Improving the Roller Shaft Subassembly Process Using Discrete-Event Modeling and Simulation: A Case Study

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Abstract

The objective of the study was twofold: to identify sources of waste, if any, in terms of materials and man-hours in order to reduce the parts' flow time and the operation cost and to conduct simulation experiments to compare and contrast three scenarios, or two-operator and three-operator workstations, under two operational conditions: a regular production versus a ramp-up production (e.g., order size is doubled) to examine which scenario results in a higher profitability. ARENA software was used to model the system and statistics such as queue time and flow time and cost were analyzed to see which scenario would be optimum. The results suggested that, although for regular production one operator is enough, for ramp-up production, two operators would be more efficient in terms of cost.

Introduction

Modeling and simulation play a vital role in systems design and business process improvement. A model is a representation of a system or a concept. They are built to help researchers better understand the system behavior and run simulation experiments to observe system's behaviors under various scenarios. In essence, simulation is "the imitation of the operation of a real-world process or system over time" [1]. In some cases, one may be able to study the actual system and modify it to observe the outcome (e.g., testing the impact of expanding the number of automated check-in kiosks on reducing passengers' waiting time) [2]; however, changing the setting of a real emergency room to study the impact on serving the patients is not a viable option.

Depending on the nature of the problem, one may need to use discrete-event or continuous simulation. For example, a typical queuing problem may be modeled using discrete-event modeling and simulation while continues modeling is suitable for heat transfer analysis in a conductor. Generally speaking, there are several important steps in building and simulating a model [3, 4]:

1. *Problem statement and initial information gathering*: The problem is clearly formulated and stated based on the information obtained through initial study.
2. *Objectives and overall project plan*: This includes the question(s) of interest, plan of study (i.e., number of people to include, cost, etc.), and scope.

3. *Data collection*: Current data relevant to the problem are collected. If data are lacking, an estimated range of input parameters will be used (i.e., typical cycle time for a process)
4. *Model building*: The model will be constructed using a specialized software package (ARENA, ProModel, etc.), although if needed one may use such program as MATLAB or C++.
5. *Verification and validation*: The model should be verified and validated to ensure that it represents the system and its outputs appropriately.
6. *Conducting simulation experiments*: Depending on the problem, typically several scenarios are developed and run to compare the results.
7. *Output analysis*: The simulations outputs are compared and contrasted in order to identify the optimal solution among various alternatives.
8. *Developing recommendation*s: A report is generated to discuss the identified solution and to make recommendations.

This paper presents the application of discrete-event modeling and simulation in a manufacturing company. The roller shaft operation was the primary focus of the study in order to analyze the impact of a ramp-up production (e.g., a sudden increase in demand) on workstation flow time, utilization, and operation cost. Three different scenarios were considered: one-operator, two-operator, and three-operator workstations. After the literature review, the details of how the model was built are discussed, followed by a discussion on the results of the simulation experiments. Finally, a set of recommendations are presented to summarize the findings of the study.

Literature Review

Modeling and simulation of manufacturing systems have been extensively studied and discussed. Smith and Negahban [5] and Smith [6] reported the results of a survey on the use of simulation in design and operation of manufacturing systems. Ferreira, Ares, Peláez, Marcos, and Araújo [7] reported the results of modeling and simulation of an automobile assembly line using ARENA in which they studied the impact of changing the production sequence on line throughput. In another study to examine the usefulness of discrete-event modeling and simulation in small companies, Patterson, Dalgarno, and Murgatroyd [8] used a different software package (Witness) to redesign a manufacturing system. They considered the relative lack of spare resource capacity as a characteristic of small companies that was taken into account. They conducted simulation experiments to study the impact of purchasing a lathe machine on the bottleneck that exited in the manufacturing system, and the results indicated an improvement in the bottleneck, though they require further validation.

The Case

Shuttleworth is a manufacturing company in the area of material handling solutions and packaging products [9]. Its customers range from food industry to automobile, medical and pharmaceutical, to name a few [10]. The authors visited the company's manufacturing facility in order to study their roller shaft workstation. The workstation consists of three sub-sections wherein processes are completed sequentially: chopping, chamfering, and cleaning. Figure 1 shows each of these subsections.

