Proceedings of the 1992 Winter Simulation Conference
ed. J. J. Swain, D. Goldsman, R. C. Crain, and J. R. Wilson

A SIMULATION-BASED DECISION SUPPORT SYSTEM FOR A SPECIALTY CHEMICALS PRODUCTION PLANT

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ABSTRACT

The subject of this paper is the development of an interactive simulation-based decision support system for a batch processing facility. This system is a decision-making tool that can be used by both the production scheduler and the production staff to help them in both long and short-term scheduling of production and equipment and in capacity planning.

Simulation has been combined with artificial intelligence methodology to produce an interactive, simulation-based decision support system that can be used in an on-line or off-line mode. Off line, the system can be used for long-term capacity and debottlenecking studies. Operated on line, the model can be used for short-term planning, scheduling, and decision-making. The different modules of the system interface with the user in a menu-driven format, collect work-in-process information from the plant's distributed control system, run simulations, and provide interpretations of the results in an easy-to-understand format.

1 INTRODUCTION

A drive to achieve manufacturing excellence is under way within the specialty chemicals industry. Components of this objective include improving capabilities for efficient technical and market information processing; responding quickly to changes in market demands and to the introduction of new products; reducing the time-consuming and costly overhead associated with documentation, recordkeeping, and safety; and coordinating the activities of operating and management personnel, scientists and engineers, and management information specialists to create a fully integrated smoothly functioning organization (Matson 1990).

Achieving a fully integrated enterprise requires that the roles traditionally held by individual departments must change and overlap. For example, the information systems department, usually involved primarily with business computing (accounting, payroll, inventory, orders, and more recently, MRP) must move out to the production floor, broadening considerably its traditional view of manufacturing as a vaguely defined black box in which raw materials are converted to finished goods. This change will in turn involve the engineering department in the development of interfaces between the management information system and the plant's process control system. Once a database is designed and production data are collected, the quality assurance department can be brought in to augment the database with laboratory results.

The benefits that can be provided by such integrated systems are clear; however, there are also problems. The volume of data typically collected electronically by an integrated system far exceeds that generated by traditional production reporting systems and could easily overload the information-absorbing capacity of plant personnel. A software tool is needed to organize and interpret the data, assisting the scheduler with both long- and short-term planning and scheduling and helping supervisors and operators on the plant floor with short-term decision-making.

Process simulation has the potential to serve all of these functions, having been used for many years to assist in the design, scaleup, control, optimization, and scheduling of specialty chemicals manufacturing facilities (Overturf 1978, White 1987, Blackwell 1986, Felder 1985, and Bassett 1985). Simulation output for an existing process provides a graphic picture of process performance and usually identifies the principal bottlenecks. Once the simulation has been built and validated, hypothetical modifications in equipment and/or labor resources and/or operating conditions and procedures can be introduced and the results used to predict how the process will respond to the modifications before major procedural changes or capital investments are actually made in the plant.

As traditionally carried out, however, simulation can be a time-consuming and expensive process that requires specialized computer equipment and detailed knowledge of complex simulation software. Moreover, once the simulation has been developed, its use is often limited to those with the specialized training needed to run the program and interpret the results. The benefits of the simulation are thus inaccessible to those who would derive the most benefit from it — shift supervisors, operators, and work leaders who make the floor-level decisions and allocate resources. Additional tools are needed to bridge the comprehension gap between the simulation and the plant personnel who will use it.

A cooperative effort has been undertaken by North Carolina State University and Miles, Inc. to develop such tools. By combining simulation with artificial intelligence methodology, an interactive, simulation-based decision support system has been created that is used for capacity planning, debottlenecking, expansion of existing facilities, and production scheduling. The system is constructed in modular fashion: different components (a) receive input on desired production targets from a plant scheduler and on current plant status from operators and a distributed control system; (b) incorporate the inputs into a database; (c) run plant simulations and subject the results to statistical analyses; (d) use heuristic rules and procedures to interpret results of the simulation; and (e) provide recommendations to operating personnel in comprehensible English. This paper provides a descriptive overview of how the system works and summarizes its intended applications and current status.

