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Abstract: Simulation so used in many arenas to aid in the decision making process. This paper uses a simulation tool to analyze tradeoff decisions in a manufacturing environment. Specifically it examines the tradeoffs between batch sizes; number of manufacturing machines and workforce level and several measurements of the system performance are analyzed.

Simulation in Manufacturing Decision Making

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Introduction

Simulation is used in many arenas to aid in the decision-making process. After a valid model of a system has been constructed, it is possible to pose 'what-if' scenarios to the simulation. This project uses a simulation tool to analyze trade-off decisions in a manufacturing environment. Specifically it will examine the tradeoffs between batch size, number of manufacturing machines, and workforce level. Several measurements of system performance will be analyzed.

The paper is divided into 4 additional parts. The *Model Description* section will characterize the manufacturing system that has been chosen for the simulation. The *Model Logic* section will introduce the Extend modeling tool and document the model. The *Model Experimentation* section will explain the parameters of the model. Finally, the results of the simulation will be reported and conclusions will be in the *Model Observations* section. Concluding remarks will be made in the *Summary* section.

Model Description

The model used for this exercise is a sample model that Extend included with it's manufacturing library. The model original model has the following characteristics:

- Four operations are performed on each part in the same sequence.
- Four product types with different processing times for each part on each operation. The processing time for each part is sampled form a normal distribution with a mean shown in Table 1 and a standard deviation equal to 20% of the mean.

Table 1 - Mean Processing Times

	Part Type				
Operation	**1**	**2**	**3**	**4**	**Average**
1	2.0	2.1	1.8	2.6	2.1
2	2.3	1.6	2.4	1.5	2.0
3	2.1	3.1	1.4	2.9	2.4
4	2.2	2.5	1.8	1.9	2.1
Total	8.6	9.3	7.4	8.9	

- Parts arrive in block orders, are broken into individual pieces, then grouped into orders for delivery to customer.
- Setup times are included when part types change on each operation. Each machine has a setup time from 10 to 15 minutes when the part type changes.

In order for the model to be more interesting, additional capability was added to the original model. Three significant capabilities were introduced. First, the blocks used to represent the operations were altered so that each operation could have multiple machines if desired. Second, the model was altered to use labor resources in addition to machine resources. Third, additional measurements of system performance were introduced.

The model had to be altered significantly in order to produce the following performance measurements:

- Average Work-In-Process
- Average Flow Time
- Average Machine Utilization
- Worker Utilization

Model Logic

The purpose of this section is to introduce the reader to the Extend modeling tool and describe how the model was implemented in Extend. Figure 1 depicts the top level model logic. The grayed area illuminates the product flow path.

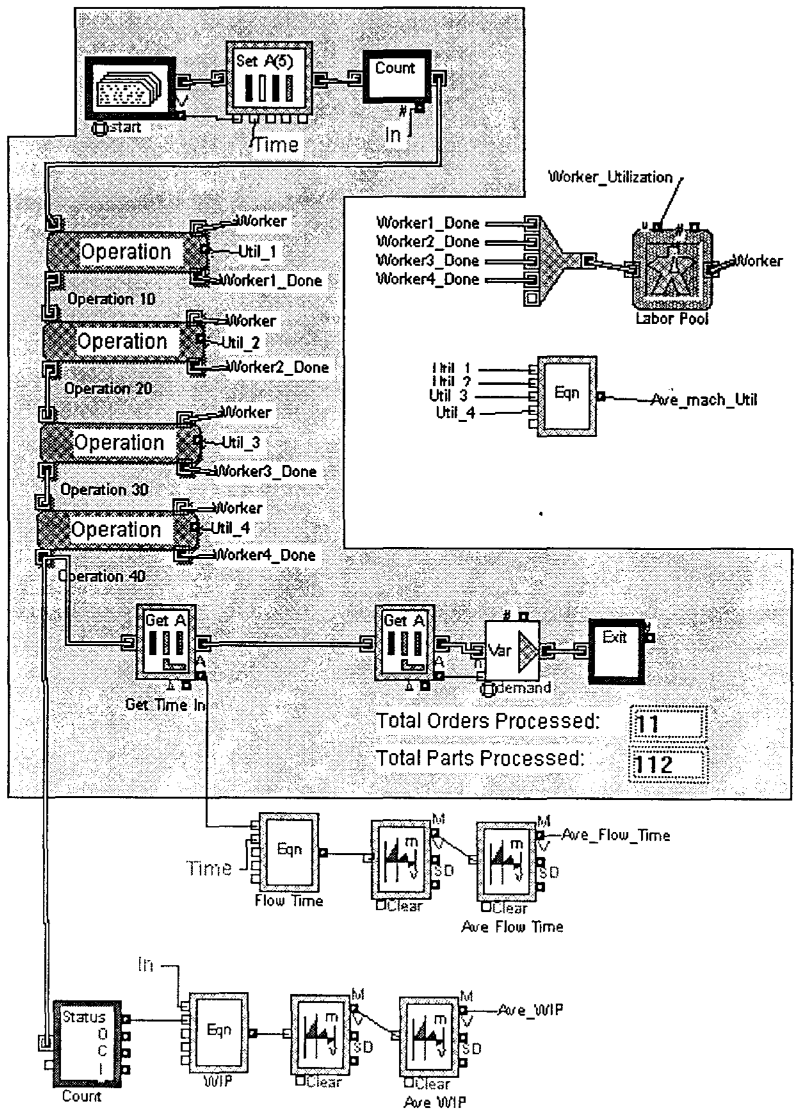
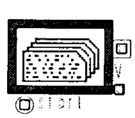
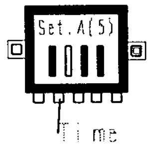
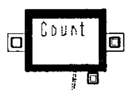


