Part IV
Supply Chain Logistics

Previous parts of this book discussed fundamental organizations of systems and strategies for operating those systems. This part deals with supply chain management which is defined by Hopp and Spearman (2007) to be: The overall system wide co-ordination of inventory stocks and flows to ensure the purpose of inventories is met with minimal dollar investment.

A publication from Jones-Lang-LaSalle (2008) defines the lean supply chain as "a set of organizations directly linked by upstream and downstream flows of products, services, finances and information that collaboratively work to reduce cost and waste by efficiently and effectively pulling what is required to meet the needs of the individual customer." The focus of part IV is on lean supply chain logistics that is the flow of product between organizations to minimize inventory and the cost of movement, particularly transportation equipment such as trucks and rail cars. A key element of lean supply chain logistics is demand management: Providing products and services when requested (pulled) by the customer. Thus, movement of product is a function of customer demand.

The use of modeling and analysis in achieving lean supply chain logistics with proper demand management is discussed. Ideally, there would be zero inventory. Product would be instantaneously delivered to customers who would immediately consume it upon arrival. There would be no in process inventory except for items currently being operated upon.

However, inventory must be kept to deal with variation, both random and structural (generated by design), in demand, production, and delivery. All inventory raises costs without adding value to a product. Thus, the management of inventory involves trading off lower costs with having enough product, raw material, and partially finished goods to meet customer demands and keep operations working.

Chapter 13 discusses the management of a retail store inventory by a supplier. Detailed operations are not included. Only daily demand and production volumes are modeled. Inventory levels as well as production schedules are determined. Analytic computations aid in setting inventory levels.

Chapter 14 discusses the logistics of moving goods and maintaining a fleet of trucks to do so. The use of simulation in determining the number of trucks required to meet customer service level expectations is shown. This is known as fleet sizing.

Chapter 15 discusses maintaining inventory at multiple locations in a complex supply chain. Rail movements between locations are described. Time varying expected demand for product is included. Building inventory in advance for periods when the expected demand exceeds production capacity is described. The use of customer services levels as the primary driver of supply chain logistics is discussed.
Chapter 13

Automated Inventory Management

13.1 Introduction

An inventory is a collection of parts or finished products that are waiting for use or shipment. Inventories increase costs by requiring storage space that could otherwise be productively used or simply not constructed. The cost of producing or purchasing what is stored cannot be recovered until the final product is delivered. Thus, minimizing inventories is important. On the other hand, not having a part or finished product when needed may lead to a stoppage of production or a dissatisfied customer who takes business elsewhere, thus decreasing revenue. Thus, having enough inventory is essential.

Lean demand management requires that manufacturers work with suppliers so that raw material or purchased parts are delivered precisely when needed. Manufacturers co-operate with large volume retailers to manage their inventories and ship product when sales records indicate that current inventory levels are low. Information gathered from scanning product bar codes at customer checkout can be aggregated and transferred electronically to the manufacturer nightly to enable this procedure.

This case study deals with an automated inventory system for a single product. The retail seller electronically collects information at the point of sale and transmits total daily sales to the supplier. The supplier must organize production and delivery to the seller such that the seller’s inventory is not excessive and sales are not lost due to a lack of inventory.

13.2 Points Made in the Case Study

The automatic inventory system in this case study illustrates a fundamental consideration of demand and inventory management: the cost of holding inventory trades off with the need to meet customer demands.

Entities sometimes do not represent physical entities. In this case, a entity represents control information flowing within the inventory system.

A system can respond to changes in state variable values. The inventory system responds to changes in the amount of inventory on hand. When critical values are reached, state events, in the form of arriving entities, occur and initiate appropriate responses. The ability to model the dynamic response of a system to state variable values changes is a unique simulation capability.

A Monte Carlo simulation is usually defined as taking samples of one or more random variables, manipulating the samples, and gleaning information from the results in a situation where time plays no substantive role. This simulation experiment has these Monte Carlo characteristics. However, multiple points in time, each separated by one day, are considered. Changes in state variable values from day to day, determined by the random samples, are significant components of the simulation.

