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THE USE OF CONTINUOUS/DISCRETE EVENT MODELS IN MANUFACTURING

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INTRODUCTION

A simulation of a manufacturing operation which handles discrete (countable) units of product throughout the system is normally developed as a discrete event model. Continuous modeling more often comes to mind when a product is processed in liquid form as in the refining of chemicals (3), food stuffs (6), or petroleum (4). Continuous concepts can be very useful, however, in discrete but high-volume manufacturing operations. In two recent projects at P&A, and in several projects reported by customers, the ability to combine continuous simulation with discrete elements greatly simplified the formulation of a model. These models all used the SLAM II® simulation language (5), which is designed to accommodate such combined modeling.

THE AUTOMOTIVE PARTS MODEL

System Description

A supplier to the automotive industry planned to install new equipment in order to increase daily production of a small metal part used in automobile assembly. The manufacturing process consists of three steps: pre-heat treat, heat treat, and post-heat treat, as shown in Figure 1. The design of the system is modular in nature, that is, a module produces a part ready for the next step in the process. This concept differs from a process center orientation, where modules perform only one operation in the step.

Pre-heat treat involves six operations in series: grind, turn, grind, bore, drill and gage, and broach. Parts are moved between machines via hard tracks, conveyors which are constantly filled with parts, and deposited on accumulator tables in front of each machine. The objective in simulating pre-heat treat was to determine the number of machines required for each operation in order to achieve the desired production rate. Estimates of input buffer sizes were also needed in order to provide a steady flow of parts between machines. Associated with each machine is a processing rate, in terms of parts per hour, and a failure rate, described as the number of parts between failures.

Parts coming from pre-heat treat are loaded into containers (200 parts per container), which are

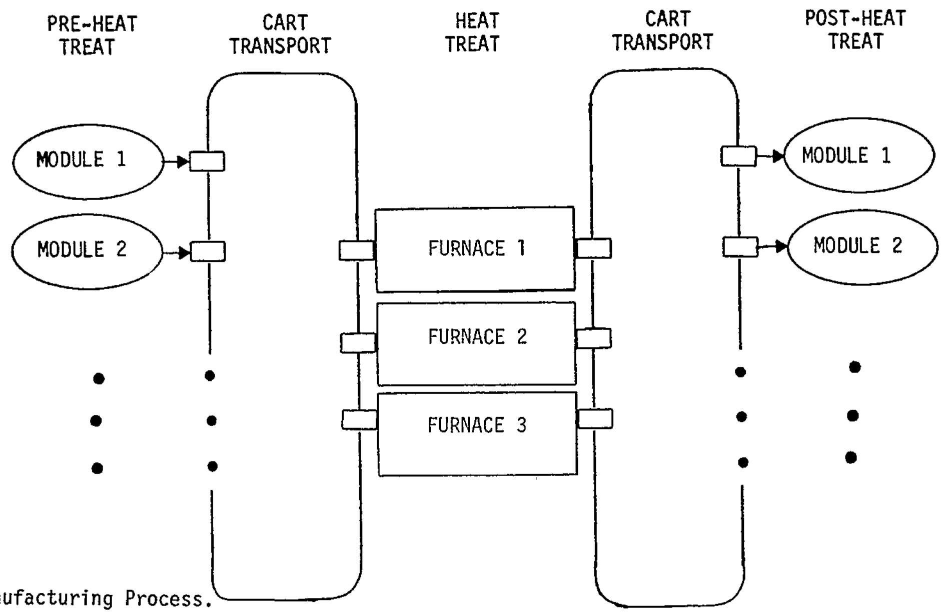


Figure 1. Manufacturing Process.

carried to heat treat via a wire-guided cart. There parts are loaded into one of three furnaces at a rate of 5,000 parts per hour and spend approximately 9 hours in heat treat. A furnace unloads at a rate of 5,000 parts per hour into containers, which travel by another wire-guided cart to post-heat treat as demanded. The objective in simulating heat treat was to determine the number of containers and carts required. Three scenarios were possible: carts holding 1, 20, or 50 containers at a time. Also of interest were the buffer sizes for parts ready to load into furnaces and unloaded parts awaiting demand by post-heat treat.

Post-heat treat involves six operations: tumble, drill, grind, hone, finish, and grind. As with pre-heat treat, hard tracks are used to transport parts between machines, while machine in-feed buffers are accumulator tables. The objective in simulating post-heat treat was identical to that for pre-heat treat, to evaluate machine configuration and buffer sizes.

