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Hulya Julie Yazici

Simulation Gaming 2006; 37; 73
DOI: 10.1177/1046878105282159

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Hulya Julie Yazici
Florida Gulf Coast University

Teaching quantitative courses can be challenging. Similarly, layout modeling and lean production concepts can be difficult to grasp in an introductory OM (operations management) class. This article describes a simulation model developed in PROMODEL to facilitate the learning of layout modeling and lean manufacturing. Simulation allows for the evaluation of layout alternatives and the testing of labor-allocation strategies. In addition, the model shows the lead-time and resource utilization advantages of cellular layouts. Implications of these advantages for lean production are analyzed. As such, students learn to formulate operation strategies and make better decisions based on the outcomes of the simulation. Furthermore, limitations of the model and the need to generalize the model for adaptation in similar classes are discussed.

KEYWORDS: *layout modeling; simulation; operations management; lean production; PROMODEL*

Academics and others have described the difficulties of teaching quantitative models within undergraduate and graduate business programs (Hill, 2002; Johnson & Drougas, 2002). Similar difficulties, such as the anxiety of students toward the quantitative material, curriculum issues, and time constraints are observed in statistics education and in teaching quantitative methods (Mukherjee, 2002; Mvududu, 2003; Peters, Kethley, & Bullington, 2002). Operations management (OM) consists of a wide spectrum of quantitative and qualitative methods that enable the efficient and effective running of businesses. In most institutions, an introductory OM course is required for business majors with a diverse range of quantitative skills. Despite the mathematics and statistics prerequisites, the quantitative aspects of the course can be troublesome. Furthermore, understanding the operating system can be challenging for students who are not familiar with manufacturing or service systems.

Facility layout refers to the arrangement of machines, departments, workstations, storage areas, and common areas within an existing or proposed facility (Russell & Taylor, 2003). Basic types of layouts are product, process and hybrid layouts. Layout modeling can be challenging to students. For instance, with regard to the line balancing of product layouts, Ragsdale and Brown (2004) pointed out the difficulties in formulating a model that will optimize the order of work elements and equalize the amount of work at each workstation. A spreadsheet model was developed by these researchers to facilitate the heuristics and optimization techniques required. Similar challenges are faced in the modeling process (job shop) and cellular layouts where different heuristics are developed. An effective layout design consists of eliminating

SIMULATION & GAMING, Vol. 37 No. 1, March 2006 73-87
DOI: 10.1177/1046878105282159

bottlenecks, reducing waste, and using labor safely and in a more productive manner. In addition, facilitating the communication among workers, an easy interaction between workers and machinery, and the flexibility to adapt to changing conditions, are significant design considerations. As these require a dynamic visual modeling and analysis tool, simulation can deliver these promises.

Simulation is a flexible tool that allows for the visualization and quantification of technological as well as the operational changes in processes for the decision maker. Similarly, simulation allows students to evaluate the impact of changes on systems. The many advantages of using simulation techniques when teaching have been previously noted (Fox, Grim, & Hogan, 1996; Lane, Mansour, & Harpell, 1993; Johnson & Drougas, 2004; Hill, 2004). Nevertheless, simulation presents challenges for the learner. The use of spreadsheets along with cases such as Goldratt's matchstick model, have been used to simplify modeling for students (Johnson & Drougas, 2004). However, even with spreadsheets, students may require assistance. Furthermore, spreadsheet capabilities are not suited for discrete–event simulation. Process simulation is used to capture complex system state changes over time. The dynamic interactions and uncertain event ordering found in OM are difficult to capture in a spreadsheet model (Hill, 2004). Therefore, process-simulation packages such as EXTEND, SIMQUICK, or PROMODEL are used to capture complex system state changes over time, where the state changes are defined by events within the system.

This article presents a simulation model written in PROMODEL. This model is introduced in an undergraduate OM class to analyze changes in cellular layout design and labor allocation, and to evaluate process outcomes such as lead-time and resource utilization. Using the simulation as an instructional tool allows for a better understanding of facility layouts and motivates students to use simulation.

Background on layout modeling

This study focuses on process (job shop) layout and on cellular layout, both of which gained popularity with the lean production principle (Shingo, 1990; Womack & Jones, 1996; Womack, Jones, & Roos, 1990). Process layouts, also known as functional layouts, group similar activities together in departments or work centers according to the process they perform. Process layout is characteristic of intermittent operations, job shops, or batch production, which serve different customers with different needs. The advantage of process layout is flexibility as workers can perform a number of different tasks in a single department. Although flexible, process layouts are inefficient. Long queues and work-in-process inventories are common problems of process or job-shop layouts. Block diagramming is a technique to improve process layouts by minimizing nonadjacent loads or quantities moved between departments (Russell & Taylor, 2003).

