure to use for data collection. The modeler should visit the site of data collection and observe the data collection process if he or she is not involved in collecting the data directly.

3.8 Determine the Audience (Usually More Than One Level of Management)

It is very important to include the highest level of management possible from the client company in the modeling process. Many times each level of management has a different agenda and will require different types of information from the model. A good_method is to informally record the information needed by each level of management from the client's organization and address these somewhere in the final report. If the study addresses as many issues as possible for these managers even though these managers may not be the direct customers of the project, the credibility and success rate of the project will increase.

3.9 Identify the Deliverables

Deliverables of a simulation study may include deliverables in report and file form as well as deliverables such as model--specific or generic simulation training, and customized user interfaces for model input and output. Deliverables in report or file form include Project Functional Specifications, Final Project Report, simulation and animation model and experimental files for different models, Project Book, raw data collection files, detailed model output files, customized input and output user interfaces, User Manual, and Maintenance Manual. In most cases, the Final Project Report coupled with or containing the Project Functional Specifications will be the deliverables of the project. Other items may be required only if the client requested a model to be used for training and/or for periodic decision-making by the client in the future (long life-cycle models). Project Book is basically a project diary that includes all the information about the project including the minutes of the meetings of the project team, the details of the verification and validation runs, and approved project scope change forms as well as the Project Proposal, Project Functional Specifications, Final Project Report, etc. Project Book is generally kept by the simulation group but may be delivered to the client if requested. Other report and file type deliverables of a study are explained in Phase 7 of the process.

Specific project model training and generic simulation training are deliverables that are common for long life-cycle simulation modeling. Development and training in customized input and output user interfaces in Excel-type spreadsheet formats are popular for long life-cycle simulation studies too.

3.10 Determine the Priority of This Study in Relationship to Other Studies

Realistic delivery dates can play an important role in a simulation study. Simulation modeling can lose its credibility with management if the results are not delivered on time. The project team should be sensitive to the timing requirements of the project while the client should give enough time to the project team so that the proper verification and validation techniques are applied in the study, The current loading of the simulation group and the timing requirements of each project should be balanced using resource- scheduling project management techniques before establishing the delivery dates of a new project (Ulgen, 1992). When the delivery dates cannot be satisfied, higher priority projects should be identified based only on the cost-benefit ratios of each project. This can be a problem especially with the in-house simulation groups in a company where higher priority projects may readily preempt the lower priority projects based on a number of factors other than cost--benefit ratio. Sound application of project management techniques coupled with management interpersonal skills of the simulation group manager should help alleviate the effects of changing priorities in a multi-project environment.

3.11 Set Milestone Dates

All the major activities of a project should be monitored carefully to satisfy the final delivery date of the project. It is important to establish 4-5 milestone dates with deliverables throughout the simulation process to facilitate timely delivery of the project results to the decision-makers. Typical milestone events in a simulation project may include completion of the Functional Project Specifications, Macro model results, input data collection and analysis, Base Model validation, Base model final results, Alternate Model validation, Alternate Model final results, and Final Report. If dates on these milestone events are set realistically and adhered closely throughout the project, the project will more likely be a successful one.

3.12 Write the Project Functional Specifications

The Project Functional Specifications is a report that includes all the information covered so far. Table 1 gave the content of such a report. The specification is a document that sets the rules of managing the project through its life. Although this document is at a macro level at this phase of the project, during the following two phases (Phases 3 and 4) of the project, more detail is added to it to make it a major resource for other phases and documents of the project. The project team should not proceed with the project until the Project Functional Specifications report is fully accepted by the client. This document is also the major source of information for the warranty of the simulation model after the project is completed.

