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SIMULATION ANALYSIS OF A FLEXIBLE INTEGRATED CHEMICAL PRODUCTION FACILITY

John E. Branstrator
Pritsker Corporation
1305 Cumberland Avenue
P.O. Box 2413
West Lafayette, IN 47906 U.S.A.
317/463-5557

ABSTRACT

The design of a "green field" chemical production facility is a complex issue. The evaluation of proven and experimental production processes is necessary. Equipment layout and switching station design should address the flexible requirements of production while adhering to budgetary constraints. Production throughput should be quantified with a valid understanding of scheduling sensitivities. The requirement and impact of critical resources such as labor, raw materials, and warehouse transactions must be realized. Finally, the sizing of various holding tanks for environmental treatment requires coordination with production levels.

The intricacies of this manufacturing process make traditional throughput calculations and linear programming approaches obsolete. These issues can be better addressed using computer simulation to model the proposed facility. This paper explores how the design of a new chemical production plant was facilitated using simulation analysis.

1. INTRODUCTION

The traditional design of chemical production facilities consists of lines of equipment dedicated to processing one, or a very limited range of, finished product. These dedicated lines normally incur high startup costs, run large campaign sizes, suffer from low equipment utilization when associated with low volume products, and require large amounts of plant space as new products or process changes are added. This approach also fails to address the needs of a dynamic customer driven market place requiring smaller orders delivered "as needed".

A flexible chemical production facility helps to address the complexities faced in today's production environment. The physical equipment used in this type of facility can handle a wider range of product types and process methods. Vessels are designed to switch from one major product type to another with little preparation and short delays. A sophisticated material delivery highway augments the capability of transferring liquors to nearly every piece of equipment. Higher utilization of this costly equipment is achieved because of the inherent adaptability to a wider breadth of chemical products. This flexible production approach also makes campaign runs dictated by customer demands feasible since the economics of small production runs is acceptable and campaign changeover costs are reduced.

The major components for this type of flexible facility are: production vessels, material flow, bulk material delivery, process resources (labor, reaction control), finishing facilities, discharge treatment, and scheduling concerns. The integration of all components involves complexity in both design and installation. Some components have high interdependencies making certain design assumptions easier. Other relationships, such as an increased amount of bulk material storage affecting scheduling concerns, are unclear and become compounded when subjected to full system integration.

2. FACILITY DESCRIPTION

A major chemical/pharmaceutical manufacturer needed a design for an integrated production facility for producing both liquid and solid product. The final product would be packaged in drums and then shipped to either distributed warehouses or "end-use" customers.

The design team desired the latest technology for equipment and processing. The availability of sophisticated production equipment made flexible production possible, but forced the justification of capital expenditures by requiring maximum equipment utilization.

2.1 Physical Equipment

Physical equipment included in the model of the production facility were: production vessels, filter presses, switching stations, bulk material holding tanks, environmental treatment components and warehousing facilities. An overview of the physical system is detailed in Figure 1. Production vessels were used for preparation of products and materials, general reaction of products, storing of in-process products, and final standardization of products before being packaged. Filter presses were used for separating final product from waste filtrate and environmental treatment. Flexible switching stations, or flow highways, were required to facilitate transferring material between vessels. On-site holding tanks were required to reduce the cost of replenishing certain bulk input materials used in product processing.

An important aspect of the plant was the processing of waste products through a sophisticated environmental treatment system. The system's processing was divided into three separate subsystems: one system treated incineration waste, another system handled dilute waste, and the third neutralized concentrated wastes. The dilute and concentrated waste system would maintain separate holding tanks but shared the same waste adsorption columns for final treatment. Additional holding tanks were needed for collecting rain water runoff being discharged to the dilute waste hold tank.

2.2 Product Processing

This facility was designed to accomplish batch chemical processing. Batch processing consists of a series of distinct stages which occur in separate pieces of equipment. Figure 2 illustrates a product that has six unique processing stages. In this example, Stage 1 initiates the beginning of a batch of product and Stage 5 yields the final product. A batch of product at a specific stage goes through a series of activities culminating in the discharge of the batch to the next stage. These activities are: input of bulk materials, requirements for operator attention, requests for production resources, reaction, delay for stage coordination, discharging of product, eventual cleaning of equipment, and transfer of wastes to the treatment system.