Model Formulation

Three separate models were developed. The pre-heat treat model generated production data used as supply input to the heat treat model, while the post-heat model generated demand data for the heat treat model. The pre-heat treat model consisted of a set of equations defining the buffer sizes between machines. Each buffer would fill according to the production rate of the preceding machine and empty according to the production rate of the following machine, as illustrated in Figure 2. The level in a given buffer would be updated continuously by SLAM II and could be monitored against size limits. The machine preceding a buffer could be shut down due to a full accumulator table on its output side, an empty accumulator on its input side, or machine failure. In this event the rate of input to the buffer was set to zero. The rate was reset when the interruption ended (the output buffer began to empty, the input buffer began to fill, or the machine was repaired). By developing the model as a set of rate equations, a very compact representation of the system was achieved. The post-heat treat model was developed in the same way.

The heat treat model was driven by data supplied by the first two models. Output from the pre-heat treat model provided a distribution of arrival times for carts supplying the furnaces. A distribution of demands at the furnace was generated by the post-heat treat model. Buffer areas before and after the furnaces, as well as the contents of the furnaces, were represented by continuous variables. These levels changed continuously as the furnaces were filled and emptied. They changed discretely whenever a dropoff cart arrived from pre-heat treat or a pickup cart arrived from post-heat treat.

Simulation Results

This project revealed that the pre-heat treat system being evaluated would not meet the desired production quota. The drill and gage operation was discovered to be the bottleneck, leading to a recommendation that one drill and gage be added for every two modules as a shared resource. The proposed buffer sizes were deemed adequate to handle in-process inventory.

The heat treat model allows for the analysis of various cart capacities (containers per cart) given a production level. The simulation showed that as the number of containers per cart increases, the pre- and post-heat treat buffers increase, the number of containers required to support production increases, and the number of carts required decreases. The simulation also showed that the contents of the three heat treat furnaces (total capacity of 145,000 parts) averaged only about two-thirds capacity. Figure 3 illustrates buffer levels and furnace contents for the 20 containers per cart scenario.

In post-heat treat, the hones were deemed to be the bottleneck. The addition of one hone per module would attain the desired throughput level. As with pre-heat treat, the proposed buffer sizes were adequate to handle inprocess inventory. A comparison of hone buffer size and utilization for six vs. seven hones is shown in Figure 4.

PACKAGING LINE MODEL

High speed/high volume packaging line design presents a common set of issues sensitive to the dynamic interactions of line components, including:

1. The determination of accumulator buffer sizes and machine surge speeds to correctly balance diminishing incremental gains in line efficiency and escalating increments of equipment cost.
2. The quantative evaluation and comparison of alternate line designs and configurations.
3. The design and evaluation of automated control systems and operating strategies.

Simulation offers a systems approach capable of effectively addressing these issues. Further, a continuous flow orientation provides both a precise and concise modeling view.

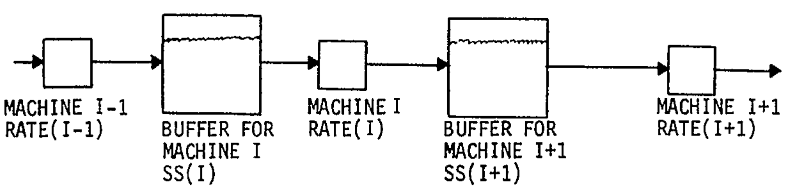


Figure 2. Modeling Buffer Levels.