4. DESIGN THE CONCEPTUAL MODEL

The modeling strategy to be used in the study is the third phase of the simulation process. Modeling strategy involves making decisions regarding how a system should be represented in terms of the capabilities and elements provided by the chosen simulation tool. The overall strategy should focus on finding a model concept that minimizes the simulation effort while ensuring that all objectives of the project are met and all specific issues are investigated. During this phase of the simulation process, one or two meetings may be held by the members of the project team all together while the simulation manager and modeler(s) have to meet separately to discuss among themselves the modeling details of different real system components within the selected simulation environment. This phase contains the following steps:

Step 1. Decide on continuous, discrete, or combined modeling.
Step 2. Determine the elements that drive the system.
Step 3. Determine the entities that should represent the system elements.
Step 4. Determine the level of detail needed to describe the system components.
Step 5. Determine the graphics requirements of the model.
Step 6. Identify the areas that utilize special control logic.
Step 7. Determine how to collect statistics in the model and communicate results to the customer.

The information that is generated at this phase of the project may be used to update the Project Functional Specifications and create the Maintenance Manual, if one is requested by the client. In any case, this information should be documented in the Project Book as part of the modeling notes.

4.1 Decide on Continuous, Discrete, or Combined Modeling

In a continuous model, the system state variables change continuously in time and difference or differential equations are used to describe the state variables. On the other hand, in a discrete-event model, the state variables change values at discrete points in time and their values stay constant between event times, In a combined discrete-continuous model, variables of both types are used to describe the system. In many cases, one may use a discrete model for a continuous system or vice versa. The modeler, based on the objectives of the study and the detail level required, should choose the appropriate type of model for the real system. For example, for the AGV study, the movement of the AGVs may be described in terms of continuous variables while the pickup and drop operations may be described as discrete events.

4.2 Determine the Elements That Drive the System

Some of the elements (parts, people) in a system are dynamic in nature, in the sense that they move through the system causing other entities to react to them in response to some signal. Other elements are static in nature in a sense that they wait for the dynamic entities or resources to act upon them and pull or push them through the system. The modeler, considering the complexity, size, and detail level of the model, decides which elements should drive the system. One may classify models as part(entity)-driven or resource(machine)-driven models. In part-driven models, the parts are dynamic and they move from one resource to another as resources become available. On the other hand, in resource-driven models, resources pick the parts that they want to serve and send them to their next resource after completion. It is generally easier to build part-driven models. Resource-driven models are generally recommended if there are too many parts in the system or the resource allocation logic is very complex. It is possible to have models with both part and resource-driven characteristics. For example, for the AGV study, the movement of parts in a manufacturing cell can be modeled with the part-driven approach while the movement of AGVs can be modeled using the resource-driven approach.

4.3 Determine the Entities That Should Represent the System Elements

Each simulation tool makes its own finite types of entities available to the modeler to be used to represent the real system components. Examples of entities available in a simulation language or simulator include generic entities, AGVs, conveyors, generic transporters, cranes, statistic - gathering entities, resource schedulers, etc. Often it is possible to model a particular system element in more than one way and, just as often, there may be no exact representation of that element available within the simulation tool. As an example, pallets in a machining system could be modeled as parts on a conveyor or as AGVs on a track. For the AGV study, an exact mapping of the real elements to simulated elements may exist. The parts in

the real system can be modeled as generic entities of the simulator and the AGVs of the real system can be represented by the AGVs of the simulator.

In some studies, dummy resources and entities may have to be defined in the model to represent decision making processes of the real system. As an example, the logic for the AGV breakdowns of the real system may be modeled using a dummy AGV downtime entity for each AGV in the model.

4.4 Determine the Level of Detail Needed to Describe the System Components

The model detail is further discussed at this step by identifying the simulation tool constructs to be used to represent each real system component. The level of detail put into a model should depend mainly on the objectives of the study. It is not always easy to eliminate the unnecessary detail since the customer may question the validity of the model if the components are not modeled in detail. It is recommended that the detail should be added to a model in stages starting with a simple macro level model of the system. For each black box that will be used to represent a system component, the modeler should list the reasons why a black box is going to be used in the model. The reasons may include lack of time, perceived indifference of the output measures to the component, the objectives of the study, lack of data, and cost of modeling.

4.5 Determine the Graphics Requirements of the Model

The animation requirements of the model are discussed in detail at this step by considering factors such as animation expectations of the client, execution speed of the animated simulation model, use of animation as a verification tool, use of animation as a selling tool, ease of building the static and dynamic animation components, and the availability of built-in icons in the animation library.