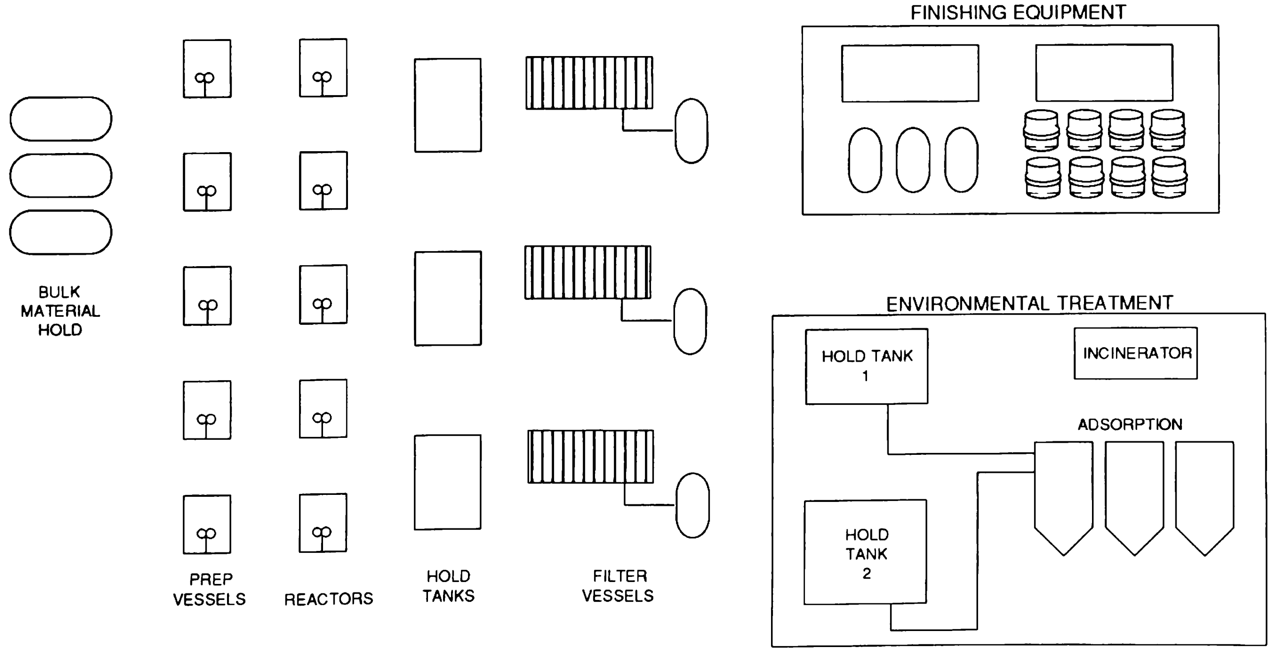


FIGURE 1. Chemical Facility Equipment Layout

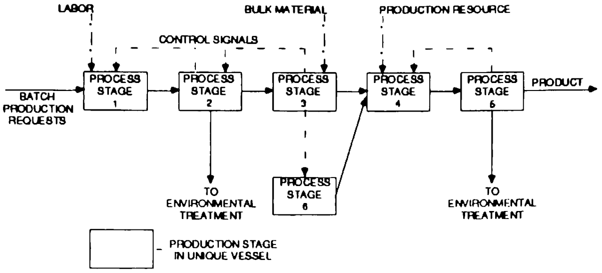


FIGURE 2. Elements of Batch Chemical Processing

In order to ensure product integrity, communication and coordination between stages is required. This precise control manifests itself in process control signals issued and used by stages. For example, before signaling an upstream stage that it is ready to receive the current product batch an unstable stage may require a signal from the downstream stage that it can accept the eventual transfer. This type of coordination between stages assures high quality product integrity while adhering to an expected production scheme.

2.3 Scheduling

Production requests are released to the floor as campaigns. A campaign consists of a set of batched stages that yield the required amount of final product. If a campaign requests 15,000 pounds of final product and the product producing stage yielded 5,000 pounds, then the final stage, and most likely all of its sequenced predecessor stages, would produce 3 batches to close out the campaign.