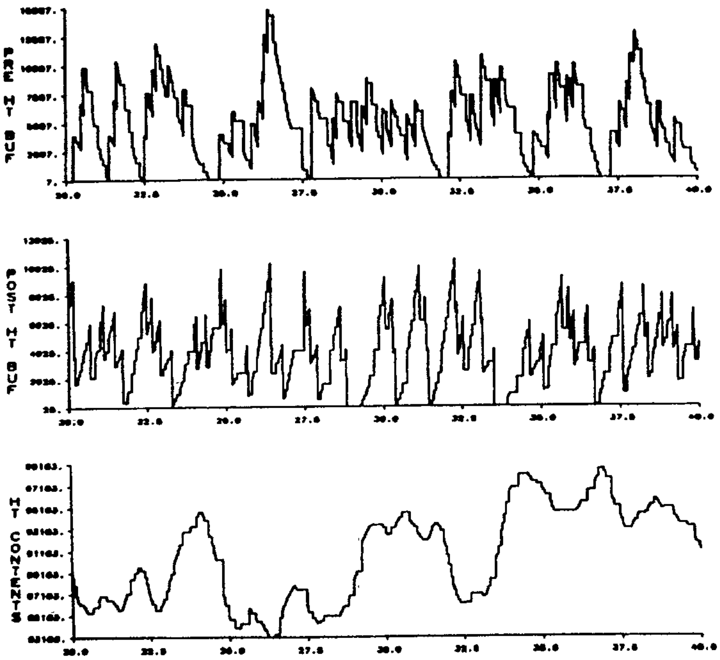


Figure 3. Heat Treat Buffer Levels and Contents

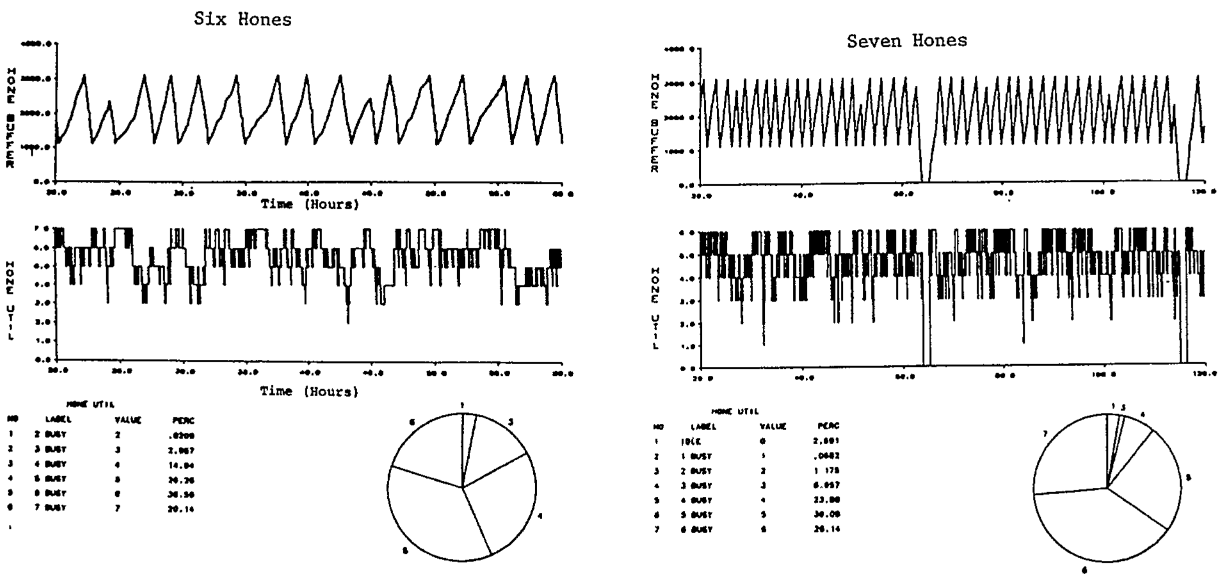


Figure 4. Comparison of Buffer Level and Utilization of Six versus Seven Hones.

System Description

Figure 5 illustrates a high speed/high volume packaging line for purposes of discussion. The line speed (i.e. filler speed) is 600 containers per minute. The depalletizer machine sources the line. Empty containers travel by conveyor to be filled, capped, labeled and cased. Slow speed belt conveyors transport cases to a palletizer for shipping (not shown).

The filler is the critical component in the design since its performance will determine the overall line productivity. The system is therefore designed to minimize filler interrupts. This is accomplished through the application of three design parameters:

Accumulation - Machines are separated by long winding conveyors which serve to accumulate containers in the event of machine interruptions. Buffer capacity may be increased by introducing accumulation tables in-line the conveyor system.

Surge Capacity - Machines up and downstream the filler may operate at higher speeds than the single speed filler. These machines may thereby surge their production rate following periodic interruptions, allowing accumulation buffers to return to their optimum level of effectiveness.

Control System Logistics - The accumulation system may sense critical container populations resulting in an automatic control action. Example actions are: accelerate the upstream machine production; divert containers to a parallel component; etc.

Model Formulation

The aforementioned design issues require a modeling approach which is a precise representation of the dynamic interactions between line components. The model must also be easily adapted to alternative designs, equipment options and control strategies. Finally, it must produce clear and understandable reports allowing the system to be measured and its interactions understood.