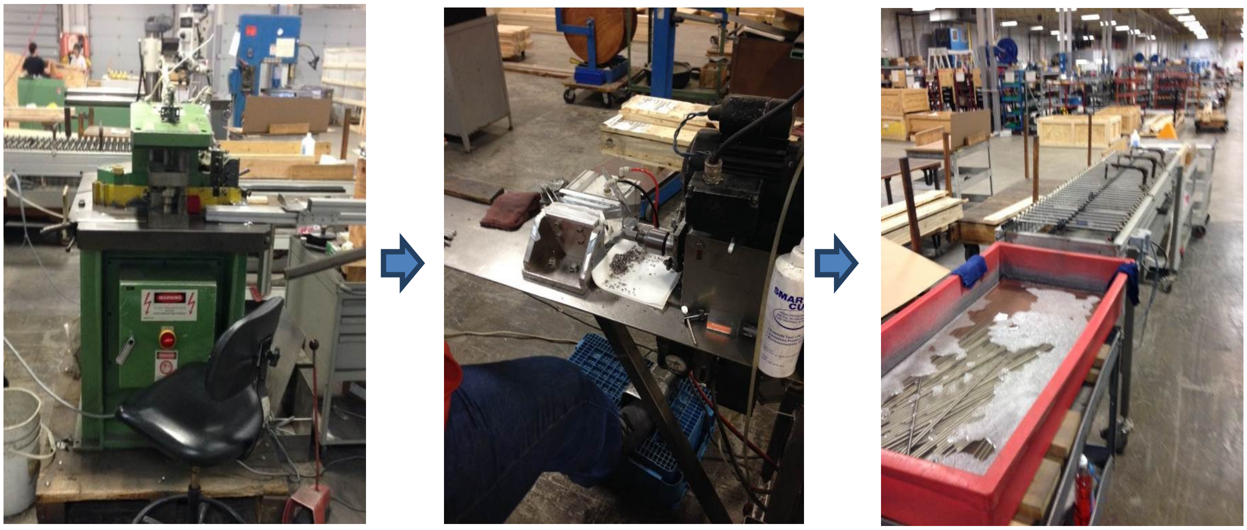

Figure 1. The sub-sections of the roller shaft workstation
(from left: chopping, chamfering, and cleaning)

Data Collection and Analysis

Orders arrive on daily basis and vary in quantity. According to the general manager, they could range from 1 to 4,000 in a typical month. He also mentioned that although the operators know how to run each sub-section and can run the workstation alone, depending on order size, more operators would be added to finish the orders quicker. Per authors' request, the general manager sent a spreadsheet including the order quantity and dates that the company had received in the past three years. Using ARENA's built-in input analyzer, the authors noticed that, except for Weibull, none of the available probability distributions (exponential, gamma, normal, longnormal, uniform, beta, Erlang, and triangular) would fit the data appropriately. Each of these distributions resulted in p-values less than 0.05. Figure 2 shows the best fit using Weibull distribution.

The fit was made based on a histogram with 40 bins. However, as shown in Figure 2, this fit would still result in a p-value close to 0.05 with a 95% confidence level. The authors therefore decided to use the real data to fit the data empirically using ARENA's input analyzer.