2 PROCESS DESCRIPTION

2.1 The Plant

The plant is a multipurpose pharmaceutical processing facility in which a number of different products are manufactured in concurrent multi-step processes that compete for equipment and other resources. The facility produces a variety of pharmaceutical products from human plasma. Such products include hemophilia medicines, immunization sera such as rabies and tetanus, and albumin and plasma protein fraction (PPF). These last two products are used intravenously to maintain patient blood pressure and circulatory system volume.

The process, first developed in the 1940's, starts with whole human plasma obtained from donor centers nationwide. The plasma is received frozen, then is thawed and purified by various protein separation techniques. The purified proteins obtained are compounded, sterile filtered, and filled into appropriate containers.

The focus of this project is the fractionation area where the plasma is processed into any of six different product intermediates, each competing for equipment and labor. Numerous batches reside in various process stages, either undergoing active processing or waiting for downstream equipment to become available. Figure 1 is a flow diagram of the process.

2.2 Scheduling and Operating Problems

Production schedules consist of dates at which processing will be initiated for batches of raw plasma and expected start and target delivery dates for intermediate products. The intermediates are protein fractions removed during the processing of raw plasma, stored until sufficient amounts are accumulated, and then reintroduced into the production area and processed into final products. The schedules are generated by matching the number of equipment hours required for each batch to be processed during the week to available equipment hours. It is the operator's responsibility to allocate equipment to new batches of raw plasma entering the area, initiate production of intermediates, and follow processing guidelines for work in process.

A number of factors make scheduling and operation of this plant particularly challenging:

- *More than 20 batches in process at any time.*
- *Over 70 equipment items to clean and maintain.*
- *Complex resource allocation requirements.* A typical resource allocation involves checking

Figure 1: Process Flow Diagram for the Plasma Fractionation Area

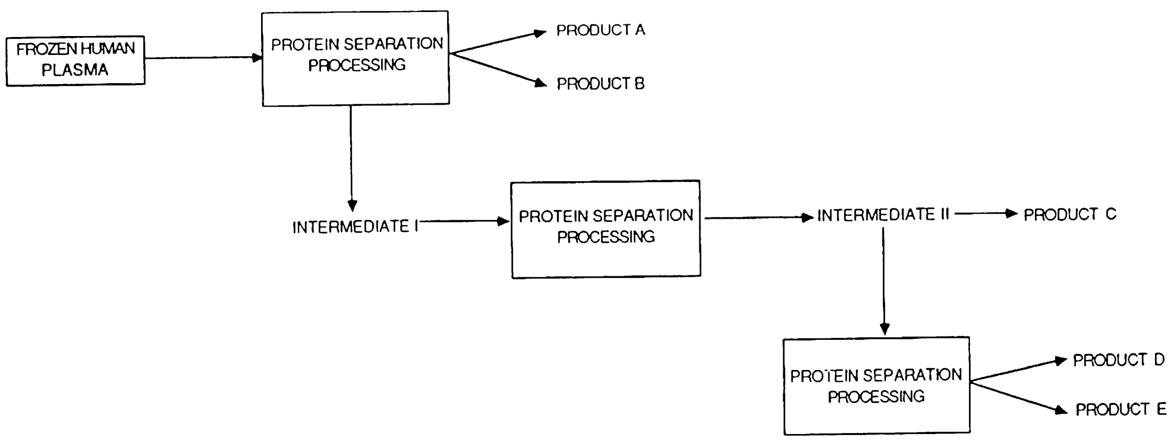
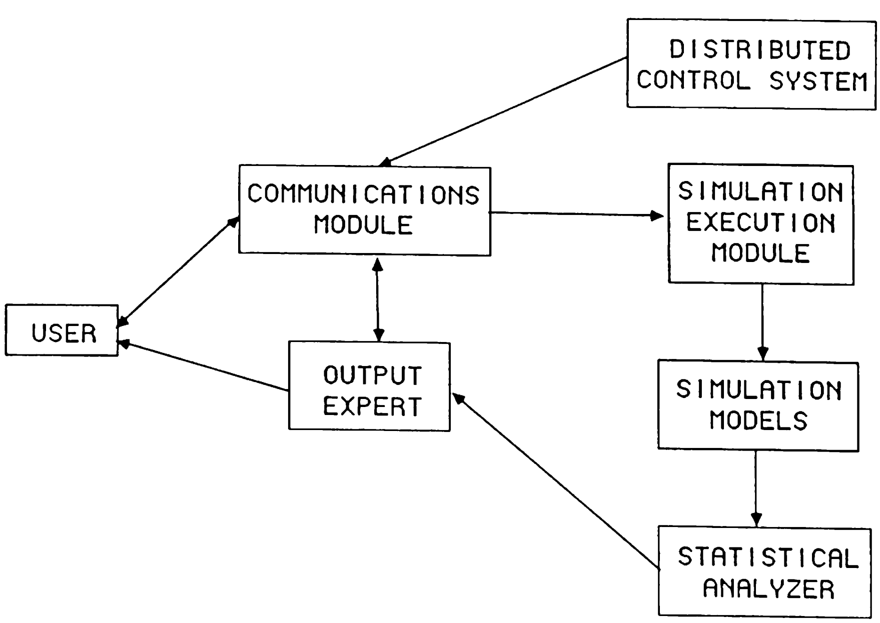