Cellular layouts combine the flexibility of a process layout with the efficiency of a product layout. Product layouts arrange activities in a line according to the sequence of operations for a particular product or service. In cellular layout, based on the concept of group technology (GT), dissimilar machines are grouped into work centers, called cells, to process parts with similar processing requirements. Cell layouts allow one-piece flow and focus on the efficient processing of complete parts and products. Therefore, cells provide an opportunity for job or service shops, to improve efficiency by simplifying routing flexibility, and streamlining production (Kher & Jensen, 2002). The simulation model presented below is based on the design of a process layout. Simulation facilitates the visualization of these layouts that, otherwise, would be challenging for business students due to their unfamiliarity with manufacturing.

Process information

A screen-printing process is selected for modeling process and cellular layouts. Screen printing begins with the processing of custom orders with varying volume. For simplicity, orders can be grouped into two types: regular or repeat orders, and special orders. Repeat orders are previously requested orders by existing customers. Therefore, these orders may skip the design process if no changes are requested. Special orders, however, are not repeat orders and are fully customized. These orders follow product design or artwork processes. Preproduction process steps follow the product design. Screen making, stock cutting, and screening are the preproduction processes. Following this, parts are manufactured based on a process or cell layout. Three major production steps are lamination, die cutting, and packing. Other production steps, not common to all orders, may include embossing, piercing, slitting, numbering, hand laminating, and punch-press operations. Figure 1 illustrates this process flow.

Simulation modeling

Simulation modeling of the screen-printing operation consists of supply or raw material generation, order generation, product design, preproduction, and production processes using cellular and process (job shop) layouts. A representation of the major components of the model including a supplier, manufacturer, and retailer are shown in Figure 2.

The model allows for the comparison of the above-described layouts and enables the evaluation of process outcomes. Table 1 shows the inputs and outputs of the simulation. Real data collected from a screen-printing manufacturer over 2 years is used to estimate process times and part generation distributions. STAT-FIT is used for finding the best fit for the data. Further information on stochastic distribution fitting can be found in Bateman, Bowden, Gogg, Harrell, and Mott (1997). The simulation clock was set to run in seconds due to the one-piece flow operation in the cellular layout.

The model consists of a raw material supply buffer with infinite capacity. The initial buffer is 20,000 parts, indicating that the factory warehouse contains 20,000 input supplies to begin with. The input supply quantity may be modified by the simulation user.