There were numerous requirements placed on the scheduling capabilities of the facility. First it should be able to support processing simultaneous campaigns of different products. Next the release of campaigns for production must be demand driven. This brings the facility more in line with the customer's needs while reducing the amount of storage required in distributed warehouses. Finally, the scheduler must ensure that equipment throughout the plant is highly utilized and that throughput of products is achieved in a timely fashion. To accomplish effective product scheduling, a scheme was introduced where product campaigns were divided into critical and non-critical production schedules.

The critical production schedule is characterized by close adherence to the schedule sequence, reserving future use of equipment required for the next product on the schedule, and getting higher priority for equipment and production resources. This helps to guarantee predictable and independent campaign cycles. The non-critical schedule attempts to optimize equipment usage by selecting the next product from a pool of candidate product campaigns. It will take equipment as needed, verifying that no conflict is created with critical campaigning. The non-critical schedule tries to produce as much product as is possible without violating release dates.

3. SIMULATION OBJECTIVES

A simulation study was required because a steady state analytical model could not incorporate the dynamic nature of product processing and scheduling logistics. The objectives of the study were to:

1. Determine the production capabilities of the facility,
2. Determine the amount of equipment required to meet production schedules,
3. Develop an understanding of product scheduling requirements,
4. Ensure adequate sizing of the environmental treatment system and hold tanks, and
5. Allow corporate and plant staff to continue support of the model through custom interfaces.

The simulation model needed to support the capacity analysis study, and subsequent changes in facility design, product processing, and scheduling coordination.

4. TECHNICAL APPROACH

To support the study objectives and the project's technical requirements, a SLAM II model was developed using full functionality of the language. The discrete environment used FORTRAN to implement custom data inputs/outputs and complex scheduling logic. The network environment accomplished batch entity processing and monitored tank levels. The continuous portion of SLAM II was used to update tank levels and model the environmental treatment facilities.

To facilitate a dynamic model that would incorporate changes, a model architecture was devised where system parameters could be defined and changed easily through input files. This input file structure is illustrated in Figure 3. Input files were used to describe product schedules, equipment layout, equipment capabilities, product "recipes", switching station design and simulation run parameters.

The flexible production facility analysis required a flexible simulation model. This required the capability to make changes to parameters and then see the effects through intelligent and specific output reports that were readable by all project staff. The main burden of analysis fell upon the interpretation of output reports and equipment Gantt charts (see Figure 3), enabling planning and production staff to gauge the success of the plant's design and recommend changes to either product schedules or plant layout for increasing throughput and utilization.

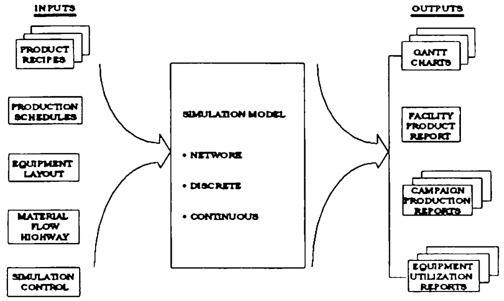


Figure 3. Flexible Simulation Model Design

The key to capturing the complexities of product processing and defining all aspects of its "recipe" lies in defining each product stage as a unique entity. The product in Figure 4 has 11 distinct stages. To produce one batch of final product, 11 unique entities would be entered to the network model. These entities have attributes, such as current batch identifiers, number of batches, product number, stage number identifiers, etc.

This scheme allows complex products employing production stages, such as shown in Figure 4 to be defined easily. Coordination of all stages is maintained by product process control signals. Control signals are SLAM II resources that are altered by one stage and used by another stage. A product stage will start with its first defined activity (i.e., add bulk material) and once all signal and production resource requirements are met, it goes through the required activity duration. At the end of the activity, the model checks to see if there are control signals which can be released. It then sets the pointer to the next stage activity. The product stage proceeds through this processing for each recipe activity. Once the stage reaches its last defined activity, it checks the current stage batch count against the total stage batch count. If they are equal, then the stage is retired for that product's campaign. If the current batch count does not equal the number required, then the attributes are updated and another batch of that same stage is started.