Figure 1

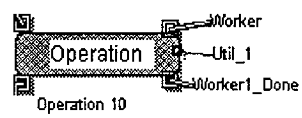
In order to understand how the Extend simulation tool works, each block will be described. The very  first block is called a *Program* block. Its function is to schedule the arrival of product orders. The schedule for various batch sizes is summarized in Table 2.



The second block is the *Set Attribute* block. At this block each product that enters the system is assigned two pieces of information, the time that it entered the system, and the size of the order that it is part of. The time that the part entered the system will be important for calculating the flow time. The size of the order is used to determine when a part type changes at each operation.



The *Count* block sums the total number of parts that have entered the system. This number is later used to calculate WIP.



Each of the *Operation* blocks is actually a hierarchical block with additional logic implemented inside of the block. The nodes on the right of the block are where workers enter and leave the block and where the utilization of the machines is passed to the top level of the model. The nodes on the left are used for passing parts from one operation to another. The logic of the operation block is depicted in Figure 2. All four operations are identical.

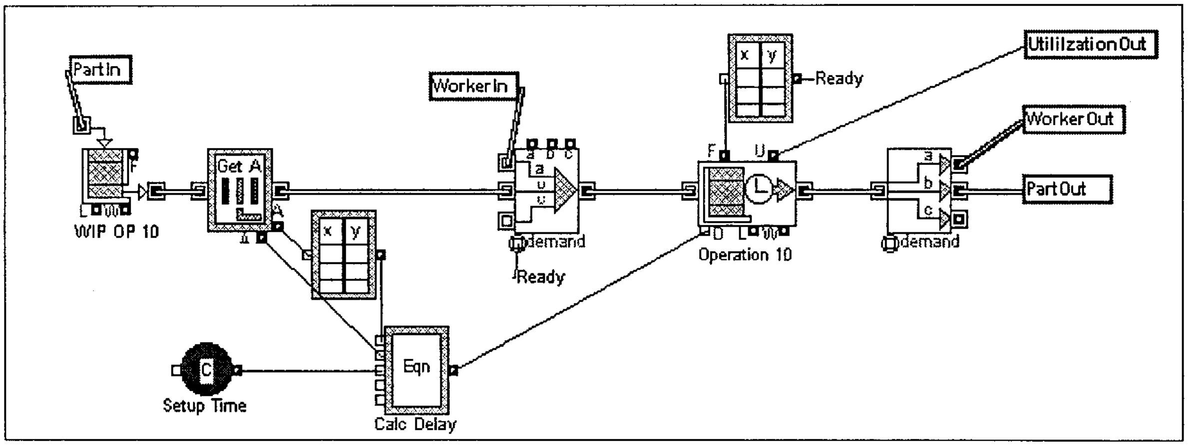
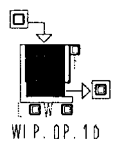
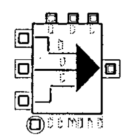


Figure 2

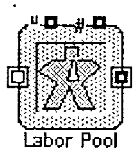
As the parts are passed from the top level model to the operation block, the *FIFO Queue* block holds the parts until a downstream machine becomes available. This queue operates on a first-in-first-out basis.



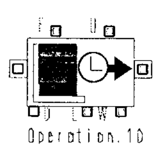
The purpose of the *Batch* block is to pair a worker with a part to be processed. The worker is pulled from the *Labor Pool* block on the top level model.