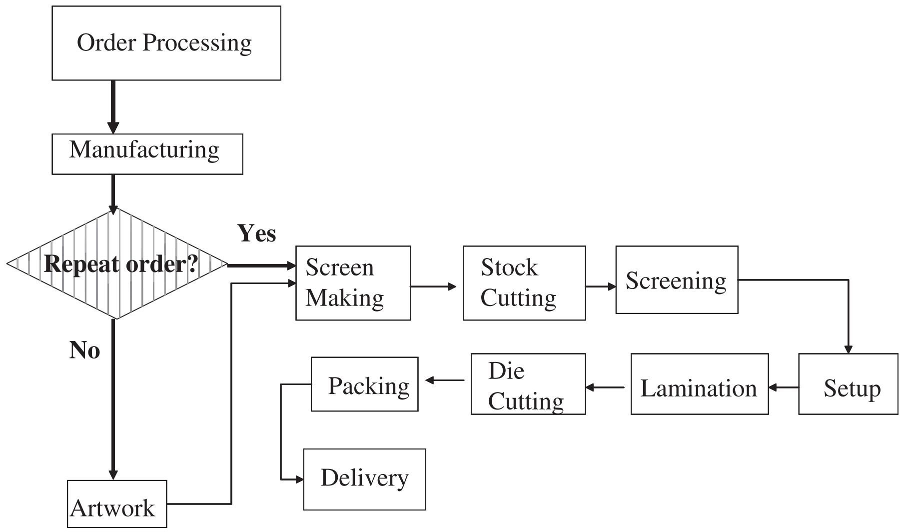

FIGURE 1: Process Flow of Screen-Printing Operation

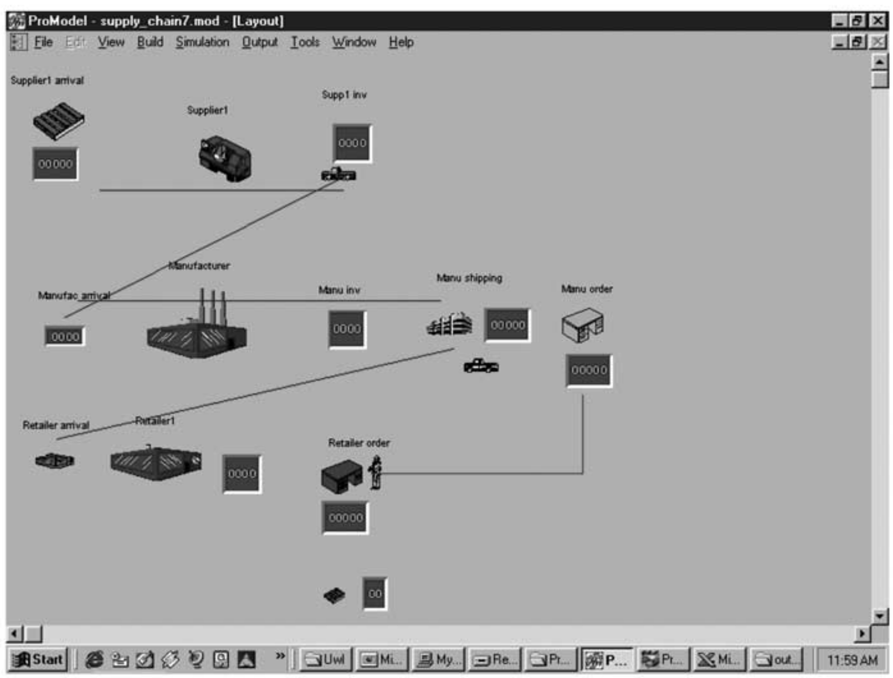

FIGURE 2: A View of the PROMODEL Supplier-Manufacturer-Retailer Modules

TABLE 1: Simulation Inputs and Outputs

Input Variables	*Output Variables*
Order part quantity	Overall lead time in days
Order arrival frequency	Lead time per cell
Order type	Resource utilization
Order release quantity	Wait times per workstation
Supply frequency of raw material	
Operating hours	
Preproduction process times per order	
Production times per part	
Production times per order	
Cell setup times	
Travel time and distance between workstations	
Number of workers	
Number of cells	
Worker preemption rules	

After the buffer is depleted, more supplies are generated with a frequency of 20 seconds per part. This is found to be sufficient to run the model without any shortage of supplies for the data used. If shortages need to be simulated, a probability distribution can be used to generate the arrival of supplies that will result in delays in production.

Typically, orders range between 50 and 20,000 parts. The volume of each order (i.e., the number of parts in an order) appears to follow an exponential distribution with a mean of 2,260 parts. The mean of the distribution can be modified to allow for orders involving either more parts or more frequent arrivals. Also, the distribution can be changed as a result of further data. As parts are generated, the program assigns an order ID to the parts. With respect to arrival frequency, based on the real data collected over 2 years, order arrivals appear to follow a Pearson 5 distribution with a shape of 3.66 and scale of 114,000.

Pearson 5 is a continuous distribution and useful when time delays occur with an unbounded maximum (Harrell, Ghosh, Bowden, 2000). A α (shape) of 3.66 represents a steep peak and slightly shorter tail. The mean frequency was around 25,000 seconds or 7 hours between orders corresponds to receiving on average of two orders within 12 hours. This was considered as a base-order frequency due to the fact that in high demand periods, orders are more frequently received, and higher order quantities are observed. Capacity of order frequency is set to infinite.

Order types are created based on a uniform distribution. An order type could be 0 or 1, 0 representing a special order and 1 representing a regular order. Based on a uniform distribution, different proportions of special and regular orders can be created, such as 75% of the orders being special and 25% regular, or 50% special and 50% regular orders. Capacity of order-type generation is 1. Figure 3 is a schematic of part-order generation.

Order generation is then followed by order processing. A fixed-order release rule is implemented that accepts seven orders to be processed at any time. Arrivals over seven

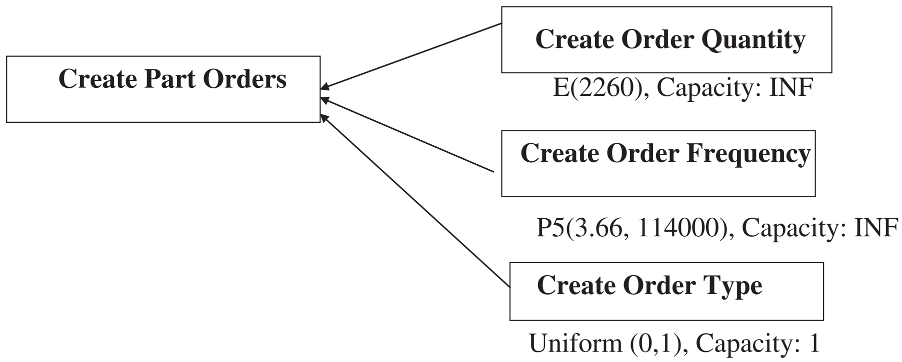

FIGURE 3: Schematic of Part-Order Generation

are rejected until a previously received order is completed and released from the system. Therefore, capacity of the queue prior to preproduction processes is set to seven. This heuristic is again based on the company data used.