4.6 Identify the Areas That Utilize Special Control Logic

Systems with multiple machines or servers may require complex decision-making and control logic. During this step, the modeler discusses the best way of modeling the complex decision-making processes in the system. For the AGV study, the modeler may decide that the built-in AGV dispatching rules in the simulation tool do not adequately represent the dispatching logic to be used by the real system. In order to model the system properly, the modeler may have to write the AGV dispatching rules in a lower-level language such as FORTRAN and this may add 20 more hours to the length of the project.

4.7 Determine How to Collect Statistics in the Model and Communicate Results to the Customer

All the simulation tools produce standard output reports that may or may not readily translate into useful information for the customer. The modeler may need to define variables, counters, histograms, time series, pie charts, etc. to collect the appropriate data in a form that communicates the results effectively to the client. In many cases, the modeler may need to write user interfaces in a spreadsheet program to summarize the output data.

5. FORMULATE INPUTS, ASSUMPTIONS, AND PROCESS DEFINITION

The formulation of the model inputs, assumptions, and the process definition is the fourth phase of the process. At this phase, the modeler describes in detail the operating logic of the system and performs data collection and analysis tasks. This phase includes the following steps:

Step 1. Specify to operating philosophy of the system.
Step 2. Describe the physical constraints of the system.
Step 3. Describe the creation and termination of dynamic elements.
Step 4. Describe the process in detail.
Step 5. Obtain the operation specifications.
Step 6. Obtain the material handling specifications.
Step 7. List all the assumptions.
Step 8. Analyze the input data.
Step 9. Specify the runtime parameters.
Step 10. Write the detailed Project Functional Specifications.
Step 11. Validate the conceptual model.

The information gathered in this phase of the study completes all the background information required to build the simulation model. Based on the previous phase (Phase 3) that identified the conceptual model design, this phase compiles the appropriate information for that conceptual model. This information can be integrated into a detailed Project Functional Specifications as well as into the Maintenance Manual (if any), Project Book, and the model code.

5.1 Specify the Operating Philosophy of the System

Operating philosophy describes the way that the management runs or intends to run the system. The issues considered include the number of shifts per day, the length of each shift, shift-end policies, scheduled breaks for workers and machines, strip logic for some machines, setup time, tool change, repair policies, off-line storage policies, production batch sizes and sequence, etc. For example, for the AGV study, at the end of each shift, all the AGVs should be returned to the recharging area after all the shift demands for AGVs have been satisfied. Description of these policies in detail should be documented as part of the Project Functional Specifications.

5.2 Describe the Physical Constraints of the System

Physical constraints refer to those studies where layout options exist for the placement of material handling equipment, machines, and storages. In "green field" systems, one may have more options in number, type and placement of equipment, machines and storages. For existing systems, options may be limited on the placement of the new equipment in the system. For example, for the AGV study, the locations of the manufacturing cells and the AGV path may be fixed.

5.3 Describe the Creation and Termination of Dynamic Elements

Once the dynamic elements of the model have been identified in the previous phase of the process, in this phase, the detailed logic of entry and exit of the dynamic elements is considered. Issues to be finalized include existence of infinite buffers before the first and after the last processors in the system and the logic to be used in arrival of entities to the system. For multiple dynamic elements case, arrival rates of each entity type, batch size, changeover time on processors and scrap and repair rates of each entity type have to be specified. For the AGV study, the stations where parts arrive to the system and the stations where parts leave the system as well as the interarrival of parts and interremoval of parts from the entry and exit stations respectively have to be specified.

5.4 Describe the Process in Detail

The process flow and the logic describing that flow as entities move through the system have to be specified in detail. The priority assignments for the entities as they compete for the resources and vice versa have to described. Repair entity logic and priorities should be identified. For example, for the AGVstudy, when there are two or more parts to be picked up at different pickup stations, which part should be given priority when an AGV becomes available? Similarly, when two or more AGVs are available and a part enters a pickup station, which AGV should be selected to pick up the part? Process description at this level of detail should be documented in the model code as well as in the detailed version of the Project Functional Specifications.