In previous case studies, detailed operations effecting individual entities are modeled. In this system, the aggregate affect of production and sales on inventory management are described. Statistical distributions are used to quantify this aggregate behavior. Manipulations of these distributions based on principles of probability and statistics assist in determining system and model parameter values.

The model used in this case study illustrates a simulation capability of fundamental importance. The model consists of three processes. Each process changes the values of the same state variables. The processes independently determine what actions to take based on the current
state variable values. However, no information is explicitly transmitted between the processes. The simulation engine transparently performs all co-ordination tasks.

13.3  The Case Study

A large manufacturer of office supplies (pens, pencils, tape, etc.) sells in large volume to a discount office supply retailer. In order to retain this customer, the manufacturer must manage the customer's inventory and automatically generate shipments of products when necessary. Missing any shipment due to a lack of available product results in a large financial penalty. However, management wishes to minimize the amount of inventory on hand to keep storage space costs and investment in unsold product low. In addition, it is in the best interest of the manufacturer if the retailer does not lose any sales due to a lack of product on hand. At the same time, the manufacturer cannot expect the retailer to keep excessive inventory.

13.3.1 Define the Issues and Solution Objective

We will consider only one product. Others can be assessed in a similar manner. Sales data supplied by the customer can be analyzed and the daily sales volume characterized by a statistical distribution. The sales data concerns one region with 37 stores. Thus, this data is a sum of 37 values. As was discussed in Chapter 5, the normal distribution may provide a good fit to such data. Using software for fitting data to distributions, it was found that a normal distribution with mean 180 cartons and standard deviation 30 cartons fits the actual daily regional sales data.

The manufacturer and the retailer have agreed that one shipment every three days on the average is acceptable. The distribution of three days sales can be determined using probability theory as follows. The distribution of the sum of three normally distributed random variables is also normally distributed with the mean equal to the sum of the three means and variance equal to the sum of the three variances. (Standard deviations don't add.) Thus, three days sales is normally distributed with mean 540 cartons and standard deviation 52 cartons. The 99% percent point of a normal distribution with mean 540 and standard deviation 52 is approximately 660. Thus, the amount of inventory needed to meet three days of sales with probability 99% is 660 cartons.

The reorder point, the inventory level that triggers a shipment from the manufacturer, must be set. Since shipments take one day, it is tempting to set the reorder point to the amount of inventory to meet one day's demand with probability of 99%, approximately 250 cartons. However, consider the consequences if the inventory at the end of a day is 300 cartons. No shipment is sent. The next day suppose the demand is 120 cartons leaving 180 cartons in inventory and triggering a shipment. The probability of the following day's demand exceeding 180 cartons is 50%. Thus, sales could be lost while the shipment is being processed.

The reorder point will be set at the amount of inventory needed to meet two days of sales with probability 99% is 660 cartons.

The reorder point is set to be 460 cartons.

The nominal maximum production level for the product is 240 cartons per day. Actual data shows the production level to be uniformly distributed between 220 and 235 due to units that fail to pass inspection and random equipment failures.

There is no production on any day if inventory at the manufacturer is sufficiently high to meet the next shipment. A range for this inventory level, called the production cut-off point, can be computed as follows. The target number of units in inventory at the retailer after a shipment is received is 660. An order, which takes one day to receive, is placed when there are 460 cartons in inventory. The average number of sales in one day is 180 cartons. Thus, the average shipment has \((660 - 460) + 180 = 380\) cartons. The maximum shipment to the retailer is 660 cartons.
There are two important parameters of the inventory system:

1. The number of cartons in the inventory of the retailer, the reorder point, that triggers a new shipment from the manufacturer, currently proposed to be 460 cartons.

2. The number of cartons in inventory at the manufacturer that allows the following day’s production to be canceled, the production cut-off point, currently proposed to be in the range 380 to 660 cartons.

Figure 13-1 summarizes the inventory system. Inventory is generated by production at the manufacturer and moved to the retailer as needed. Inventory levels, product movement, and production status are shown. Note again how this system is driven by dynamic decisions based on the values of state variables.