Each order or part group passes through three preproduction processes. These are screen making, stock cutting, and screening. One hour constant duration is assigned to screen making, whereas stock cutting follows an exponential distribution with a mean of 1,610 parts. The screening process follows a Pearson distribution with a shape of 3.48 and scale of 20,200. Figure 4 shows the buffer of orders and the preproduction processes that the orders go through prior to cell or job-shop operations.

Simulation of the cellular layout

One of the important modules of the simulation model is the representation of the cell layout that allows for a one-piece flow of parts for each order. "Ungroup" and "Group" functions are used in PROMODEL for this purpose. *Ungroup* allows the process steps to be implemented to each part of an order whereas *Group* regroups the parts to an order that will be delivered to the customer. In the cell model, after an order was ungrouped to parts, each part of the order completes four production processes, namely, setup, lamination, die cutting, and packing (see Figure 5). When all parts of the same order are completed, parts are grouped back to an order, and leave the system.

The real data collected for this simulation model appears to follow these distributions: The cell set-up process follows a gamma distribution with a shape of 2.67 and scale of 0.675. Cell operation is 1 (i.e., lamination follows a Pearson 5 distribution with a shape of 4 and scale of 9.43). Cell operation 2, the die cutting of parts, follows a Weibull distribution (shape: 1.75, scale: 1.18) and packing follows a Pearson 5 distribution (shape: 4.01, scale: 8.2).

Objects in PROMODEL allow for defining attributes and collecting object specific data. Ungrouping of an order to parts is shown below. In the model, product group1

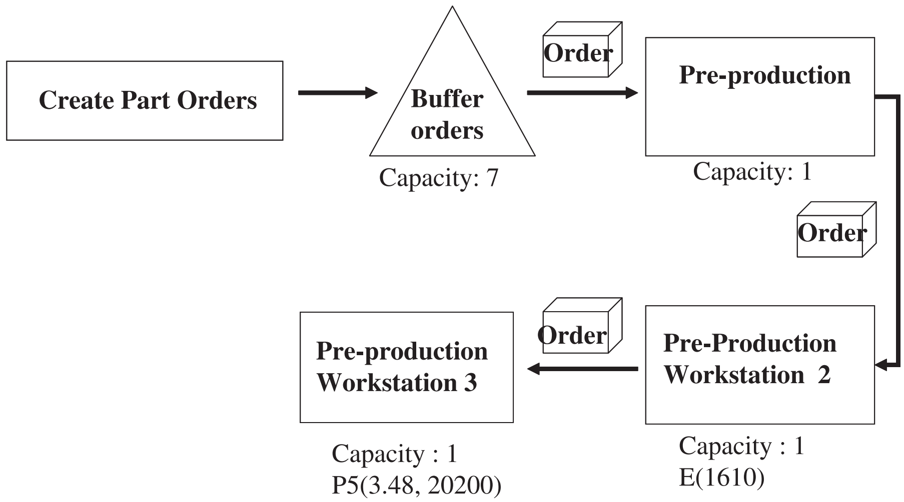

FIGURE 4: Illustration of Preproduction Processes With Time Distributions per Order

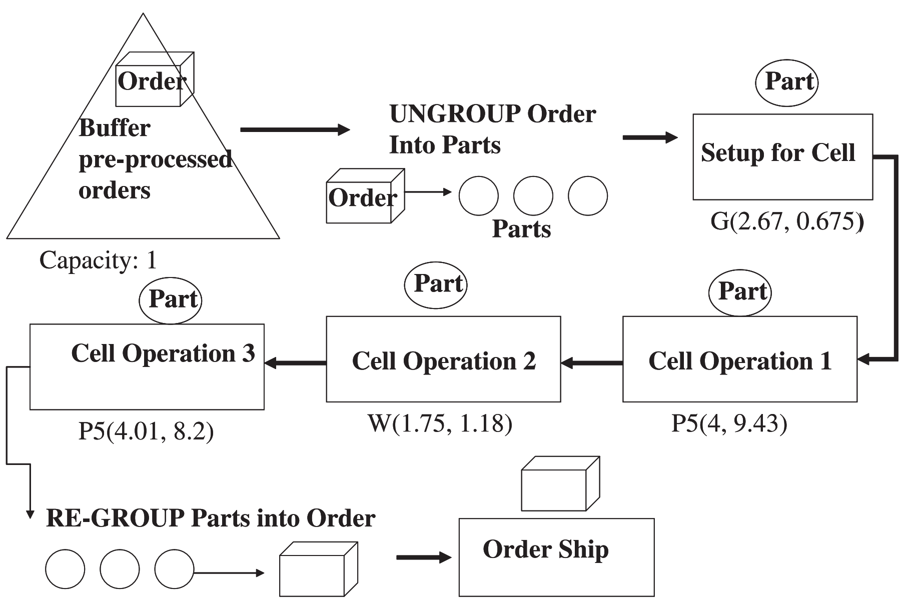

FIGURE 5: Illustration of One-Part Flow Cell Processes

represents an order. Product 1 represents one part of the order and it is the outcome of the ungrouping.