5.5 Obtain the Operation Specifications

Operation specifications include data for each operation in the model including processing time, downtime distribution, percentage down, scrap and reject rate, setup time, capacity, etc. "Operation" in this case may refer to machining or service operations but excludes the material handling and storage activities in the system. For example, in the AGV study, the manufacturing cell operations and cell downtime characteristics constitute the operation specifications.

5.6 Obtain the Material Handling Specifications

Material handling specifications include data for each type of material handling equipment in the model including transfer times in terms of acceleration, deceleration, minimum and maximum speeds, downtime distribution, percentage down, capacity, pickup and drop times, etc. For the AGV study, station drop and pickup times, AGV maximum velocity, acceleration deceleration, capacity, recharge time, time between recharges, minimum distance between AGVs, downtime percentage and distribution constitute the material handling specifications.

5.7 List All the Assumptions

All the macro and micro level assumptions of the model are summarized at this step. This includes assumptions regarding the behavior of model components, input data, model detail level, startup conditions of the model. etc. For example, for the AGV study, representing manufacturing cells with two distributions, one for retrieval interarrival times and one for the pickup interarrival times is a macro level assumption. On the other hand, ignoring AGV acceleration and deceleration times in the model is a micro level assumption.

5.8 Analyze the Input Data

Input data should be analyzed and tested for reasonableness by the project team and line engineers and operators. Patterns in data should be identified, if any, and incorporated as part of input data generation. Theoretical distributions should be fitted to actual data and used in the model whenever possible (Law). For the AGV study, time between part retrieval and pickup requests at a cell, time between AGV recharges, time between AGV breakdowns and time to repair an AGV are examples of input data that need to be analyzed and fitted before usage in the model.

5.9 Specify the Runtime Parameters

Runtime parameters are the variables whose values are to be changed from one simulation run to another in the study. For example, for the AGV study, in the Base Model analysis, one may need to observe the effects of different AGV speeds, number of AGVs, and AGV recharge times on the throughput of the system. Runtime parameters may be assigned for the Base Model as well as the Alternate Models of the system. The project team should also identify the opportunities for design of experiments at this point in the process.

5.10 Write the Detailed Project Functional Specifications

The detailed information gathered at the previous and current phases of the project should be used to update the Project Functional Specifications. This information should further be incorporated into the Maintenance Manual, model code, and the Final Project Report. By default, the information should be in the Project Book too. The detailed version of the Project Functional Specifications should be read carefully by the client engineers familiar with the system and corrected, if necessary.

5.11 Validate the Conceptual Model

Acceptance of the model assumptions, operating philosophy, process flow, operation and material handling specifications, input data analysis, and runtime parameters by the client implies that the client validates the conceptual model of the modeler(s). Figure 2 shows the relationship between the conceptual validation, verification, and operational validation of a model. A rigorous validation procedure for the conceptual model as discussed here is as important as the verification and operational validation of the model because, being earlier than the others, it saves time and redirects the project team in the right direction before a lot of time is wasted in the study.

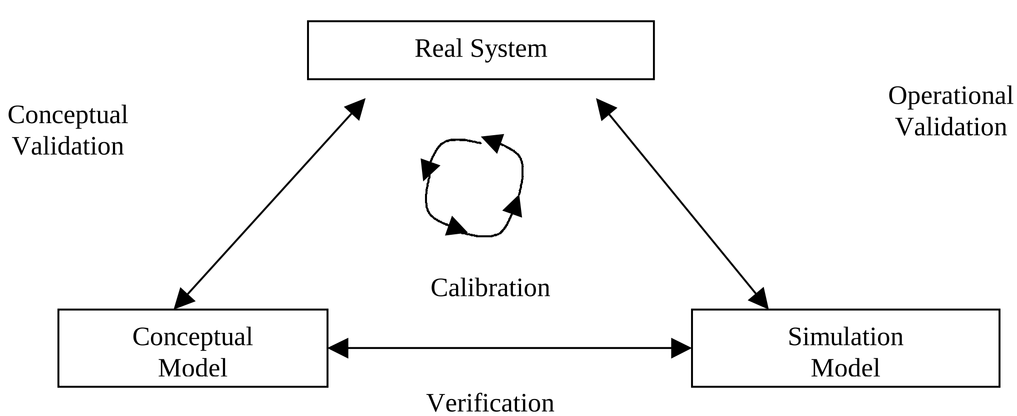

Figure 2. Conceptual Validation, Verification, and Operational Validation in Simulation.