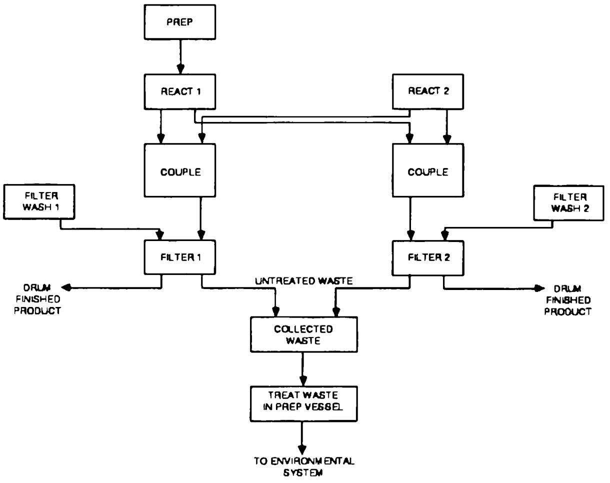


Figure 4. Complex Batch Process Diagram

5. ADDRESSING SCHEDULING ISSUES

Two distinct scheduling algorithms were developed to handle priority and non-priority product campaign streams. A series of critical product campaigns is termed a priority stream to ensure that these campaigns occur in the order specified with little or no delay during campaign transitions. The control scheme for enforcing this schedule begins when a critical product campaign is initiated. The equipment expected to be required for the following product is reserved with the anticipated start and finish time marked. This enables products evaluating initiation in the critical and non-critical streams to know when a piece of equipment is expected to be used, creating a window of unavailability for this equipment to any other product. Before the next critical product is started, an evaluation is done to make sure the initial equipment that was reserved is still available. If it is not available, then the scheduler makes an evaluation of alternate equipment to be used for the stage, or stages, where equipment is specified as unavailable. If the product is still unable to be initiated the priority production stream is stopped. Evaluations are constantly made at the beginning and end of any product stage to determine when this stream can be restarted.

The maintenance of an uninterrupted priority product campaign stream degrades the flexibility of the chemical production facility and reduces equipment utilization by forcing suboptimal equipment choices to be made—often idling equipment to maintain a production stream. An effort to optimize throughput is made through the use of the non-critical campaign scheduler. Non-critical product campaigns do not reserve equipment. They have the capability of initiating campaigns in any sequence as long as their release date has been met and equipment required are expected to be available when needed. To help increase throughput, the non-critical schedule tries to maintain as many simultaneous campaigns as possible.

6. ENVIRONMENTAL SYSTEM

The environmental treatment system processes waste independent of production operations. A product's stage will discharge filtrate, reaction by-products, or effluence from the cleaning of a vessel to the environmental treatment system. A limited number of collection tanks are available, each having a maximum holding level. Once a tank's maximum level is reached, capacity to discharge to that tank ceases and the product's campaign may be interrupted.

To model environmental operations, vessel discharges to holding tanks were modeled as a single discrete discharge. Tank levels change according to discharge rate and elapsed time, therefore, they are best modeled using continuous equations. The tank level is assigned the continuous SLAM variable SS(1). The variables used by the model are:

SS(1) = hold tank level (gallons)

XX(1) = hold tank discharge rate (gal/hour)

XX(2) = hold tank discharge signal (1=ON/0=OFF)

DTNOW = continuous time element (.1 hour)

Then a discrete discharge by the cleaning activity for a product's stage can be represented by:

SS(1) = SS(1) + discharge amount from a vessel

The continuous update of decreasing the tank level due to waste treatment is:

SS(1) = SS(1) - XX(1)*XX(2)*DTNOW

To facilitate faster tank depletion as tank levels increased, the hold tanks had the additional requirement that the discharge rate would change with the tank level. To adjust the hold tank discharge rate to adsorption treatment according to the hold tank level, the following variables are defined:

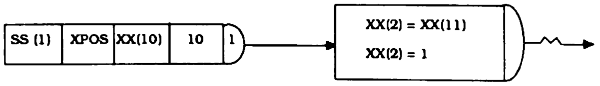
XX(10) = hold tank 20% level (gallons)

XX(11) = hold tank discharge rate for 20% level (gal/hour)

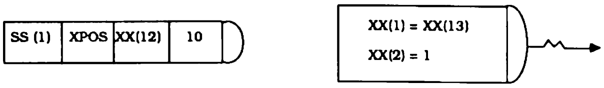
XX(12) = hold tank 30% level (gallons)

XX(13) = hold tank discharged rate for 30% level (gal/hour)

Detect nodes allow the model to automatically monitor the hold tank level and update the discharge rate accordingly.