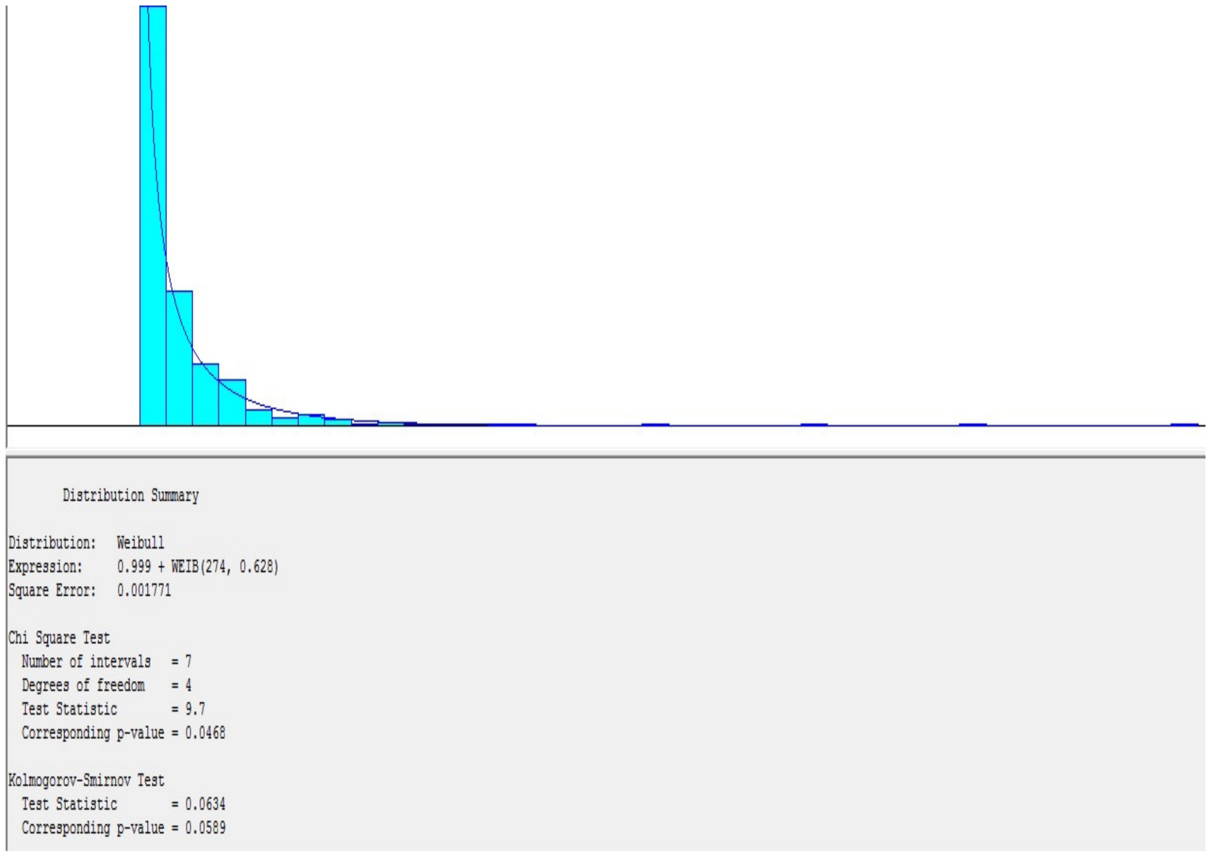

Figure 2. The probability distribution function estimated by ARENA's input analyzer

Table 1 includes the cycle time for each sub-section (in seconds). These are obtained from the general manager based on their historical day-to-day operations.

Table 1. The cycle time for the three sub-sections (in seconds)

Sub-section	**Chopping**	**Chamfering**	**Cleaning**
Cycle time	8 - 15	10 - 14	10 - 14

Model Building and Simulation

For the purpose of the simulation, three scenarios were considered:

1. One operator handles all the three sub-sections (i.e., chopping, chamfering, cleaning),
2. Two operators handle all the three sub-sections. In this case, one operator works only on the chopping sub-section, and the second operator switches between chamfering and cleaning, once s/he finishes 50 parts in each sub-section.
3. Three operators, one for each sub-section.

The computer model was built using ARENA 14.00.00000. Figure 3 shows the generic flowchart used to build the model for all the scenarios. New orders arrived according to the empirical probability distribution calculated by ARENA's input analyzer, as discussed earlier. The interarrival time was modeled using a uniform distribution function with 1 and 30 as the number of days between two consecutive orders.