13.3.2 Build Models

The model consists of three parallel processes:

1. Production at the manufacturer.
2. Sales at the retailer.
3. Shipments from the manufacturer to the retailer.

The first two processes schedule entity arrivals every day. The latter processes event triggered arrivals that occur when the retailers inventory drops below 460 cartons. First the variables used throughout the model will be defined.
Define Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProductionInv</td>
<td>Amount of inventory at the manufacturing plant</td>
</tr>
<tr>
<td>RetailInv</td>
<td>Amount of inventory at the retail plant</td>
</tr>
<tr>
<td>Cutoff</td>
<td>Production cut off level</td>
</tr>
<tr>
<td>DailyProd</td>
<td>Daily production at the manufacturing facility</td>
</tr>
<tr>
<td>Sold</td>
<td>Daily sales</td>
</tr>
<tr>
<td>Demand</td>
<td>Daily demand</td>
</tr>
<tr>
<td>Reorder</td>
<td>Reorder Point</td>
</tr>
<tr>
<td>Ordered</td>
<td>Order volume from retailer</td>
</tr>
<tr>
<td>Shipped</td>
<td>Number of units shipped from the manufacturing</td>
</tr>
</tbody>
</table>

Consider production at the manufacturer. A entity arrives once per day to control the production of new units. If the number of units in inventory is less than the production cut-off point, new units are made and added to the inventory. The model of this process follows.

Define Arrivals:
- Time of first arrival: 0
- Time between arrivals: 1 day
- Number of arrivals: Infinite

Process Manufacture
Begin
  If ProductionInv > CutOff then
    Begin // No need for production today
      Tabulate 0 in Production
    End
  Else
    Begin // Produce today
      Tabulate 100 in T_Production
      Set DailyProd = uniform 220, 235
      Increment ProductionInv by DailyProd
    End
End

Next consider the process for sales at the retailer. One entity representing sales information is created each day. The number of units demanded may exceed those available in inventory. This is an undesirable situation. The number of units demanded beyond those that are available in inventory represents lost sales. The model of the sales process follows.

Final consider the order process. A state event occurs when the number of units in the retail inventory becomes less than 460. The time till delivery is one day. The ordering process follows.
Define Arrivals:
  Time of first arrival: 0
  Time between arrivals: 1 day
  Number of arrivals: Infinite

Process Sales
Begin
  Set Demand = normal 180, 30
  If RetailInv > Demand then
    Begin // Sufficient Inventory to meet demand
      Tabulate 100 in DailySales
      Set Sold = Demand
    End
  Else
    Begin // Insufficient Inventory to meet demand
      Tabulate 0 in DailySales
      Set Sold = RetailInv
    End
  Decrement RetailInv current by Sold
End

Define Arrivals:
  When RetailInv becomes less than Reorder
  Number of arrivals: Infinite

Process Ship
Begin
  Set Ordered = min (660, 660 - RetailInv + 180)
  If Ordered > ProductionInv then
    Begin // Insufficient inventory for today’s order
      Tabulate 0 in Shipments
      Set Shipped = ProductionInv
    End
  Else
    Begin // Sufficient Inventory
      Tabulate 100 in Shipments
      Set Shipped = Ordered
    End
    // Make shipment
    Decrement ProductionInv by Shipped
    Wait for 24 hr
    Increment RetailInv by Shipped
End

13.3.3 Identify Root Causes and Assess Initial Alternatives
Table 13-1 gives the experiment design for the inventory system simulation.
**Table 13-1: Simulation Experiment Design for the Inventory System**