A discrete modeling orientation is clearly inefficient and cumbersome due to the high volume/high speed nature of the system. These same qualities make a continuous view particularly well suited to this application. The system may be viewed almost as if the product were a liquid. The accumulator tables behave like tanks in which product is stored; the conveyors are similar to pipelines which transmit product from component to component, and the machines behave like valves which regulate product flow rates.

Careful study of the packaging line problem yields a "generic" approach to model construction. Specifically, a flow graph may be constructed to represent the system in which machines and accumulators are represented as nodes (with appropriate attributes), and conveyors as arcs which imply precedence of operations.

The resulting network is translated into data statements which become the input statements to the SLAM II packaging line model. This approach is useful because it allows line component parameters to be easily adjusted and configurations easily changed.

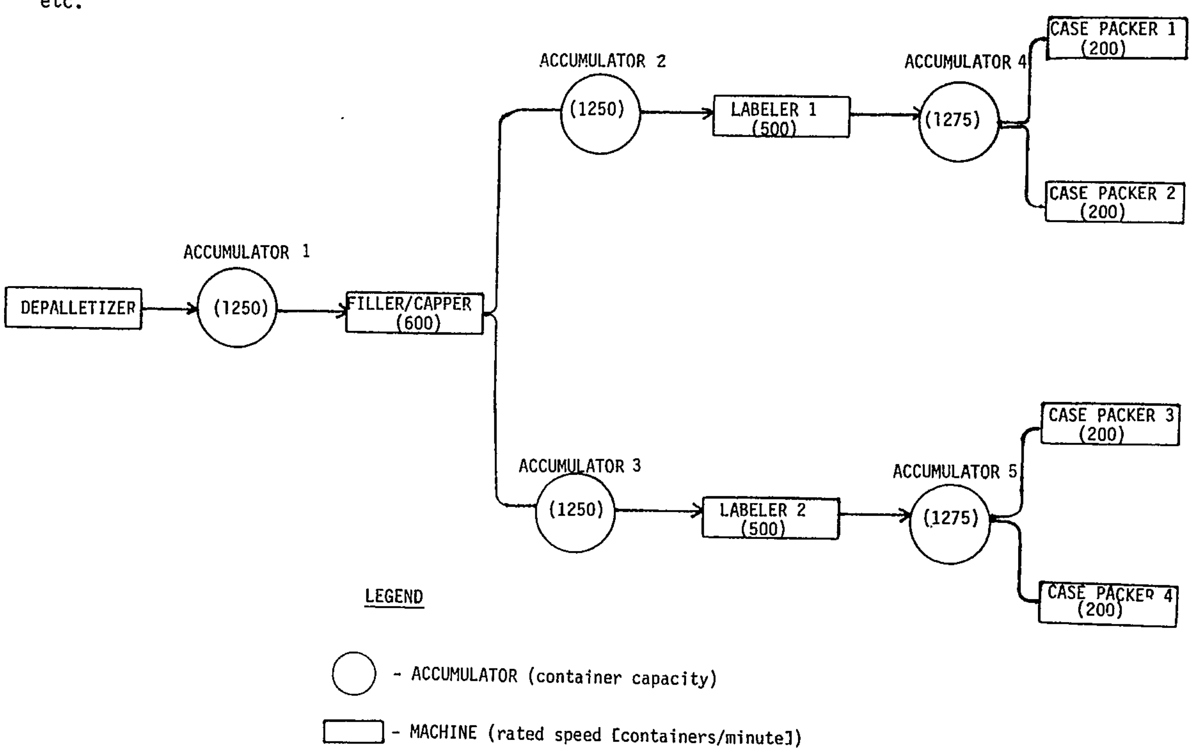


Figure 5. Example Package Line System Configuration.

Machine Dynamics

The "generic" machine component is represented by two rate equations. These equations describe container consumption from infeed conveyors and delivery to discharge conveyors.

$$X_{IN} = (\alpha)\,(\pi_1)\,(\pi_2)\,(\pi_3)$$

$$X_{OUT} = (X_{IN})\,(\beta)\,(\Theta)$$

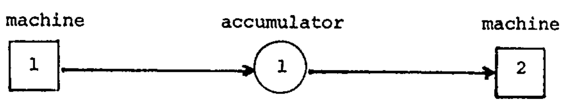
α = speed setting (BPM)
π_1 = prime status (1 = primed 0 = otherwise)
π_2 = block status (0 = blocked 1 = otherwise)
π_3 = service status (1 = available 0 = otherwise)
β = ratio of input to output processing rates
Θ = container survival fraction (i.e. to account for breakage/loss)

Conveyor Dynamics

The "generic" conveyor section is represented by a complement of discrete event procedures. These procedures model the transportation of groups of containers with constant density (i.e. containers per foot) from source to sink component paced by the conveyor speed. Discrete events serve to actuate component "prime" (π_1) and "block" (π_2) status update, as well as other changes to the mathematical basis.