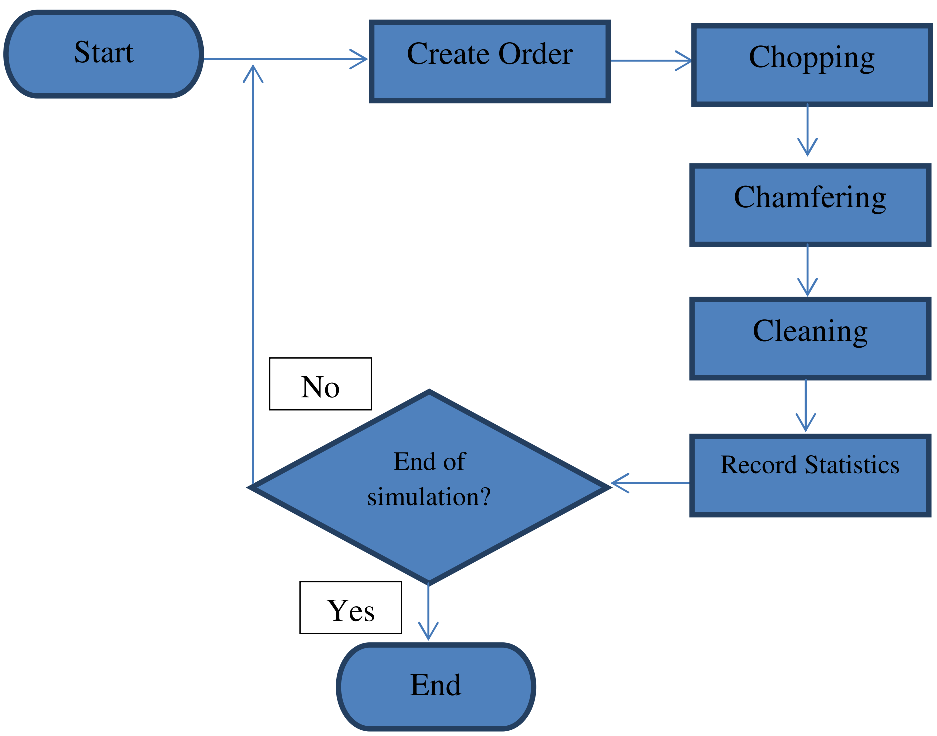

Figure 3. The overall simulation flowchart

The model consists of two segments: the actual workstation model and a controller. The job of the controller is to shift the operator from one sub-section to the other in the case of one- and two-operator scenarios. The three-operator scenario does not include the controller segment, since each sub-section has one operator. Figures 4, 5, and 6 show each segment. The model was verified by analyzing its output and comparing the model components and parameters with the ones provided by the company. The verification was not completed because the experiments were hypothetical. A total of five replications were run for an 8-hour shift for the entire length of one year (365 working days).

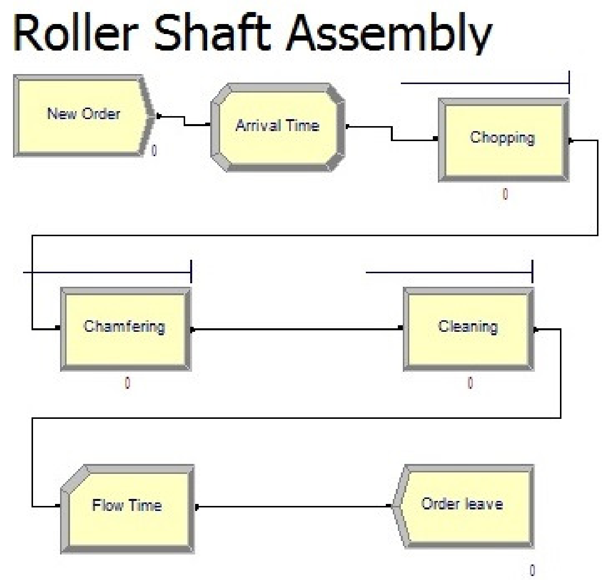

Figure 4. The workstation segment (the same for all the scenarios)