<table>
<thead>
<tr>
<th>Element of the Experiment</th>
<th>Values for This Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Experiment</td>
<td>Terminating</td>
</tr>
<tr>
<td>Model Parameters and Their Values</td>
<td>1. Re-order point for retailers inventory, 460 units</td>
</tr>
<tr>
<td></td>
<td>2. Production cancellation point based on manufacturer’s inventory (380, 660) units</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>1. Number of days with lost sales</td>
</tr>
<tr>
<td></td>
<td>2. Amount of inventory at the retailer</td>
</tr>
<tr>
<td></td>
<td>3. Number of days with no production</td>
</tr>
<tr>
<td></td>
<td>4. Amount of inventory at the manufacturer</td>
</tr>
<tr>
<td></td>
<td>5. Number of shipments</td>
</tr>
<tr>
<td></td>
<td>6. Number of shipments with insufficient units</td>
</tr>
<tr>
<td>Random Number Streams</td>
<td>1. Number of units manufactured</td>
</tr>
<tr>
<td></td>
<td>2. Number of units demanded</td>
</tr>
<tr>
<td>Initial Conditions</td>
<td>1. Inventory at the retailer – average of the reorder point and the maximum desirable</td>
</tr>
<tr>
<td></td>
<td>inventory level or 460 - 660. The average of these values, 560, will be used for the</td>
</tr>
<tr>
<td></td>
<td>initial conditions. A typical number of units at the manufacturer should be within the</td>
</tr>
<tr>
<td></td>
<td>range of the cut-off level for production, 380 - 660 units. The mid-point of the range</td>
</tr>
<tr>
<td></td>
<td>520, is used.</td>
</tr>
<tr>
<td>Number of Replicates</td>
<td>20</td>
</tr>
<tr>
<td>Simulation End Time</td>
<td>365 days (one year)</td>
</tr>
</tbody>
</table>

Management felt that demand data would be valid for no more than one year. Thus, a terminating experiment with a time period of one year was used. The number of units demanded each day and the number of units produced each day that production occurs are modeled as random variables. Thus, two random number streams are needed. Twenty replicates will be performed.

The initial inventory at the manufacturer and at the retailer must be set. Management believed that typical conditions are as follows. The number of units at the retailer should most often be between the re-order point and the intended maximum inventory level or 460 - 660. The average of these values, 560, will be used for the initial conditions. A typical number of units at the manufacturer should be within the range of the cut-off level for production, 380 - 660 units. The mid-point of the range, 520, is used.

As discussed previously, model parameters are the re-order point for the retailers inventory, whose value in the first experiment will be 460 units, and the production cancellation point. The values used for this latter quantity are the average shipment size, 380 units, and the maximum shipment size, 660 units.

There are several performance measures. The number of days with lost sales measures how well the inventory management system helps the retailer meet demand for the product. In addition, the inventory level at the retailer is of concern. At the manufacturer, the number of days without production and the inventory level are of interest. Finally, the total number of shipments from the manufacturer to the retailer, as well as the number of shipments with less than the requested number of units, should be estimated. The latter results from a lack of inventory at the manufacturer.

The inventory level at the retailer must be examined. Figures 13-2 and 13-3 show the inventory level at the retailer over time from the first replicate for each value of the cut-off point. In both graphs, the majority of the values are between 100 and 500 cartons.
Figures 13-4 and 13-5 show the inventory levels at the manufacturer for each value of the production cut-off point. The higher cut-off value, 660, results in an inventory between 400 and 800 cartons most of the time. The lower value, 380, results in an inventory between 200 and 500 cartons most of the time.
There were only 4 days of lost sales over all 20 replicates when the cut-off point was 660 and 3 days when the cut-off point was 380. This indicates that the reorder point was set correctly, or at least not too low.

Table 13-2 summarizes the other performance measure values resulting from the simulation experiment.

The number of days with no production is approximately the same for both values of the production cut-off point. The number of days per year without production is about 78 or 1.5 days per week. Thus, 5.5 days of production per week should be sufficient.

When the higher production cut-off point is used, all shipments contain the number of units requested by the retailer. When the lower cut-off point is used, slightly less than half of the shipments have an insufficient number of units, that is fewer units than requested by the retailer. The lower cut-off value leads to an average of 10.4 additional shipments per year.
Table 13-2: Results of the Inventory System Experiment