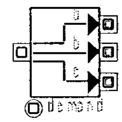
The labor pool is the central depository for all the workers. This is useful for calculating one overall worker utilization rate for the entire manufacturing operation.



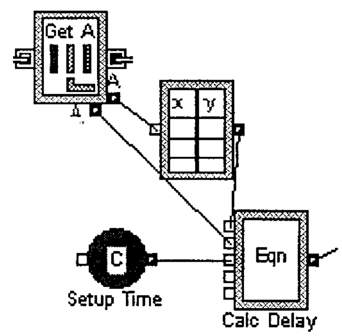
After the product is matched with a worker, the *Multiple Activity* block performs the manufacturing operation on the part. This block has the capability to work on multiple parts at one time thus simulating multiple machines at that operation.



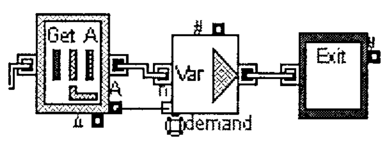
Finally, the worker is separated from the product in the *Unbatch* block. The worker is then returned to the labor pool on the top level and the product is sent to the next operation. While in reality a worker would not really go anywhere in between completing each part the returning of the worker to the labor pool is inconsequential since there is no time delay associated with the movement. It is necessary to implement the use of workers this way in Extend in order to get a correct worker utilization measure.



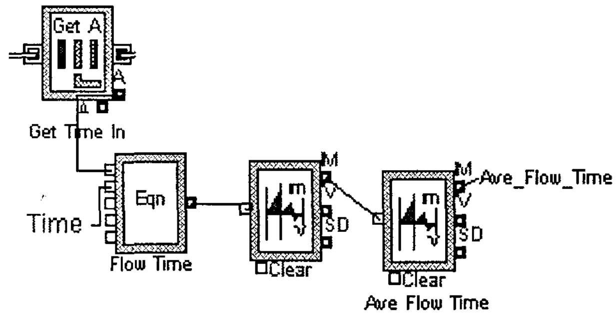
The remaining blocks in the operation block serve the purpose of calculating the processing time for the part at the operation. The *Get Attribute* block determines what part type is to be processed. The *conversion table* then finds the mean processing time for that part and the *equation block* samples from a Normal distribution to determine the processing time plus any setup time that would be required if the part type changes. The values in the conversion table can be observed in Table 1.



After all four operations have been performed on the part it is then held for batching with the rest of the order and then the order exits the system. The *Get Attribute* block reads the order quantity that the part belongs to then feeds the information to *the Batch (Variable)* block. *The Batch (Variable)* block then holds the parts until the complete order has been processed. The entire order then leaves the system through the *Exit* block.

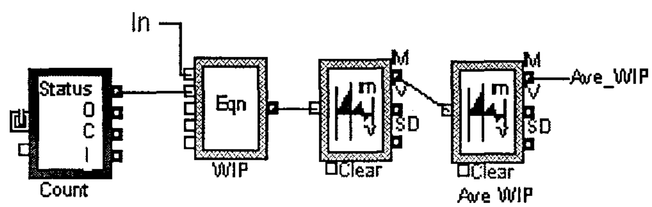


Most of the remaining blocks in Figure 1 serve the purpose of calculating statistics. These four blocks are used to calculate the flow time of each part and the average flow



time of the simulation. The *Get Attribute* block reads the time that the entity entered the system. The *Equation* block subtracts that number from the current time to determine the total time that the part was on the manufacturing floor. The first *Mean & Variance* block calculates the statistics for the current simulation and the second block calculates the statistics over multiple simulations.

These four blocks calculate the average Work-In-Process over the course of the simulation and multiple simulations. The *Status* block counts the number of parts that have completed all four operations. The *Equation* block subtracts that number from the total number of parts that have entered the system. The first *Mean & Variance* block calculates the statistics on WIP for the current simulation while the second block calculates the mean and variance over multiple simulations.



Model Experimentation

In order to experiment with different models, several parameters of the model were varied. The parameters chosen for this project were batch size, number of machines, and number of workers.

The simulation tested three parameters, batch size, number of workers, and number of machines. Each of the parameters took three values. This resulted in 3x3x3 = 27 different model configurations. In addition, because of the randomness involved in the processing times, each configuration was run 50 times to get an meaningful result.