Figure 2: Architecture for the Decision Support System



availability of several equipment items and operators and determining that no other work in process has priority.

- *Complex logic for scheduling batches in equipment.* Operators determine the sequencing of batches in order to maximize equipment and operator efficiency.

- *Complex logic for initiating intermediate product processing.* Intermediates are started only when sufficient equipment is available. This rule requires that the model have the capability of determining equipment demand up to 72 hours ahead. Equipment gridlock can occur if demand is improperly forecast.

- *Lack of some critical information about the scheduling and flow of materials through the production area.* No one had ever asked some of the questions that had to be asked to develop the simulation, so no one knew the answers.

Under some circumstances, several batches can be processed through certain equipment before cleaning is required. Operators plan such sequences in order to minimize equipment cleaning, but the sequencing may have a negative impact on time in process for other batches and in some cases may lead to equipment gridlock. The operators attempt to look several hours ahead to determine whether sufficient equipment will be available to receive new batches of material arriving from an upstream process and/or to initiate production of an intermediate. It is nearly impossible to see much beyond a few hours, however, considering that of the multiple processing steps required for each batch, many steps require use of a number of types of equipment plus operating personnel; smaller batches may sometimes be combined; intermediates are occasionally split into sub-batches; and certain batches may have higher priorities depending on product stability and downstream processing considerations.

Without a decision support system, these difficulties and chronic variations in process times from one run to another make it almost impossible to schedule production more than a few hours in advance, to determine what throughput can be expected, and to ascertain whether equipment or labor constitutes the principal productivity bottleneck. Decisions made by the operators usually serve to resolve short-term problems but also occasionally create more serious long-term problems.

3 DECISION SUPPORT SYSTEM

3.1 Overview

The decision support system is used to assist schedulers, planners, operators, engineers, and managers in manufacturing decision-making. It allows the user to simulate and analyze various shop floor scenarios such as development and evaluation of production schedules and assignment of equipment and labor to meet alternative production goals. Operated in an off-line mode, it is used to evaluate master production schedules and for debottlenecking and capacity planning studies; on line, it may be used to prepare and evaluate short-term production schedules and to assign equipment and labor to work in process.

3.2 System Architecture

A diagram of the system architecture is shown in Figure 2. Two blocks external to the system are labeled "User" and "Distributed Control System." The user may either be a scheduler, who would use the system to develop weekly or long-term production schedules, or an operator, who would use it to plan equipment assignments. The distributed control system, a Taylor MOD 300, collects and stores data on critical process parameters such as temperatures and flow rates.

The system runs on a DEC Microvax 3200 operating under VMS, and consists of the following modules:

1. **Communications module.**

   This module is written in a combination of Fortran and DCL (Digital Command Language) and provides a menu-driven user interface to facilitate changes in up to 123 model parameters. It performs several statistical functions including determining the number of runs necessary for proper analysis of a given scenario; combines the results of multiple simulation runs of a given scenario into a single summary file; and performs hypothesis testing of the results. Shop floor status is obtained from the distributed control system (DCS) through a separately purchased software package called AIM (Biles and Associates, Houston, Texas). This package provides an interface to the DCS and was configured to create a data file containing a detailed snapshot of all controlled process parameters as well as the status of equipment and batches in process.