Operation for Product-group1:
temp_attr1=in_time
temp_attr2=order_id
temp_attr3=group_quantity
temp_attr4=order_type
temp_attr5=due_date
order_in_process_at_cell=1
Ungroup

Regrouping of parts to the order that was previously ungrouped is shown below. Product 1 represents a part. The operation for product 1 that groups product_1 to product_group1 is as follows:

temp_attr1=in_time
temp_attr2=order_id
temp_attr3=group_quantity
temp_attr4=order_type
temp_attr5=due_date
temp_attr6=cell_lead_time
Group group_quantity as Product_group1

Simulation of labor allocation in cells

This module allows for the evaluation of labor-allocation strategies within the cellular layout. More important, it allows students to understand how multitasking works. In cellular layout, workers are cross-trained to perform more than one type of job. The question is to determine the type of jobs and the number of workers that are multitasked within a cell and across cells. In the case of one cell, fixed allocation of workers is compared with multitasking of jobs as workers become idle. For the two-cell scenario, several worker allocation and preemption policies are implemented. Figure 6 shows a snapshot of the two-cell model. In this model, two identical cells are setup at a close proximity.

One of the labor allocation strategies is to give priority to the cell that receives a high volume order. Whichever cell receives a high volume order, two operators, one from lamination and one from the packing operation, are moved to that cell until the completion of the parts. Therefore, two operators are shared between the two cells based on order quantity. Initially, four operators are assigned to cell-1 and two operators are assigned to cell-2. In case of high volume in cell-1, these operators remain assigned to cell-1. However, if cell-2 receives a high volume demand, the two operators move to cell-2. In regards to multitasking within a cell, setup and die cutting operators are assigned to two jobs as they become idle. The allocation strategies can be modified based on user input as shown here.

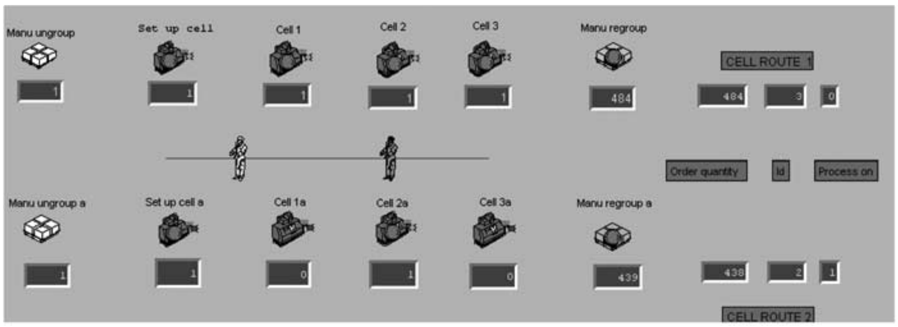

FIGURE 6: A Snapshot of the Two-Cell Simulation

```
if group_quantity_route1group_quantity_route2 then
{
GET Machinist2
wait P5(4, 9.43)
FREE Machinist2
}
else
{
GET Machinist
wait P5(4, 9.43)
FREE Machinist
}
wait 2
```

Simulation of process (job shop) layout

In the job-shop model, instead of a one-piece flow, batch-production principles are applied. Also, workers and orders need to travel between production workstations until all parts of the same order are processed. Therefore, travel time and distance between process stations are taken into account in the simulation model. One worker per process per workstation is assigned. In PROMODEL, "Path Networks" is used to identify travel distance between workstations. In the example herein, workstations are set 1,500 ft. apart, based on the conditions of the factory. Similarly, because workers and semifinished products move between workstations, "Entities" is used to describe the speed of transport in feet per minute (fpm). Regarding labor allocation, one worker is assigned to each workstation. Due to time delays and distance between workstations, sharing of resources in not economical. Therefore, no multitasking is implemented. A snapshot of the job-shop simulation is shown in Figure 7.

The major difference with the job-shop model is the need to process the entire batch of parts of an order at each workstation, as opposed to one part in the cell, then transport the parts to the next workstation, and wait until the next workstation is available. Therefore, for each operation, a waiting time is included. The waiting times appear to follow a triangular distribution with a minimum, average, and maximum wait times.