To monitor 20% tank level



To monitor 30% tank level:

Likewise, detect nodes would be needed to decrease the tank discharge rate as the hold tank level decreased. An additional detect node would be needed to set the discharge rate signal, XX(2), to 0 once the tank level reached a cut off point.

7. VERIFICATION

Pritsker defines verification as "the process of establishing that the computer program executes as intended" (Pritsker, 1986). A typical method of performing this would be to generate statements corresponding to every significant event and examine this file after a simulation run was complete. Though this was possible, the volume of data generated to examine would have been unwieldy. A visual tool such as animation would have been useful but lacks the required detail.

To facilitate accurate descriptions of what was occurring in the model, Gantt charts were developed to accomplish verification. The charts contained relevant, detailed information pertinent to model processing while allowing visual comparisons to be made. An example of Gantt charts for a specific equipment class type (filtration, preparation, reaction) is shown in Figure 5. This output report details how each piece of equipment was used. The field description contains the product number in the vessel, the specific product stage number, and the current production batch number. The Gantt chart also contains a character designator corresponding to the specific processing state of the equipment. Using this Gantt chart, all project members could verify the processing of any specific product over any piece of equipment. The structure of the chart also made equipment idle time clearly visible.

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TIME(HRS)   VESSEL 1     VESSEL 2     VESSEL 3     VESSEL 4
---------   - --------   - --------   - --------   - --------
   455.20   K  7. 2. 2   I  7. 1. 2   W  7
   455.50   P  7. 2. 2   I  7. 1. 2   W  7
   455.60   P  7. 2. 2   I  7. 1. 2   W  7
   455.80   P  7. 2. 2   I  7. 1. 2   W  7
   455.90   P  7. 2. 2   I  7. 1. 2   W  7
   456.00   P  7. 2. 2   I  7. 1. 2   W  7
   456.40   P  7. 2. 2   I  7. 1. 2   K  7. 3. 2
   456.70   P  7. 2. 2   I  7. 1. 2   P  7. 3. 2
   456.90   P  7. 2. 2   I  7. 1. 2   P  7. 3. 2
   457.40   P  7. 2. 2   P  7. 1. 2   P  7. 3. 2
   457.50   P  7. 2. 2   P  7. 1. 2   P  7. 3. 2
   457.60   P  7. 2. 2   O  7. 1. 2   P  7. 3. 2
   457.70   T  7. 2. 2   D  7. 1. 2   P  7. 3. 2
   458.00   P  7. 2. 2   K  7. 1. 3   P  7. 3. 2
   458.00   P  7. 2. 2   K  7. 1. 3   I  7. 3. 2
   458.30   P  7. 2. 2   P  7. 1. 3   I  7. 3. 2
   458.40   P  7. 2. 2   P  7. 1. 3   I  7. 3. 2
   458.50   P  7. 2. 2   P  7. 1. 3   P  7. 3. 2
   458.80   D  7. 2. 2   P  7. 1. 3   P  7. 3. 2
   458.90   D  7. 2. 2   I  7. 1. 3   P  7. 3. 2
   459.00   D  7. 2. 2   I  7. 1. 3   P  7. 3. 2
   459.20   W  7         I  7. 1. 3   P  7. 3. 2
   459.50   W  7         I  7. 1. 3   P  7. 3. 2
   459.60   W  7         I  7. 1. 3   T  7. 3. 2
   459.70   W  7         I  7. 1. 3   P  7. 3. 2
   459.80   W  7         I  7. 1. 3   D  7. 3. 2
   460.20   W  7         I  7. 1. 3   W  7
   467.60   K  7. 2. 3   I  7. 1. 3   W  7
   467.90   P  7. 2. 3   I  7. 1. 3   W  7
   468.00   P  7. 2. 3   I  7. 1. 3   W  7
   468.20   P  7. 2. 3   I  7. 1. 3   W  7
   468.30   P  7. 2. 3   I  7. 1. 3   W  7
   468.40   P  7. 2. 3   I  7. 1. 3   W  7
   468.80   P  7. 2. 3   I  7. 1. 3   K  7. 3. 3