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Days with No Production</th>
<th># of Insufficient Shipments</th>
<th>Total # of Shipments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cut-off Point 660</td>
<td>Cut-off Point 380</td>
<td>Difference</td>
</tr>
<tr>
<td>1</td>
<td>80</td>
<td>81</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>76</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>74</td>
<td>75</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>79</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>79</td>
<td>80</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>73</td>
<td>74</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>76</td>
<td>77</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>76</td>
<td>77</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>76</td>
<td>77</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>78</td>
<td>79</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>75</td>
<td>77</td>
<td>2</td>
</tr>
<tr>
<td>12</td>
<td>72</td>
<td>74</td>
<td>2</td>
</tr>
<tr>
<td>13</td>
<td>74</td>
<td>75</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td>78</td>
<td>79</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td>72</td>
<td>74</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>74</td>
<td>75</td>
<td>1</td>
</tr>
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<td>17</td>
<td>78</td>
<td>79</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td>81</td>
<td>82</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td>72</td>
<td>73</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td>77</td>
<td>78</td>
<td>1</td>
</tr>
<tr>
<td>Average</td>
<td>75.9</td>
<td>77.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>2.7</td>
<td>2.6</td>
<td>0.4</td>
</tr>
<tr>
<td>99% CI Lower Bound</td>
<td>74.2</td>
<td>75.4</td>
<td>0.9</td>
</tr>
<tr>
<td>99% CI Upper Bound</td>
<td>77.7</td>
<td>78.8</td>
<td>1.4</td>
</tr>
</tbody>
</table>

13.3.4 Review and Extend Previous Work

Management felt that the foremost objective is to satisfy the retailer. The automated inventory management system appears to meet the objective. The retailer is able to meet all customer demand without carrying excessive inventory. Most of the time, the inventory is less than three days average demand for the product.

The higher value for the cut-off point is preferred. This results in no shipments with less units than the retailer demanded as well as fewer total shipments. Management is willing to accept a larger inventory at the manufacturer to better satisfy the customer.

Management noted that the variance between replicates is small. This small variance should make the automated inventory system easier to operate and control.
Production of the product 5.5 days a week will be scheduled.

13.3.5 Implement the Selected Solution and Evaluate

The automated inventory system will be installed and will operate with a reorder point of 460 units and a production cut-off point of 660 units. The retailer was assured by the simulation results of the ability to meet customer demand completely and consistently as well as holding a relatively low inventory. System performance will be monitored using the measures defined for the simulation experiment.

13.4 Summary

This chapter illustrates how dynamic decision making based on state variables may be incorporated into models. System details are not modeled directly. Aggregate behavior is modeled using statistical distributions. Graphs show the dynamics of inventory levels. System behavior due to alternative values of inventory system parameters is assessed.

Problems

1. Provide verification evidence for the inventory system experiment based on the following results.

   Number of days processed: 365
   Number of days without production: 77
   Number of days with production: 288
   Number of shipments: 145
   Number of shipments of sufficient quantity: 78
   Number of shipments of insufficient quantity: 67

2. Provide validation evidence for the inventory system experiment based on the simulation results presented in this case study.

3. One possibility that could arise during the simulation experiment is the following. Suppose a shipment of insufficient units failed to bring the inventory at the retailer above the reorder point. What would be the consequences for the simulation experiment? What conclusions could be drawn about operating the system with the particular reorder and cut-off point values?

4. Discuss management’s decision to use the higher cut-off point value. Defend using the lower value since the customer can still meet all demand.

5. Include detection and response of the condition described in problem 3 in the model and resimulate the using the lower value of the cut-off point.

6. Find a cut-off point value between 380 and 660 that improves system operation. Use a reorder point of 460 units.

7. Find a reorder point lower than 460 units that either improves system operation or makes it no worse.

8. Print out a trace of the inventory at the retailer. For each day, include the inventory at the start of the day, the deliveries, the demand, and the inventory at the end of the day.

9. Modify the model so that product occurs Monday through Friday at the current rate and Saturday at half the current rate. This implements the conclusion of the analysis that 5.5
days per week production on the average is sufficient. At the same time, customer demand at the retailer occurs 7 days per week. Would you expect more or less inventory to be needed at the retailer? Defend your expectation.

Case Problem

A product inventory changes daily due to customer demand that withdraws from it and production that replenishes it on the days when it is operating. Customer demands and production are random variables. Production is subject to down times of random frequency and duration. Customers do not backorder. Thus, any customer demand that cannot be met results in a lost sale.