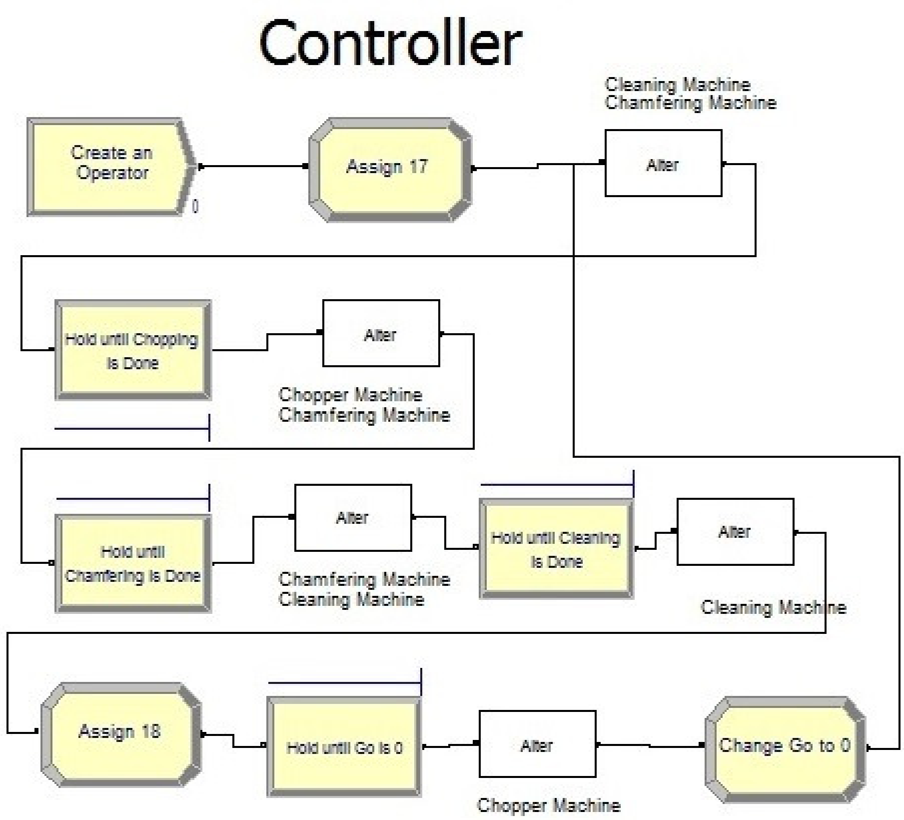

Figure 5. The controller segment (for one-operator scenario)

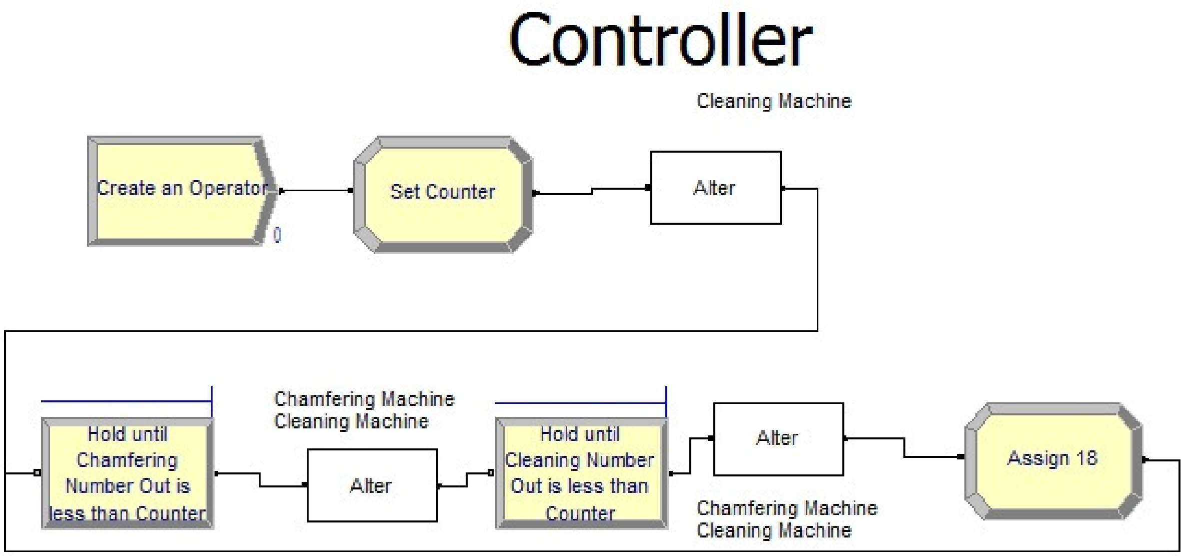

Figure 6. The controller segment (for two-operator scenario)