Batch Size

In order to test the effect of varying batch size of the performance of the system, three different batch sizes were tested. Table 2 describes the three schedules that were implemented in the simulation. The large batch size was the batch size of the original model. It was chosen as the largest batch size because batches any larger would cause some part types not to be scheduled in an eight hour (480 minute) day. The simulation runs in the unit of minutes.

Table 2 - Order Schedule

Large Batch		*Medium Batch*		*Small Batch*	
Time	Size	Time	Size	Time	Size
0	80	0	40	0	16
240	50	120	25	48	10
360	30	180	15	72	6
420	30	210	15	84	6

The order schedule for large batches repeats every 480 minutes, the schedule for medium batches every 240 minutes, and the schedule for the small batches every 96 minutes. It is important to note that under each schedule the same number of parts is scheduled every day, just in different quantities at different times.

Number of Machines

The original configuration of the model specified that each operation consists of exactly one machine. The model was altered to introduce the capability of adding additional machines to each operation. The simulation was tested with the total number of machines at 4, 5, and 6. The operation that received the additional machines was chosen based the average length of the queue for one day. The operations with the largest average queues were the first and third operations. The first operation obviously had a large average queue length because as part orders came in, all the parts entered the queue for the first operation. The third operation had the second longest average queue length because the average processing time at that operation was the highest as can be seen in Table 1.

Number of Workers

The initial number of workers in the labor pool was chosen rather arbitrarily. The minimum number of workers was 6 because it would be the minimum number of workers needed under the scenario with 6 machines. The number of workers used in subsequent simulations was eight and ten.

Model Observations

Without an algorithm for deciding which parameters lead to the best result it is useful to examine the results from varying each parameter while holding the others constant. Next we will examine the effect from varying each parameter. Table 3 summarizes the results from all runs.

Table 3 - Simulation Results

Simulation #	# m/c	Batch Size	# workers	Ave WIP	Ave Flow Time	Ave m/c Utilization	Worker Utilization
1	4	Large	6	48.7	139.4	80.7%	53.8%
2	4	Large	8	48.7	139.2	80.7%	40.3%
3	4	Large	10	48.7	138.9	80.8%	32.3%

4	4	Medium	6	43.2	113.0	87.4%	58.2%
5	4	Medium	8	43.2	112.8	87.4%	43.7%
6	4	Medium	10	43.5	113.7	87.3%	34.9%
7	4	Small	6	48.8	120.2	90.3%	60.2%
8	4	Small	8	49.1	120.8	90.3%	45.2%
9	4	Small	10	48.9	120.5	90.3%	36.1%
10	5	Large	6	44.4	129.8	73.5%	74.7%
11	5	Large	8	44.5	130.4	73.5%	56.0%
12	5	Large	10	44.7	130.6	73.6%	44.8%
13	5	Medium	6	39.0	104.0	80.7%	62.8%
14	5	Medium	8	38.7	103.1	80.9%	47.2%
15	5	Medium	10	38.8	103.3	80.8%	37.7%
16	5	Small	6	45.5	113.6	89.1%	71.3%
17	5	Small	8	45.4	113.4	89.1%	53.5%
18	5	Small	10	45.5	113.6	89.1%	42.8%
19	6	Large	6	38.3	114.5	66.2%	85.7%
20	6	Large	8	38.6	114.8	66.3%	64.3%
21	6	Large	10	38.7	115.4	66.2%	51.4%
22	6	Medium	6	31.2	86.0	72.9%	66.5%
23	6	Medium	8	31.3	86.2	72.9%	49.9%
24	6	Medium	10	30.9	85.5	72.9%	39.9%
25	6	Small	6	40.1	101.7	82.3%	77.2%
26	6	Small	8	39.9	101.2	82.4%	57.9%
27	6	Small	10	40.2	101.8	82.3%	46.3%

Batch Size

Batch size was varied while holding the other variables constant. Three important observations about the effect of batch size on the system performance are:

1. As batch size increases, machine utilization decreases. This can be easily observed from Table 4. The reason for the increase in machine utilization is effect of setup time on the amount of work each machine must do. As batches become smaller, machines must setup for new part types more often. This takes more time and leads to a higher machine utilization.

2. The best (lowest) Work-In-Process (WIP) level is obtained under the medium batch size. This is the tradeoff between the amount of product that is on the floor at any one time and the effect of setup times. The larger batch sizes will increase WIP because a lot of product is put into the queue from the start of the simulation, however, change-overs are required less often at the machines. The smaller batch sizes decrease the amount of product put in the queue at the beginning of the day but cause an increase in WIP because the setup times slow the movement of product through the system. This can be observed from Table 4.