2. **Simulation Execution Module.**

   This module, written in Fortran, loads the work-in-process information obtained from AIM into the simulation model. When the decision support system is used in the search mode, the module loads each schedule to be explored into the simulation model.

3. **Output Analysis Module.**

   This is a "smart" module written using the Level5 Pascal-based expert system shell (Information Builders, New York, New York) to interpret the vast array of numbers that constitute the raw output from a simulation, draw inferences from this output, and provide recommendations to the user in clear English.

3.3 Plant Simulation

The first step of the project was to develop a simulation model using SLAM-II (Pritsker 1986) to represent the plasma fractionation area. Nodes were defined and combined to model all processes, equipment, and activities in this facility; the final model involved roughly 4000 lines of SLAM-II code and 14,000 additional lines of Fortran code.

Prior to developing the model, a series of interviews with plant personnel were conducted to provide detailed information about the process, equipment used, and procedures followed. Most process step durations and stream flow rates were available from batch production records and others were obtained by direct measurement. Labor requirements and average service times were available from an eight-year-old study conducted by a plant industrial engineer. Service times were assumed to be normally distributed about those average values with a standard deviation of 10% of the mean, an assumption supported by observation. Production records were collected and combined with information obtained from plant personnel to develop scheduling algorithms, procedures regulating the initiation and sequencing of batches.

The scheduling of intermediates was the most difficult aspect of the operation to simulate. Operators used many vague rules of thumb to judge when there would be sufficient equipment available to initiate processing of an intermediate. Early attempts to model the decision-making process led to frequent simulated "gridlocks" — severe overloads of material to be processed and not enough reactors in which to do the processing. This situation is occasionally experienced at the plant but not nearly as often as the simulation predicted. The problem was eventually resolved by expanding the code to keep track of all information relating to the status of batches in process and using a separate Fortran subroutine to perform the required assessment.

The model was initially developed for off-line use. In this mode, the simulated production floor starts clean and empty and goes through a three-week startup period to reach a pseudo-steady state. Statistics collected during startup are not saved, as this period is not representative of actual production. At the end of the startup period the statistical registers are cleared and collection of information from the simulated production floor commences. Data collected include throughput times and production rates for each product, durations of all processing steps, and statistics on equipment and labor utilization. The latter statistics were reported as histograms.

In the second phase of development the simulation model was expanded to perform short-term on-line simulations. For these applications the model must start with the current work-in-process on the actual production floor. Since many batches are in process at any time and a tremendous number of parameters are therefore needed to describe the floor status, a link was created to the plant distributed control system to obtain frequently updated snapshots. The AIM report generator creates a data file containing the work-in-process information and the simulation execution module reads it, loads all simulated queues and equipment items with batches in process, and calculates process times remaining for those batches.

Model validation consisted of the following steps:

- Code was reviewed with operators to verify that production logic was correctly represented.
- Simulated production rates and durations of 45 process steps were compared; if necessary, the simulation program was adjusted to better match actual plant values.
- Output, tailored to include data in a typical production report, was provided along with actual production reports to see if the staff could distinguish between the two.
- Historical production schedules were run and the simulated results were compared with actual production floor equipment and labor utilization data.

Illustrative comparisons of actual and simulated production rates are shown in Table 1. The results show very good agreement.

3.4 User Interface

The next phase of the project involved creation of a DCL/Fortran-based menu-driven user interface to enable plant personnel to obtain information and make predictions about plant scheduling and operations

Table 1: Comparison Between Actual and Simulated Production Rates*

PRODUCTION DATA	ACTUAL	SIMULATED
# Batches/time	24.2 ± 1.6	23.9 ± 2.4
# Batches A/time	20.9 ± 2.6	20.1 ± 3.0
# Batches B/time	3.1 ± 1.6	3.8 ± 2.0
# Batches C/time	8.0 ± 3.6	7.7 ± 3.0
# Batches D/time	4.4 ± 2.4	4.0 ± 2.2
# Batches E/time	2.0 ± 1.6	1.9 ± 1.4

*Interval represents $\pm$ 2 standard deviation

without having extensive knowledge of the simulation model, SLAM II, Fortran, or the computer operating system. The interface enables the user to change up to 123 model parameters relating to resources, process flowrates, and production schedules.