Discussion

The authors compared two hypothetical operational conditions: Shuttleworth receiving a contract with a typical ("normal") volume order (1 to 4000 per month), and one with double amount (ramp-up production). Furthermore, the workstation ran under the following conditions:

- Originally, there was one operator that ran the entire workstation (one-operator scenario).
- The average work week was 50 to 60 hours per week for one operator. The normal work week was composed of 10 hours per day with the extra on Saturday
- The salary for the operator with no overtime was $36,400 per year. With the time and a half after 40 hours, the operator was being paid $96,005.00 per year for an average work week of 57 hours. This was producing the product at a $59,605.00 overrun on standardized pay level for the operator. Such an operation could result in a potential problem: the operator would become burnt out (s/he would be working too many hours). The operator morale could be also very low due to the lack of planning.

The challenge to management is to see what the profit opportunities are to

- Improve the process
- Add revenue
- Improve return on its investment(ROI)
- Offset the above overloaded operation (one-operator scenario) with the new ones (two- and three-operator scenarios) and gain management acceptance
- Offset new employment costs with added internal revenue
- Offset the cost of new equipment with better process economies of scale

What follows include a summary of the results of the simulation for each of the three scenarios, under normal and ramp-up operations:

First Scenario (one operator handling all three sub-sections)

Normal operation

- The value-added time = 0.0098600 hours
- The orders' quantity (number in) = 13,634
- The finished order (number out) = 13,634
- Work in progress = 67.96
- The average wait time in the queue = 12.2197 hours
- The total time = 12.2296 hours

Ramp-up operation

- The value-added time = 0.00985994 hours
- The orders' quantity (number in) = 15,912
- The finished order (number out) = 15,864
- Work in progress = 199.33
- The average wait time in the queue = 34.0025 hours
- The total time = 34.0124 hours

Second Scenario (two operators: one for chopping, the other for both chamfering and cleaning)

Normal operation

- The value-added time is 0.00985991hours
- The orders' quantity (number in) = 13,831
- The finished order (number out) = 13,871
- Work in progress = 59
- The average wait time in the queue = 10.7737 hours
- The total time = 10.7836 hours

Ramp-up operation

- The value-added time = 0.00986178 hours
- The orders' quantity (number in) = 18,532
- The finished order (number out) = 18,511
- Work in progress = 64
- The average wait time in the queue = 9.6623 hours
- The total time = 9.6722 hours

Third Scenario (three operators, one for each sub-section)

Normal operation

- The value-added time is 0.00986821 hours
- The orders' quantity (number in) = 13,634
- The finished order (number out) = 13,634
- Work in progress = 14
- The average wait time in the queue = 2.4948 hours
- The total time = 2.5046 hours

Ramp-up operation

- The value-added time = 0.0098601 hours
- The orders' quantity (number in) = 18,291
- The finished order (number out) = 18,291
- Work in progress = 20
- The average wait time in the queue = 2.7965 hours
- The total time = 2.8063 hours

By comparing the results, the authors found that under normal operation, the ratio of value-added work to the total time (also called VSM) had significant variance depending on the scenario. In the first scenario, and under normal operation, the VSM is 0.0098600/12.2296 = 0.0806%. The VSM for this scenario, under the ramp-up operation is 0.0290%. For the second scenario, the VSM is 0.0914% and 0.1020% for normal and ramp-up operation, respectively. For the third scenario, the VSM is 0.2919% and 0.3514% for normal and ramp-up operation, respectively. The highest VSM, which is the case of the ramp-up operation with three operators, illustrates the most efficient use of the workforce. In terms of the average wait time in the queue for the ramp-up operation, the one-operator scenario has the highest amount (34.0025 hours), followed by the second scenario (9.6722 hours) and the third scenario (2.7965 hours). The same order is also observed for normal operational conditions.