Accumulation Dynamics

Simplistically, the container buffer level between machines is represented as a continuous (difference) equation as illustrated below.



$$y'_{12} = y_{12} + (X_{IN}(1) - X_{OUT}(2))\,\Delta t$$

y'_{12} = container population between machines 1 and 2 at the current time step.

y_{12} = container population at the last accepted time step.

Δt = current time step size.

The buffer level is updated by SLAM II at discrete time steps (i.e.Δt) and compared against a set of threshold values. When crossed from the appropriate direction, a discrete control action is triggered. These actions may, for example, set the speed of machine 2 to high if the container population reaches 75% of capacity; stop machine 1 if the container level reaches capacity; etc.

The SLAM II model results in tabular reports summarizing line efficiencies, accumulator behavior, control system performance, etc. Figure 6 is an example of a time series plot demonstrating the dynamic interactions of line components. In the example, labeler 1 experiences an interruption at time 15 lasting 10 minutes. The plot illustrates the compensating actions initiated by the control system resulting in a relatively small loss of filler productivity.

RESULTS

Use of this approach to packaging line design has provided the tools necessary to accomplish the following goals:

1. Predict - The performance of a design.
2. Compare - A design's performance to competing designs.
3. Understand - The relationship between system components and overall system performance.
4. Improve - The design through better understanding and experimentation.

OTHER APPLICATIONS

The combination of continuous and discrete event modeling concepts is useful in a wide variety of situations. In addition to the models described above and the published references, we have heard of several interesting applications in the SLAM II user community. A sampling follows. The authors wish to thank Dr. Bruce Powell of Westinghouse Electric Corporation, Mr. Michael Gasperi of Allen-Bradley Company, and Mr. Richard McKee of Vitro Corporation for providing information on their applications.

NUCLEAR FUEL PRODUCTION

At Westinghouse Electric Corporation, a SLAM II model was built of a proposed automated facility for the production of nuclear fuel for power plants. Unlike the typical production process, in which discrete units of a product flow through a sequence of operations, the manufacture of fuel involves a combination of continuous and discrete processes. The first step is to convert UF6 gas into mixed oxide powder. The powder is blended, then pressed into small pellets which are loaded into containers for sintering. Finally, after inspection, pellets are loaded into tubes to form final fuel assembly bundles. The model was required to include only a minimum of in-process queuing between operations as well as brief periods of shutdown for equipment adjustment.

During the blending process, the level of powder in each of several blenders was monitored continuously. The following pelleting operation produces many hundreds of pellets per minute, and while not strictly a continuous process, it was modeled as one. Discrete components of the model included the opening and closing of "valves" which were activated when blenders became full or empty. A large part of the model consisted of a network in which containers of pellets were moved from the sintering furnaces through the many inspection and assembly stations. Equipment failure was handled with a small subnetwork which altered the capacity of the proper resource.

The model showed that the initial design very nearly met the production objectives. However, it was pointed out where the system was most sensitive to bottlenecks which could occur if the original estimates of flow rates and equipment adjustment frequency were in error.

ELECTRONIC CIRCUITRY

Allen-Bradley Company is interested in gauging the performance of electronic circuits before actually constructing and testing them. Most modern electronic circuits contain both digital and analog components.