The main interface menu allows the user to create or review parameter files (Options A, B, and C), run the simulation model either interactively or in batch mode (Option D), view and print various output reports or access the output analysis module (Options E and F), change the scenario to be reviewed or simulated (Option G), check batch job status (Option H), or log off (Option Q). Main menu Options B and C allow the user to specify up to 123 model parameters, including equipment, labor, and production schedules to be simulated. Although Options B and C both perform the same function, Option B was tailored for use by production personnel while Option C was designed for schedulers involved with master production planning.

The user may choose to display the simulation output in a format identical to the production reports routinely prepared by the plant or as a summary report of pertinent production data and equipment and labor utilization. The report contains the results of inference testing in which the target values input by the user are compared to simulated output. A certainty factor is also provided, reflecting the stochastic nature of the simulated process. The user may also get a report of how the simulation model scheduled the centrifuges and interrogate the expert system for an interpretation of the results.

3.5 Output Analysis Module

The output analysis module performs the following tasks:

1. Evaluates the simulation results and output from the statistical analysis module and, invoking an 80-rule knowledge base, draws inferences that are reported to the user as recommendations. For most of the analyses performed, recommendations include a certainty factor.
2. When search through a solution space is necessary, as when finding the "best" production schedule, the output analysis module evaluates all output from individual simulation runs and identifies the production schedule that meets the search criterion.

4 SYSTEM APPLICATIONS: OFF-LINE MODE

When run for long-term analyses, the simulation begins with the plant in a clean and empty state. The model simulates several weeks of production to load up the simulated production floor and achieve a pseudo-steady state before statistics are collected. Operated in this mode, the system has been used to:

- Determine the number of people and equipment required to process a production schedule
- Develop capital expansion plans based on target production rates
- Determine process equipment utilization
- Provide equipment-hour specifications used in scheduling production
- Provide information on the impact of reworks on capacity
- Determine labor utilization as well as the percentage of time in which all operators are busy
- Determine the feasibility of various production schedules
- Identify bottleneck(s) for specific schedules
- Evaluate the effect of process and procedural changes on throughput
- Project usage of materials and supplies
- Generate statistics on process hold times

The model has provided information to support the combining of individual lots to form a single batch at a certain processing step; to illustrate the benefit of just-in-time processing on capacity; and to determine the benefit to the fractionation area resulting from expanding the operating hours of a downstream process area. Figure 3 illustrates a representative debottlenecking study in which the number of units of a resource was increased and the resulting effect on throughput was determined.

The most important use of the model to date has been to update the equipment-hour allocations used by scheduling personnel to prepare weekly production schedules. To do this, the simulation model was modified to capture equipment utilization statistics. Previous monthly schedules were simulated and the simulated equipment-hours required by each product type were compared to the allocations used to prepare the weekly schedules. For one product, the allocations were about 20% higher than the simulated values. A review of the archived production records showed that the simulated requirements matched those for the actual process. Correcting the equipment-hour allocations resulted in a more accurate representation of process flow through the department.

5 SYSTEM APPLICATIONS: ON-LINE MODE

To be useful for on-line decision support, the system must be able to run short-term simulations, looking ahead several hours or days instead of several weeks or months. Questions to be addressed in on-line operation of the system include:

- What is an achievable processing schedule for next week based on this week's schedule and work currently in process?
- What schedule produces the highest acceptable utilization of equipment?
- Are sufficient reactors available to start a new run?
- Will there be an equipment conflict within the next few hours or days? (Having this information, operators can take steps to avoid the conflict.)
- Would it be advantageous to move operators from one area to another temporarily?
- If several batches are awaiting processing, in which order should they be processed?
- How should we proceed in an upset situation? For example, if a loadcell malfunctions making a reactor inoperable, what would be the best strategy to avoid gridlock with the remaining reactors?