The final decision ultimately will be based on the highest profit model utilizing a more uniform work schedule. There is a saying that it is a privilege to make a profit in corporate America, and the second scenario yields the highest profit. We only needed to change the mindset of upper management by running the second scenario to prove the point. This is discussed in the next section. Table 2 includes cost and revenue analysis of each scenario under the two operational conditions. Based on these results, the third scenario with a ramp-up operation seems to be dominant with the highest revenue and best profit, which is 15% better than the first scenario with a ramp-up operation.

Table 2. Financial calculation for each scenario

	Scenario					
	One operator		Two operators		Three operators	
	Normal	Ramp-up	Normal	Ramp-up	Normal	Ramp-up
Average Inventory	$339.78	$996.65	$296.40	$319.52	$121.28	$99.29
Cost of Production per Day	$136,338.00	$159,118.00	$138,716.00	$185,324.00	$209,530.00	$182,912.00
Cost of Employee and Overtime per Day	$251.03	$822.83	$353.07	$323.90	$420.00	$420.00
Hourly Rate per Day	$17.50	$17.50	$17.50	$17.50	$17.50	$17.50
Revenue per Day	$218,144.00	$253,824.00	$221,296.00	$296,176.00	$218,140.80	$292,659.20
Inventory Cost per Day	$0.41	$1.20	$0.36	$0.38	$0.15	$0.12
Profit Cost per Day	$81,554.57	$93,882.77	$82,226.52	$110,527.70	$8,190.39	$109,326.79
Value-added ×Revenue	$2,150.89	$2,502.69	$2,181.96	$2,920.82	$2,152.66	$2,885.65

A Change in Management Opinion

Throughout the evaluation process, the authors were sold on the idea of three operators. Prior to conducting this study, the company's management was in the hiring process to add two additional operators, thus implementing the third scenario. The simulation shows that the three operators would be significantly underutilized. The three operators would work 3.3802 hours per day and 2.8063 hours per day under normal and ramp-up operation, respectively. The results supported the authors' convictions that a two-operator workstation would be the best alternative. Under the ramp-up operation, this scenario gave the operators the best schedule to work with and also benefited them.

In the third scenario, under normal conditions, each operator received an annual salary of $36,400 and was tremendously underutilized. For the ramp-up operation, the two-operator scenario allows the operators to work 9.67722 hours per day. This equates to 8 hours per day at $17.5/hour plus 1.67722 hours per day at 1.5 x $17.5/hour = $36,400 + $10,920.00 (Overtime) = $47,320.00. This is a 30% increase in pay.

Conclusion

The fundamental decision came down to the final valuation of profitability. The third scenario resulted in the lowest total time, 2.5046 hours and 2.8063 hours for normal and ramp-up operations, respectively. However, as shown in Table 2, the revenue of the second scenario is $221,296.00 and $296,176.00 for normal and ramp-up operations, respectively, which are higher than other scenarios under similar operational conditions. The additional profit can be invested partially in new capital equipment and in training the new operator, should the company decides to implement the two-operator scenario.

In terms of resource utilization, the ARENA reports indicate that in the first scenario, for either operational condition, all the sub-sections' scheduled utilization was almost 100%. For the second scenario and under normal operation, the scheduled utilization for the cleaning sub-section was close to 100%, while for chopping and chamfering it is 1.5% and 1.6%, respectively. Under a ramp-up operation, the chopping and chamfering sub-sections had 2.1% and 2.0% scheduled utilization, while the cleaning sub-section had close to 100%. As far as the third scenario, all three sub-sections had scheduled utilization of about 1.5% for normal operation and around 2.0% for ramp-up operation. At the first glance, most of the scheduled utilizations seems very small. The reason is that the orders may arrive several days apart, with various quantities. The model considers that the chopping operator, for example, "stays" with the machine even on the days when there is no order. This is not the case in reality, as operators move to other workstations in the factory to do other tasks. Nonetheless, these estimates suggest that while the one-operator scenario is overloaded and the three-operator scenario is underutilized, the two-operator scenario seems to be the optimal solution for both normal and ramp-up operations. As far as waste in terms of materials, the authors did not observe any significant waste in the workstation.

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