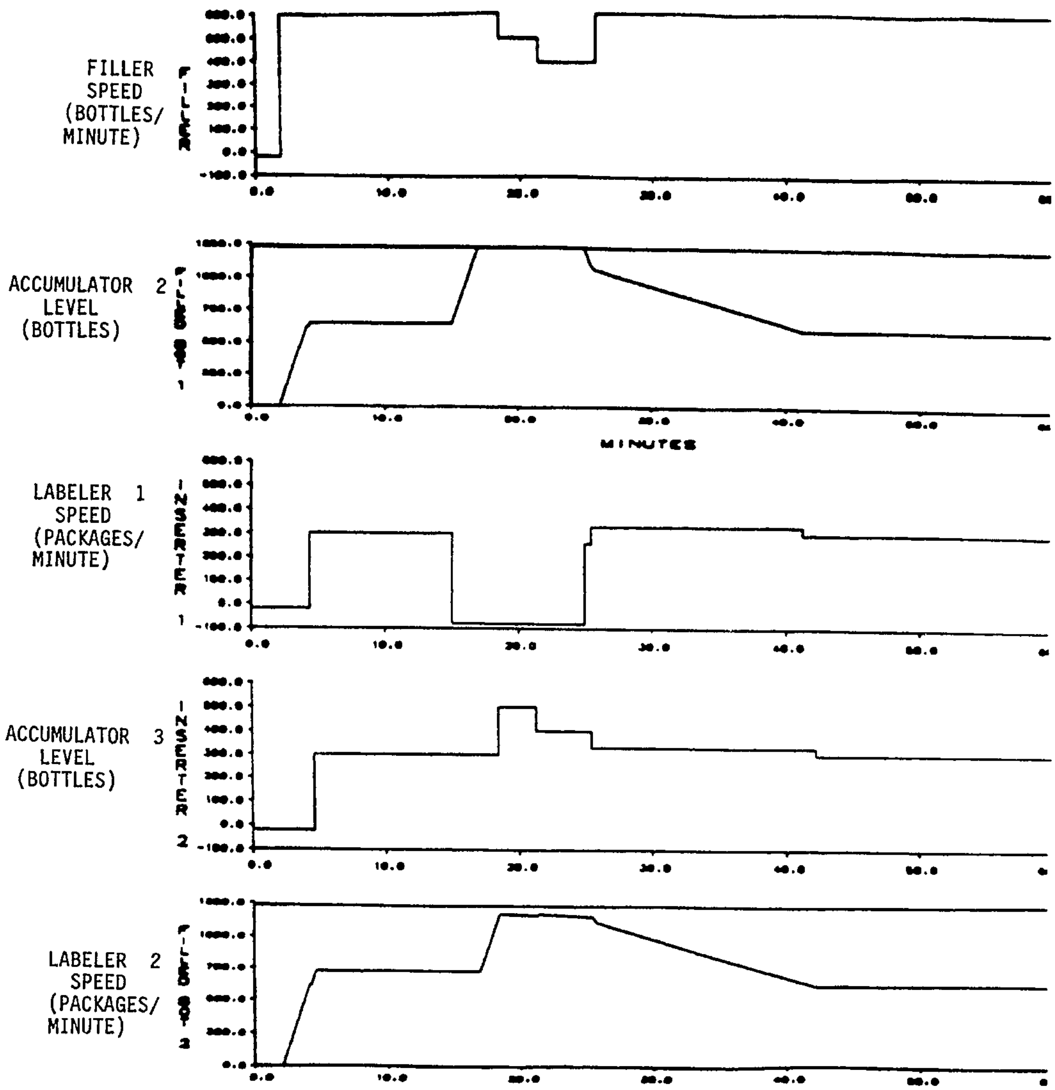


Figure 6. Time Series Plot Illustrating Packaging Component Interactions.

Classical electrical engineering system analysis tools (i.e. Nyquist) can be used for pure analog circuits. However, when digital logic elements are introduced, the analysis becomes too complex. For this reason, a combined continuous/discrete simulation language is used to analyze electronic circuits. They are not modeled with the precise functional detail that would be available with a circuit analysis package (i.e., SPICE), but are treated as blocks that have gain, integrate, compare, count, and so on.

The analog portions of circuits are modeled continuously. Amplifiers, filters, adders, and integrators can be easily modeled with one or more state variables per block. Discrete modeling is used for the digital portion of the circuits and to provide excitation for dynamic response measurements.

Circuits have threshold points that cause gains to be altered or voltage levels to be set to known values. Also, circuits are often paced by a periodic clock signal that can be provided with SLAM II network elements.

COMBAT OPERATIONS

Combined modeling is used quite often to represent a combat system, where the location of attackers and defenders is critical to the simulation. Vitro Corporation has developed an antisubmarine warfare model to simulate the combat performance of any surface ship. The user of the model specifies the attributes of his force, such as course, speed, escort position, weapons effectiveness, and detection mechanisms (radar, sonar). A mix of targets