Initial results obtained from the simulation about equipment demand and usage lead to the following conclusions and recommendations:

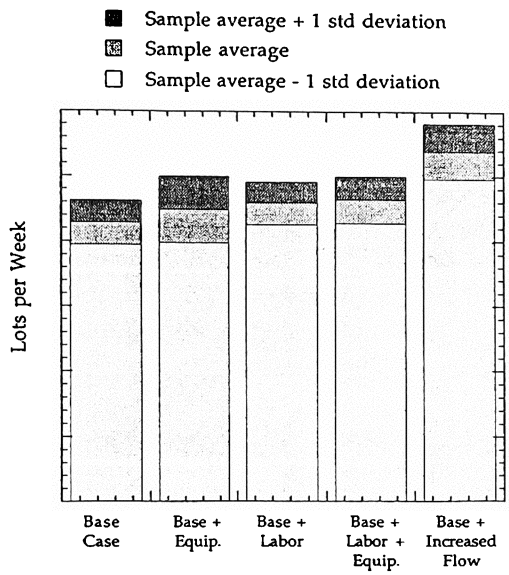
1. Operators scheduling batches on equipment to minimize cleanings leads to cyclical downstream equipment demand and occasionally to gridlock. Instead, the objective should be to minimize flow time or alternatively, to reduce critical equipment wait time. This policy will reduce work-in-process inventory to an extent that the bottleneck resource is never starved, downstream equipment demand is leveled, and the potential for kettle gridlock is essentially eliminated.
2. The scheduling approach currently in use does not accurately reflect the capabilities of the production department as determined by the model and should be reevaluated. Implementation of the decision support system will allow the generation of weekly production schedules.
3. The staff should consider the application of just-in-time processing to this department. A significant amount of equipment capacity is wasted when a batch is available well before it can be processed in the next step.

6 PROCEDURAL RECOMMENDATIONS

Based on our experience with this project, we would offer several suggestions to anyone contemplating similar efforts:

- A task of this nature cannot be carried out successfully by someone who is told to do it in addition to the things he/she is already doing. Someone, either in the plant or an outside consultant, must be dedicated to the project through at least the initial stages of the learning curve; otherwise the project will fail.
- It is also critical not to be too ambitious in the early stages of the project. Rather than attempting to simulate the entire plant at once, the work should begin with a relatively small piece of the operation and gradually evolve to encompass larger pieces.
- Perhaps the most vital key to the success of the simulation is the quality and quantity of process information that goes into it. The personnel on the floor — group leaders and operators — must be brought into the project from the outset as collaborators and sources of needed information about process conditions and procedures.

Figure 3: Representative Debottlenecking Study



- Everyone who will be using the final product — operators, supervisors, schedulers, and administrative personnel — should be asked to provide information on precisely what questions they would like the decision-support system to answer, and their responses should be the principal guiding factor of the system development.

- The same personnel should be given the chance and *strongly* encouraged to get hands-on experience with the software during its development. They will then be in a good position to provide helpful suggestions regarding its continued development and to make good use of it as soon as it is ready to apply.

- The task of ensuring that the simulation runs properly (verification) and accurately represents plant operations (validation) is a team effort. It is essential that both the modeler and plant personnel work together closely during these phases of the project (Carson 1986).

ACKNOWLEDGMENTS

The authors would like to thank the people of Miles, Inc. for their support of and participation in this project, including Duncan Patterson, Terry Monroe, Joel Youngblood, Billy Morris, Bobby Norris, Billy Byrd, Charlie Carroll, Doug Waddell, Tom Rains, Shirley Hargis, Sue Cullen, Ella Norris, Price Heritage, Ben Strickland, John Parrish, Jeff Parrish, Renee Perry, Debby McCormick, Mike Lynette, Marsha Quinton, E.C. Neal, Sandra Robinson, Jeff McDaniels, Cliff Lee, Joe Macak, Mike Jethro, Jerry Sellers, Lessie Johnson, Darlene Coor, Karen Raiford, Tony Bailey, Rusty Barbour, Randy Anderson, Albert Sykes, Don Petti, John Buck, Larry Bagwell, Tim Keith, Ken Tart, Dennis Barnes, and David Coil. We would also like to thank Barry King at N.C. State University for computer assistance and Al Krigman for initiating the collaboration.

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