Periodically, an analyst can review the inventory and make adjustments by purchasing or selling product on the spot market. The time between these reviews is called the review period. At each review, the analyst can do the following:

a. If the current inventory is less than the safety stock, buy a quantity of product equal to (safety stock – current inventory) on the spot market.
b. If the current inventory is greater than the maximum inventory, sell a quantity of product equal to (current inventory – maximum inventory) on the spot market.

The safety stock level is an operating parameter of the inventory system set such that the probability of meeting all customer demand between periodic reviews is at least a specified value, typically 90%, 95%, or 99%. This probability is called the effective service level.

The maximum inventory level is less than the physical limit on inventory storage, called the capacity, to avoid having no place to store items.

Figure 13-6 summarizes the inventory control system. Note the following definitions and notation.
Target inventory – The desired inventory to avoid purchases and sales on the spot market, in the range [safety stock, maximum inventory].

Delta inventory – The change in inventory each day due to production (+) and demand (-).

Nominal service level – The probability that the inventory will be greater than the safety stock at the time of a review given that it was equal to the target at the time of the last review. As well, the probability that the inventory will be greater than zero at the time of a review given that it was equal to the safety stock at the time of the last review.

\[ d = \text{number of days in the review period} \]

\[ \mu_d = \text{the mean of the delta inventory distribution for a review period of } d \text{ days} \]

\[ \sigma_d^2 = \text{the variance of the delta inventory distribution for a review period of } d \text{ days} \]

\[ \mu_p = \text{the mean of the conditional daily production distribution (given that production is greater than zero).} \]

\[ \sigma_p^2 = \text{the variance of the daily production distribution} \]

\[ \mu_c = \text{the mean of the daily customer demand distribution} \]

\[ \sigma_c^2 = \text{the variance of the daily customer demand} \]

\[ A = \text{the percent of days that production occurs (the availability of production)} \]

\[ L = \text{the nominal service level as a percent} \]

\[ L_{\text{eff}} = \text{the effective service level} \]

\[ L = 1 - \sqrt{1 - L_{\text{eff}}} \]

\[ L_{\text{shut}} = \text{the probability of exceeding the capacity during the next review period given that the inventory level is equal to the maximum inventory at the current review} \]

\[ z_L = \text{The } L\% \text{ point of the standard normal distribution} \]

The average demand is equal to the average production over a long period of time such as a year. This means that \( \mu_c = \mu_p \times A \). In other words, the expected production each day (including an allowance for down time) is equal to the expected daily demand.

Ignoring down times, the delta inventory can be viewed approximately normally distributed with parameters:

\[ \mu_d = 0 \]

\[ \sigma_d^2 = \sum_{i=0}^{d} \left[ \sigma_p^2 + \sigma_c^2 \right] = d \times \left[ \sigma_p^2 + \sigma_c^2 \right] \]
The problem is to determine the review period, safety stock, maximum inventory, and target inventory given an effective service level. Performance measures should include the service level as well as the number of purchases and sales made to the spot market by the analyst.

Consider the following specifications.

Capacity: 4,000.
Distribution of customer demand: Normal (1000, 250).
Distribution of production when production occurs: Normal(1000/A, 300).
A = Availability: 30/(30+1.92)
Review period: 7, 10, or 14 days.
Effective service level: 0.95 or 0.99.

First, determine the required quantities assuming that there is no production downtime. Use analytic models to compute the safety stock, target inventory, and maximum inventory for each review period. Use simulation to validate the analytic computations. Make adjustments to the analytically computed quantities if necessary. Validate your final recommendation using simulation. Validate means to show that the required effective service level is met.

Next, consider production downtime. Establish and validate quantities for the safety stock, target inventory, and maximum inventory using simulation. The average time between periods of no production is 30 days. The average length of each period of no production is 1.92 days. The distribution of the period of no production follows.