6. BUILD, VERIFY, AND VALIDATE THE SIMULATION MODEL

The building of the model, its verification, and operational validation constitute the fifth phase of the simulation process. At this phase, the modeler uses well-known software techniques for model building, verification and validation. Thirty to forty percent of the simulation process may take place at this phase and has to be repeated for each major Alternate Model to be considered in the study. During this phase, the modeler meets two to three times with the project team and line engineers and operators of the real system. This phase includes the following guidelines:

1. Beware of the tool limitations.
2. Construct flow diagrams as needed.
3. Use modular techniques of model building, verification, and validation.
4. Reuse existing code as much as possible.
5. Make verification runs using deterministic data and trace as needed.
6. Use proper naming conventions.
7. Use macros as much as possible.
8. Use structured programming techniques.
9. Document the model code as model is built.
10. Walk through the logic or code with the client.
11. Set up official model validation meetings.
12. Perform input-output validation.
13. Calibrate the model, if necessary.

The model obtained at the end of this phase of the study is ready for experimentation in the next phase of the study. At this phase of the study, the project team may decide to collect more data and add more detail to the model as part of the calibration requirements of the model. Since the practical aspects of this phase of the process are well documented elsewhere (Balci (1989), Balci (1990), Banks and Carson (1990), Law and Kelton (1991)), we won't discuss this phase further.

7. EXPERIMENT WITH THE MODEL AND LOOK FOR OPPORTUNITIES FOR DESIGN OF EXPERIMENTS

Experimentation with the model and applying the design of experiments techniques constitute the sixth phase of the simulation process. At this phase, the project team may decide to investigate other Alternative Models and go back to the previous phases of the process for each major model change. During this phase, rather than building a design of experiments for the whole study, the modeler generally identifies the major variables and eliminates the insignificant variables one step at a time. Once a few major variables are identified, a design of experiment ' s study may be conducted in detail, especially if the study has a long-life cycle. The project team meets with the clients of the model as major results become available, and the client is expected to play a major role in identifying the new parameter values to be tested in the study. One of the objectives of this phase is to involve the client as much as possible in the evaluation of the output under different conditions so that the behavioral characteristics of the system as modeled are well understood by the client. The steps of this phase are as follows:

Step 1. Make a pilot run to determine warm-up and steady-state periods.
Step 2. Identify the major variables by changing one variable at a time for several scenarios.
Step 3. Perform design of experiments if needed.
Step 4. Build confidence intervals for output data.
Step 5. Apply variance reduction techniques whenever possible.
Step 6. Build confidence intervals when comparing alternatives.
Step 7. Analyze the results and identify cause and effect relations among input and output variables.

This phase of the process is well documented in the literature (Banks and Carson (1990), Law and Kelton (1991)) and won't be discussed further here.

8. DOCUMENTATION AND PRESENTATION

Project documentation and presentation is the seventh phase of the simulation process. Good documentation and presentation play a key role in the success of a simulation study. The tasks of this phase are performed in parallel to the tasks of other phases of the process. The important factors that should be considered at this phase are that (a) different levels of documentation and presentation are generally required for a project, (b) long-term use of models requires better model documentation. (c) selling simulation to others require bottom-line measures (e.g., cost savings) to be highlighted as part of the project presentation, and (d) output values from the simulation should be supported with the factors causing those results. This phase includes the following elements of documentation:

1. Project Book.
2. Documentation of model input, code, and output.
3. Project Functional Specifications.
4. User Manual.
5. Maintenance Manual.
6. Discussion and explanation of model results.
7. Recommendations for further areas of study.
8. Final Project Report and presentation.