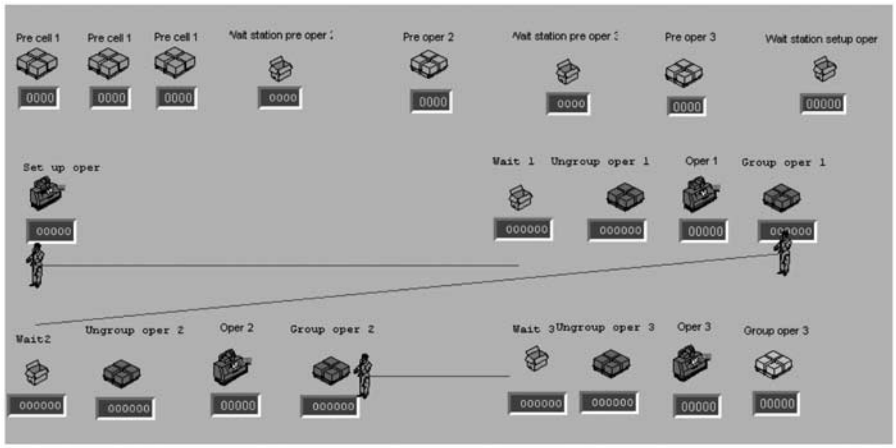

FIGURE 7: A Snapshot of the Job Shop Layout

For instance, parts wait 320,400 seconds on average prior to operation 1. Once the workstation is available, the part group is ungrouped to individual parts and operation 1 is implemented to each part. The duration of operation 1 follows a Pearson 5 distribution (shape: 2.62, scale: 3.04). After the completion of the operation at the workstation, parts are regrouped to part groups and transported to the next workstation. As such, Ungroup and Regroup subroutines are used at each process step. Also, no new parts are allowed in Setup until all parts leave the last workstation. Figure 8 represents an illustration of the job-shop simulation.

The simulation illustrates several disadvantages of the job shop layout: (a) the large distance between workstations causes delays and communication problems, and (b) operations are more costly due to rejecting whole batches of parts. In addition, as a result of routine handling of a batch of parts at each workstation, workers' fatigue is increased and quality is reduced.

Simulation results

Following the order completion, the last step of the simulation is to convert leadtime to days and to report overall lead time per day. The simulation model is programmed to run for 5,000 hours, where the system was found to be in steady state. A total of 5,000 hours corresponds to 7 months of operation in the plant. Then model runs are replicated 10 times, which correspond to a 91% confidence interval. As 90% and greater is desirable, 10 replications were found sufficient for this model. A detailed explanation of determining replication number or sample size and steady state conditions can be found in Banks and Carson (1984) and Harrell et al. (2000). Besides the overall lead time in days, the simulation output consists of the results of 10 replications, the average of these replications, and the standard deviation of the following: lead time per cell for the cellular layout, lead time per workstation for the job shop,