<table>
<thead>
<tr>
<th>Days Down</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>25%</td>
</tr>
<tr>
<td>3</td>
<td>13%</td>
</tr>
<tr>
<td>4</td>
<td>7%</td>
</tr>
<tr>
<td>5</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>

Case Problem Issues

1. Identify the processes that are needed in the model.
2. Specify all of the combination of the values of the parameters that should be simulated.
3. Compute the safety stock, target inventory level, and maximum inventory level for each parameter value combination using a spreadsheet.
4. Specify the initial conditions for the simulation.
5. In addition to service level, define the performance measures.
6. Determine how production downtime should be modeled.
7. Discuss how verification and validation evidence will be obtained.

The time period of interest is one year.
Chapter 14

Logistics

14.1 Introduction

Logistics has to do with the procurement, storage, transportation, and delivery of goods or people. A logistics system deals with the way finished products move from producer to customer or raw material moves from a supplier to the producer. Logistics systems must be responsive to customer requirements for short lead times. That is the amount of time between the placement of an order and its delivery should be minimized. Using excessive amounts of inventory or capital equipment to accomplish this objective increases costs and thus is inconsistent with lean principals.

Movement of goods may involve truck, rail, water, and air transportation. Facilities for loading and receiving products by each mode of transporation employed are necessary. Evaluating trade-offs between using various transporation modes can be a part of a simulation study.

Inspection and repair of transportation equipment is important. Inspection is often required after each round trip to a customer and returning to the shipping site. Inspection delays and subsequent repair times if necessary must be included in a simulation model.

Determining how many trucks, rail cars, or aircraft are needed must be accomplished. This is known as fleet sizing. Fleet size estimates are often made using simple algebra based on the expected round trip time to a customer, including inspection and repair as well as the number of round trips needed per planning period. This result is the lower bound on the fleet size. Simulation allows the effects of variability on meeting customer requirements for timely deliveries to be considered when sizing a fleet so that a more precise estimate is obtained. Variability sources include transportation times and customer demands.

Staffing plans for logistics systems are necessary. A lack of staff may prove to be a constraint on the number of loads shipped. Staff may work only certain shifts during the day and only certain days of the week. Such scheduling may result in structural variability that causes the need for additional inventory or capital equipment.

Logistics systems add no value to products. Thus, their cost needs to be minimized. On the other hand, they are critical to making sure customers are satisfied by receiving products on time.

A simple logistic system is shown in Figure 14-1. A factory creates product which is stored in an inventory. Customer demands result in shipments via truck to the customer site. After the shipment is unloaded into the customer’s inventory, the truck returns to the factory for inspection and repair as well as to await its next shipment.

This chapter discusses a basic and straightforward logistic system with an emphasis on fleet sizing. A more complex logistic system as required in a supply chain is discussed in the next chapter.
14.2 Points Made in the Case Study

Arrivals represent daily shipping demand. There is one arrival per day at the beginning of the day. The number of shipments per day is modeled as a random variable.

Trucks used in shipping are modeled with a single resource. Each unit of the resource represents a truck. The number of trucks (resource units) required can be determined dynamically in the model during execution. An additional truck (resource unit) is created whenever needed to make a shipment, subject to an upper limit. Thus, the number of trucks needed to meet a performance level can be determined.

A sequence of experiments can be used to determine the relationship between the maximum number of trucks (resource units) available and system performance. The values of the number of trucks depend on the results of previous simulation experiments. After the number of trucks is established, the number of workers is set in the same way.

Simulation experiments can be run to determine the affect of structural variability on system performance. Various staff schedules with regard to shifts worked per day and days worked per week can be tested to determine their relationship to system performance and to estimate the number of workers required. This is left as an exercise for the reader.

14.3 The Case Study

Resource requirements in a logistics system include capital expenditures for transportation mechanisms such as trucks and operating costs such as personnel salaries. Minimizing capital and operating expenditures while providing the level of service demanded by customers is a fundamental issue.
14.3.1 Define the Issues and Solution Objective

A new logistics system is being designed to deliver truck loads of finished product over a large area from a main terminal supporting a manufacturing plant. The logistics system works in a similar way to the one shown in Figure 14-1. Truck loads are shipped seven days per week every day of the year. For the next year, the daily shipping volume is estimated as follows: a minimum of 20, a mode of 35 and a maximum of 65. Thus, the average daily shipping volume is 40 loads per day \( \left( \frac{20 + 35 + 65}{3} \right) \). This means that there are 14600 loads shipped per year on the average.