The majority of the tasks of this phase are performed in parallel with the steps of the other phases of the process and should be performed even though the client may be less interested in documentation activities.

8.1 Project Book

The Project Book is the project document folder that keeps all project related information accumulated through the life of the project. Project Proposal, Project Functional Specifications, project team meeting minutes, input data records and files, etc. all belong to this book. Copies of the project program diskettes should be kept with this book too. The book should be kept in the library of Project Books of the simulation group for at least ten years. It can be used if the client requests additional work on the same project later, or for code reuse for similar projects.

8.2 Documentation of Model Input, Code, and Output

Model input and output should be in a form familiar to the client's everyday terminology rather than simulation software's terminology. It is desirable to minimize the model input by the client if the client is eventually going to use the model on a regular basis. Model output should be given in multiple levels of detail to the client, more of it only if the user asks for it. It is desirable in many cases to have all the important input and output of a simulation on one page. Graphical and time-based charts should be used whenever possible for major output variables. Model code should be documented in the client's terminology to facilitate the model validation step.

8.3 Project Functional Specifications

This report, as given in Table 1, may exist in different forms. At the end of Phase 2 (Design the Study), it is first put together based on the initial understanding of the study to allow the client verify the modeler's understanding of the system and the issues to be investigated in the study. In Phases 3 and 4, this report is further enhanced with details of the system, data, and modeling issues such that it becomes the main guide for the model development. It may be incorporated later into the Final Project Report.

8.4 User Manual

This is a manual that is written for users wishing to run the model under different parameter values. It may describe the fields of input data that the user may change, give possible ranges for different input items, and interpret the output data fields. The modeler may develop a user-friendly input and output spreadsheet (e.g., EXCEL) to simplify the model usage by the client.

8.5 Maintenance Manual

This a manual is written for the modeler who may later go back and change the model or use segments of it for different purposes. Model code with detailed documentation including in-line and between-line comments, detailed logic used in the model, naming conventions used in the model, and the purpose of each major program segment are generally included in this manual.

8.6 Discussion and Explanation of Model Results

All results of the study should make sense to the client and the modeler. As model parameters change, the output obtained should make sense to everybody involved in the project. Relating the output values to the input values and other output values should be the goal of the project team and in that way they can have a better understanding of the system. Macro level input-output models can also be obtained from such data (Kleijnen (1987)) to expand the use of the simulation study further. Presentations as well as the Final Project Report should highlight the input and output causality relationships observed by the model.

8.7 Recommendations for Further Areas of Study

In applying simulation methodology to solve a problem, the modelers gain insight into the operational weaknesses and strengths of the process being investigated. These understandings generally suggest ways to improve the system. These should be passed to the client as often and as early as possible throughout the simulation study and listed in terms of recommendations for further study at each project team meeting and presentations. One of the goals of the project should be to have the client learn as much about the nature of the modeled system as the modeler does in the study.

8.8 Final Project Report and Presentation

The Final Project Report is a document that summarizes the entire study and should be designed as a selling tool for simulation in general, the project team, and others involved with the project. Table 3 gives the contents of a Final Project Report. The report should have an Executive Summary section that summarizes the findings of the study in one or two pages. Base and Alternate Model input and output should be delineated in tables, charts, and graphs for ease of comparison. Reports and presentations should use colored graphs and presentations may be highlighted with animation as needed to show the secondary effects of different policies. The presentation should involve the whole project team in some capacity with at least the simulation manager from the simulation group and the client engineering supervisor in the project team giving the presentation as a team.

Table 3. Contents of a Final Project Report

1. Executive Summary
2. Introduction
3. Scope of Work
4. Model Assumptions
5. Model Specifications
6. Model Input
7. Model Output
8. Base Model Description and Results
9. Alternate Model Descriptions and Results
10. Comparison of Results and Discussion
11. Conclusions and Recommendations for Further Study