3. The best (lowest) Flow Time measure is realized under the medium batch size as well. The reasons for this are identical to the reasons why the medium batch size performs best by the WIP measurement.

4. The medium batch size results in the lowest worker utilization. The large batch size results in the highest worker utilization.

Table 4 - Results by batch size

# m/c	# workers	Batch size	Ave WIP	Ave Flow Time	Ave m/c Utilization	Worker Utilization
6	6	Small	40.1	101.7	82.3%	77.2%
6	6	Medium	31.2	86.0	72.9%	66.5%
6	6	Large	38.3	114.5	66.2%	85.7%
6	8	Small	39.9	101.2	82.4%	57.9%
6	8	Medium	31.3	86.2	72.9%	49.9%
6	8	Large	38.6	114.8	66.3%	64.3%
6	10	Small	40.2	101.8	82.3%	46.3%
6	10	Medium	30.9	85.5	72.9%	39.9%
6	10	Large	38.7	115.4	66.2%	51.4%

Number of Machines

Next, we will hold the other variables constant and observe the effect of the number of machines on our performance measurements. All else equal, an increase in the number of machines will lead to:

1. A decrease in flow time. Parts are processed more quickly as more machines are added at bottlenecks. See Table 5 for these results.
2. A decrease in Work-In-Process level. Basically, as machines are added parts spend less time in queue waiting for processing and are completed more quickly. This reduces the amount of product on the manufacturing floor.
3. A decrease in average machine utilization. Idle time caused by the additional machines at operations 1 and 4 decreases the overall machine utilization.

4. An increase in worker utilization. If the number of workers is held constant, adding additional machines will demand more labor thus increasing the utilization rate of existing workers.

Table 5 illustrates the above principles for the medium batch size product schedule. It can be clearly seen that as the number of machines increases, flow time decreases, WIP decreases, average machine utilization decreases, and worker utilization increases. These observations hold for the small and large batch size product schedules as well.

Table 5 - Effect of # of machines

# workers	Batch size	# m/c	Ave WIP	Ave Flow Time	Ave m/c Utilization	Worker Utilization
6	Small	4	48.8	120.2	90.3%	60.2%
6	Small	5	45.5	113.6	89.1%	71.3%
6	Small	6	40.1	101.7	82.3%	77.2%
6	Medium	4	43.2	113.0	87.4%	58.2%
6	Medium	5	39.0	104.0	80.7%	62.8%
6	Medium	6	31.2	86.0	72.9%	66.5%
6	Large	4	48.7	139.4	80.7%	53.8%
6	Large	5	44.4	129.8	73.5%	74.7%
6	Large	6	38.3	114.5	66.2%	85.7%

Number of Workers

Table 6 indicates that as the number of workers increases, there is no effect on average WIP, average flow time, or average machine utilization. And, of course, as the number of workers increases, worker utilization decreases.

This makes sense if we remember that the minimum number of workers was chosen to staff all the machines in each scenario. Therefore, there are always enough workers to staff each machine.

Table 6 - Effect of # of Workers

# m/c	Batch size	# workers	Ave WIP	Ave Flow Time	Ave m/c Utilization	Worker Utilization
6	Large	6	38.3	114.5	66.2%	85.7%
6	Large	8	38.6	114.8	66.3%	64.3%
6	Large	10	38.7	115.4	66.2%	51.4%
6	Medium	6	31.2	86.0	72.9%	66.5%
6	Medium	8	31.3	86.2	72.9%	49.9%
6	Medium	10	30.9	85.5	72.9%	39.9%
6	Small	6	40.1	101.7	82.3%	77.2%
6	Small	8	39.9	101.2	82.4%	57.9%
6	Small	10	40.2	101.8	82.3%	46.3%

If the number of workers were not enough to staff each machine then increasing the number of workers would have the same effect on WIP and Flow Time as increasing the number of machines. Deciding what level of labor to use would depend on the desired worker utilization rate. In this simulation, lunch and breaks are not scheduled. This would need to be taken into effect when deciding the appropriate worker utilization rate.

Summary

Simulation has been a useful tool for analyzing the effects of multiple parameter changes to a manufacturing simulation. While simulation is best suited for analyzing well-crafted 'what-if' scenarios, it is inefficient for finding the optimal solution to a manufacturing problem. Another strength of simulation is the ease of use for changing single parameters and observing the outcome.

Because of the complexity involved in analyzing the tradeoffs between different performance measurements, this simulation was used to analyze the effect of changing single parameters and observing the outcome. The model proved useful for analyzing a limited number of tradeoff decisions in a manufacturing environment.