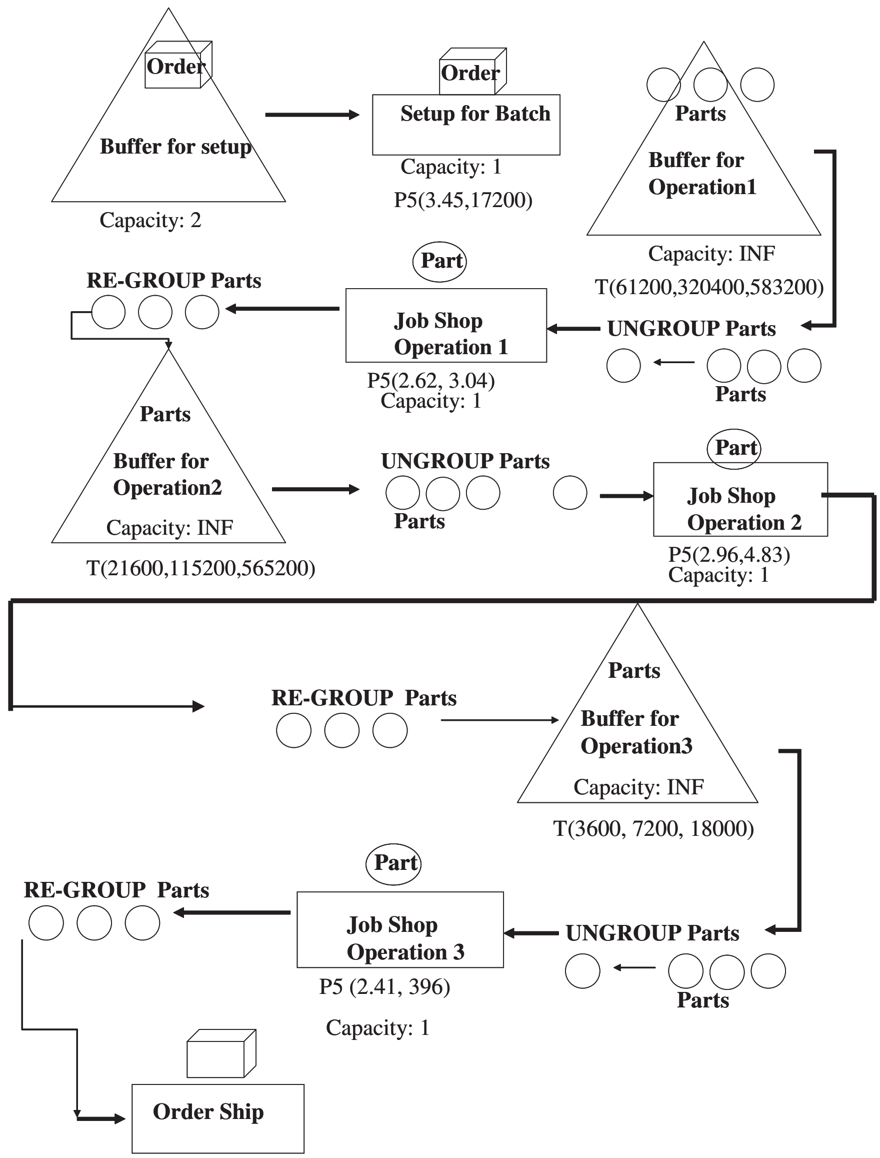

FIGURE 8: Illustration of the Job Shop Simulation Modules

resource utilization per worker, and wait times per workstation for both layouts. An example of lead-time simulation output is given in Table 2.

In this model, emphasis is given to lead-time and resource utilization and students are asked to compare the process (job shop) and cell layouts with respect to these measures, produce graphs in Excel, and comment on the differences. A typical

TABLE 2: A Simulation Output on Lead Time

Lead Time for Job Shop Layout	*Lead Time for Two Cell Layout*	*Lead Time per Cell*
10.19 (Rep 1)	1.93 (Rep 1)	.41 (Rep 1)
10.89 (Rep 2)	1.53 (Rep 2)	.39 (Rep 2)
10.09 (Rep 3)	1.79 (Rep 3)	.34 (Rep 3)
10.12 (Rep 4)	1.83 (Rep 4)	.45 (Rep 4)
9.81 (Rep 5)	1.94 (Rep 5)	.43 (Rep 5)
10.50 (Rep 6)	2.02 (Rep 6)	.46 (Rep 6)
10.59 (Rep 7)	2.08 (Rep 7)	.46 (Rep 7)
10.21 (Rep 8)	1.79 (Rep 8)	.52 (Rep 8)
10.55 (Rep 9)	1.78 (Rep 9)	.44 (Rep 9)
10.49 (Rep 10)	2.47 (Rep 10)	.55 (Rep 10)
10.34 (Average)	**1.92 (Average)**	**.45 (Average)**
0.31 (*SD*)	**0.24 (*SD*)**	**.05 (*SD*)**

representation of a graphical lead-time comparison versus part volume is shown in Figure 9. Students are required to prepare short papers describing the advantages and disadvantages of the process and cell layouts. In addition, implications of these outcomes on lean production and quality strategies are studied. Several questions are considered: How is the shorter lead time related to lean production, what is the impact of lead time on quality and cost performance, and what operation and business strategies can be formed as a result of the study?

Advantages and disadvantages of PROMODEL

One of the advantages of PROMODEL is that it is specifically written for production operations. A large number of elements, such as path networks, locations, resources, entities, and attributes of these elements can, as such, be modeled. Furthermore, PROMODEL allows the modeling of material handling systems, including cranes, conveyors, and other industrial vehicles. The syntax of PROMODEL fits well with an assembly process. Another advantage of PROMODEL is that it comes with StatFit that can be used for fitting a wide range of probability distributions to your data. Once a working code is generated, the change of parameters, attributes, or simple programming rules seems to be uncomplicated. PROMODEL offers a range of icons that can be selected for visual representation. Graphics for the program are very satisfactory.

PROMODEL, though, has several drawbacks. One of the biggest challenges is to fit the PROMODEL syntax to cellular manufacturing. Most of the ready-to-use model elements needed to be modified. Although the GROUP and UNGROUP routines did work, it required many revisions to model one-part flow versus batch production. Documentation in the user and reference manuals seemed convoluted at times and difficult to follow. The author had to refer to several other books, published in conjunction with the PROMODEL simulation, to gain a better understanding of the PROMODEL logic