9. DEFINE THE MODEL LIFE CYCLE

The model life-cycle tasks constitute the eighth and final phase of the simulation process. This phase applies to long-term simulation life-cycle studies where the simulation models are maintained throughout the life of the real system. On the other hand, short-term simulation studies are those where once the simulation results are used in the decision-making, the model is not used any more by the client. Currently, about sixty to seventy percent of the simulation studies can be categorized as short-term studies while the rest are longer term in the way that they will be reused after the initial simulation study has been completed. The long-term simulation studies require a long-time ownership of the model by a modeler and/or engineers that are going to use the model. One may categorize long-term life-cycle models into four categories in terms of use, namely; (a) training, (b) scheduling, (c) system redesign, and (d) launching phase analysis. Training models are built to train client personnel in simulation as part of a simulation class or to familiarize the new personnel in the system. Scheduling models are models such that when the product-mix and batch sizes change, the scheduling rules are tested under the new conditions for best resource utilization and product deliveries. These two categories may require no or minimum modeler follow-up once the model has been transferred to the client.

The models for system redesign and launch phase studies may require a close modeler-and-client-engineer interaction so that the model is not misused. System redesign models are used whenever a change in design of the system is to be implemented. Models that are used for launching phase analysis are those used during system launch to allocate resources (e.g., manpower) effectively in the partial operation of the whole system. In many cases, long-term life-cycle models are used for multiple purposes including all four categories. The long-term life-cycle models require additional tasks as given in the following steps of this phase:

Step 1. Construct user-friendly model input and output interfaces.
Step 2. Determine model and training responsibility.
Step 3. Establish data integrity and collection procedures.
Step 4. Perform field data validation tests.

It is important that the long-term of the model usage should be identified as part of the original objectives of the study because the model design is highly influenced by it. A representative of the long-term users of the model should become a member of the project team right from the beginning of the study.

9.1 Construct User-Friendly Model Input and Output Interfaces

In order to increase the use of the simulation model by non-modelers, spreadsheet-based (e.g., EXCEL) user-interfaces should be developed as part of the model environment. These interfaces should employ the terminology of the user and be designed jointly with the user. The input interfaces should have default values assigned for all the fields with a reference column of original values identified for each data field. The output interface should look like reports familiar to the user and incorporate some of the input data too. Check points should be established in the process to avoid misuse of the tool in terms of building confidence intervals for output and establishing the length of the warm-up and steady-state periods.

9.2 Determine Model and Training Responsibility

The responsibility for model maintenance and training must be assigned to a modeler and/or a user. The users should be directed on the proper use of the model and have their questions answered in a timely manner. The User Manual should describe the objectives and identify the specific issues that the model can address. The input and output fields should be described in detail and the range of expected values for each field should be given. A sample of exercises showing the proper use of the model should be incorporated into the manual as well as a section on the answers to the questions asked mostly by first time users.

It is also important that the successful use of the model should be highlighted in corporate simulation meetings and internal company newsletters circulated to potential users. Unique applications of the model should be incorporated into the User Manual and key model users (champions) at different company locations should be identified.

9.3 Establish Data Integrity and Collection Procedures.

For long life-cycle models it is important that the integrity of the data should be checked through the life of the model usage. Time-sensitive input data should be identified and tested on a regular basis by the person responsible for the model maintenance. Such data may include machine downtime and repair characteristics, product-mix changes, material handling equipment response times, operator dependent processing times, new operator rules, etc. Long term data collection procedures should be established for revalidating the input data of the model through the model life-cycle.

9.4 Perform Field Data Validation Tests

The final model validation should be performed when the actual system or its components are built and the actual output data becomes available under controlled input conditions. As the model is applied to similar systems, a revalidation of the model may be required for the new system. The model maintainer plays an important role in the continuous successful use of the simulation model by emphasizing the scope of the model and revalidating it for each new application during its life cycle.

10. CONCLUSIONS

The successful application of simulation in industry requires a lot of up front work prior to building a computer simulation model. In this paper, we described a simulation methodology based on a rigorous step-wise approach comprising eight major phases for successful application of simulation to solve real-world problems. The roles of project management, teamwork, conceptual model design and validation, model life-cycle, and project documentation are highlighted as factors just as important as the traditionally emphasized factors such as model coding, input and output data analysis, and verification and validation methods used in the study.

11. ACKNOWLEDGMENT

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