                     GANNT CHART LEGEND

 EQUIPMENT STATE CODES
   K = EQUIPMENT PRECHECK            K   7. 2. 3.
   I = INPUT DELAY                   |   |  |  |__BATCH NUMBER
   T = TRANSFERING IN MATERIAL       |   |  |
   P = PROCESSING                    |   |  |__STAGE NUMBER
   O = DELAY ON DISCHARGE            |   |
   D = DISCHARGING                   |   |__PRODUCT NUMBER
   C = CLEANING                      |
   W = IDLE, NOT CLEANED             |__ EQUIPMENT STATE
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Figure 5. Equipment Gantt Chart

Another Gantt chart was developed that reported all equipment in the facility on one page. It also listed any critical or non-critical products running on the schedule. Though this chart did not reveal batch and stage numbers, it could be used to verify campaign coordination and monitor success of the scheduling algorithms. Without the use of these custom charts, model verification would have been much more time consuming. Additionally, scheduling algorithms would not have been as easy to debug or refine to the necessary degree of accuracy.

8. ANALYSIS OF RESULTS

Simulation runs were accomplished for expected production schedules totaling one calendar year. A set of measurement parameters were developed for gauging the success of a run and allowing for further scenario comparisons. The chosen parameters were:

1. Total system production,
2. Deviation from schedule,
3. Equipment utilization, and
4. Usage of production resources; i.e., bulk material, labor, etc.

Custom reports were developed that concentrated on each of these analysis parameters. The reports were robust enough to enable those on the project team to understand precisely the model's performance. These reports were also descriptive enough to allow people outside the project to comprehend the results and aid in analysis.

The overriding concern during the analysis phase was that the projected output for the year be met. It became evident that the facilities output was very sensitive to changes in both the critical and non-critical schedules. Though the non-critical schedule would optimize output based on available equipment it tended to run all the small simple product campaigns first. Therefore, a long string of complex campaigns remained at the tail end of the non-critical scheduler. The critical campaign schedule had little room for adjustment since its composition came from marketing demand estimates. It was also known that certain critical products could run in tandem with some of the more complex non-critical products.

To increase output and help increase equipment utilization, a preference matrix was implemented for getting non-critical, complex products spread throughout the schedule. For a particular critical product, this matrix specified which non-critical product types must first be evaluated as candidates for campaign initiation. This scheme was in conflict with the pure optimizing non-critical schedule, but overall it produced more product over less calendar time.

The analysis for requirements of production resources (i.e., bulk materials, labor, ice, etc.) was performed in two modes: one where these resources were assumed infinitely available, and another where realistic limits were placed on all resources. The scenario having infinite production resources gave insight into the profile of these resources used "as needed" and gave an indication of what production was possible under a fully automated, "fine tuned" facility.The output from this scenario was used as a starting point for the limited resource scenario. As expected, the impact of unavailable resources decreased system throughput and lowered equipment utilization.

Even though this was a flexible production facility, some dedicated equipment was required for specific products. This forced the utilization of most equipment to 70% on average. The model predicted the facility would be able to meet the required production needs with limited equipment and resources.

9. CONCLUSIONS

A "green field" production facility is a major investment in capital, philosophy, complexity and operation. The success of this particular flexible, integrated chemical facility is more assured due to the application of simulation technology. A simulation model will incorporate the detail and logic necessary to replicate the dynamics and difficulties of controlling a facility of this nature.

The flexible data-driven approach to model design was a cornerstone to this effort because:

1. It allowed the model to be accurate through many design cycles.
2. Complex processes, like product recipes, were contained in readable, robust user interfaces.
3. Results turn around was quicker and less expensive for both project staff and current plant support personnel.

This modeling effort not only made design and production people discuss facility operation, but it still acts as a database for layout and processing information.

It gave project team members key insight into scheduling issues, equipment bottlenecks, resource impacts, and environmental treatment capabilities. This model will continue to be used as process plans, facility layouts, and marketing forecasts change in the future. It can be expanded upon to handle additional questions for this project as well as being adaptable to the needs of future related projects.

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AUTHOR'S BIOGRAPHY

John E. Branstrator is a Senior Systems Analyst in the Field Operations organization of Pritsker Corporation. He holds a Bachelor of Science Degree in Industrial Engineering from Purdue University. He has led projects applying simulation to steel making, discrete part manufacturing, material handling systems, airline operations, and chemical processing.