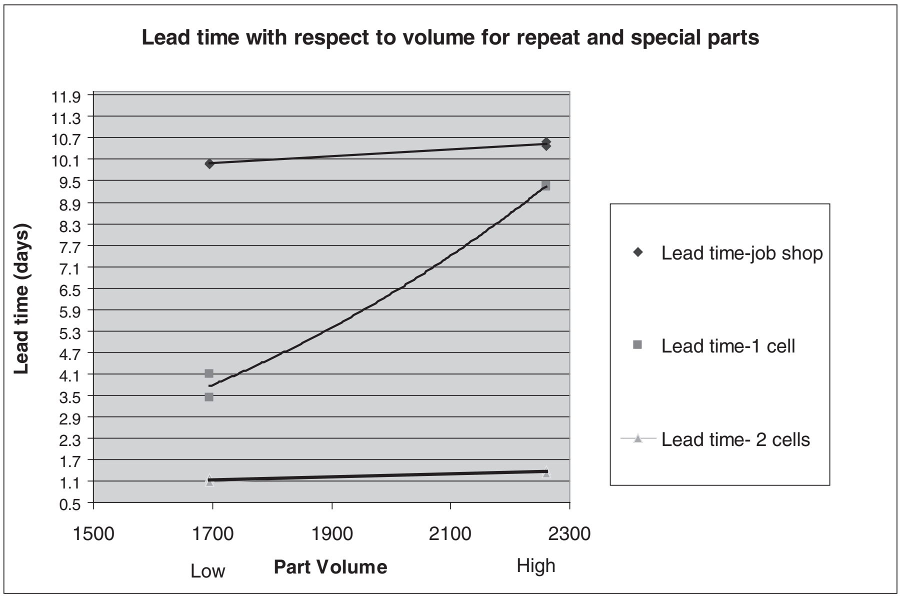

FIGURE 9: Lead Time Comparison of Three Layout Scenarios

and the Statfit program (these are shown in the references). A significant difficulty was that Statfit did not work on the Windows 2000 platform (since rectified) and that distribution fitting had to be done separately with the Windows 95 operating system using a second hardware. The PROMODEL technical service people tried to help but could not do much about this compatibility issue as PROMODEL fell behind Windows updates.

More important, the current model could not be expanded to include many of the realities of cellular manufacturing modeling. One of these is the representation of breakdowns and repairs. The failing of a process equipment station within a cell was not accomplished. The model could not be customized any further as this caused failures of the model in other areas. In other words, the model could not be made robust enough to incorporate further realistic details. Furthermore, the PROMODEL syntax, as it existed in version 4.2, was not suitable to program various-order release mechanisms. Too much emphasis was given to modeling a typical assembly shop floor operation and not enough to preproduction processes. The author assumes that the current version of PROMODEL offers more flexibility or that the Supply Chain module of PROMODEL enables the many drawbacks mentioned above to be overcome.

Conclusion

A simulation model using PROMODEL was developed to teach job shop (process) and cellular layouts in an undergraduate OM class. The simulation model developed allows students to better understand layout modeling and evaluate various manufacturing and labor-allocation strategies. Implications of these strategies on process lead-time and resource utilization, two widely accepted performance measures, were analyzed. Visual representation of the cell and job-shop layouts facilitates the understanding of layout modeling. The understanding of multitasking and resource sharing in cells helps to illustrate the lean-production concept. Although the performance of the students was not specifically analyzed (and that can be extended to further studies), the instructor observed increased performance in these areas as a result of the simulation model. The simulation allows the learners to be independent thinkers by inquiry, practice, and discovery, and provides the opportunity to share their findings with others.

In addition, students become familiar with stochastic modeling and engage better with simulation and operations research techniques by learning how a simulation model works. Furthermore, because the simulation model enables the testing of operations strategies, students appreciate its use as a decision-making tool and see its benefits in further areas, such as in financial and marketing strategy formulation.

One of the limitations of the simulation model created is that it is implemented on a small scale. To generalize the use of the layout-simulation model, a network version of the simulation program and an easy user interface are needed. Students require guidance to use the model, to make changes in the data, and to generate outputs from the model. Furthermore, for simplicity, no breakdowns or material shortages were incorporated into the model. These additions would make the simulation model more realistic and, at the same time, the impacts of any failures could be analyzed. Another possible addition to the model is the simulation of scheduling policies. This would allow for a more comprehensive layout-simulation model.

Further additions to this study would be to compare two or three simulation packages, as suggested by one of the reviewers of this manuscript. This would allow for a determination of which simulation package works better for task scheduling, which for labor allocation, and so on. A comparison matrix based on these programming characteristics would be useful for instructors and novice programmers.

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Hulya Julie Yazici is currently an associate professor of operations management and decision sciences at the Florida Gulf Coast University. She holds a B.Sc. in mining engineering and a M.Sc. and PhD in engineering management from the University of Missouri–Rolla. Her research interests include advanced manufacturing systems, supply chain simulation, quality management, organizational communication systems and innovative education. She has authored 12 refereed journal articles, two chapters, and 21 conference proceeding articles. She is a senior member of IIE, DSI, IEEE, EMGT, and PMI.

ADDRESS: HJY: Department of Computer Information Systems and Decision Sciences, Florida Gulf Coast University, 10501 FGCU Boulevard South, Fort Myers, FL 33965; telephone: +1 239 590 7309; fax: +1 239 590 73 30; e-mail: huyazici@aol.com.