A truck waits at the terminal until it is loaded. Loading time is uniformly distributed between 2 and 4 hours. A sufficient number of workers are available for loading. The truck will make all of its deliveries and then return to the terminal. The time from the terminal to the customer site, in either direction, is triangularly distributed with a minimum of 4 hours, a mode of 12 hours and a maximum of 30 hours. The time at the customer site is triangularly distributed with a minimum of 2 hours, a mode of 4 hours, and a maximum of 8 hours.

Upon its return to the terminal, the truck must be inspected by a worker. Inspection time is uniformly distributed between 1 and 2 hours. Approximately 90% of the trucks pass inspection or require only minor adjustments and are then ready for another load. The other 10% require significant maintenance that is performed by the same worker. Repair time is triangularly distributed with a minimum of 4 hours, a mode of 8 hours and a maximum of 12 hours. Workers are available 16 hours per day.

Management does not want to significantly constrain the number of loads delivered each year. At the same time the number of trucks and number of workers needs to be minimized for cost reasons. Management has determined that differences of more than 1% in the number of round trips completed are operationally significant. This difference can affect company profitability. Difference of less than 1%, even if statistically significant, are considered to be operationally unimportant.

The objective is to determine the number of trucks and workers required for the effective operation of the product delivery system. Effective operation requires minimizing costs without significantly reducing the number of loads delivered.

14.3.2 Build Models

The expected number of trucks and workers needed can be estimated using simple algebra. This is a lower bound on the actual number of trucks and workers needed. Simulation is used to determine if additional trucks and workers are needed to meet the delivery criteria established by management.

The expected time for a truck to complete the delivery process and be ready to begin another delivery is shown in Table 14-1.
Table 14-1: Expected Time to Complete Delivery Process

<table>
<thead>
<tr>
<th>Process</th>
<th>Expected Time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Truck</td>
<td>3.0</td>
</tr>
<tr>
<td>Travel to Customer</td>
<td>15.3</td>
</tr>
<tr>
<td>At Customer</td>
<td>4.7</td>
</tr>
<tr>
<td>Travel to Terminal</td>
<td>15.3</td>
</tr>
<tr>
<td>Inspection</td>
<td>1.5</td>
</tr>
<tr>
<td>Repair</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40.6</strong></td>
</tr>
</tbody>
</table>

There are approximately 8760 hours in a year. Thus, a truck could be expected to make 215 deliveries per year \( (= 8760 / 40.6) \). Thus, the number of trucks required to make 14600 deliveries is 68 \( (= 14600 / 215) \).

The expected number of workers needed can be determined in the same way. A worker is required for inspection and repair with an expected time of 2.3 hours per delivery. Thus, a single worker who works 16 hours per day could inspect and repair on the average of 2539 trucks per year. Thus, 6 workers on each shift \( (= 14600 / 2539) \) are needed.

The model of the logistics system can be divided into the following processes:
1. Daily generation of loads.
2. Truck loading and round trip to the customer site.
3. Truck inspection and repair.
4. Worker shift changes.

The first process Daily Loads operates as follows. The number of loads per day is generated as a sample from a triangular distribution with the appropriate minimum, mode, and maximum: 20, 35, 65. While the daily number of loads is an integer, it is also sufficiently large to model as a continuous random variable.

In order to avoid “loosing” fractional loads, the fractional part of the sample for one day is added to the number of loads for the next day. For example, suppose the value for the number of loads is 30.6. Then, 30 loads are created today and 0.6 is added to the number of loads for the following day. Suppose the value for the number of loads on the following day is 40.7. Next, 0.6 is added. Thus, 41 loads are created and 0.3 is added to the number of loads for the next day.

In this process, the variable LoadsWaiting contains the quantity described above and the variable NLoads contains the integer portion of LoadsWaiting. N Loads loads are sent to the second process, RoundTrip, each day.
Define Arrivals:
   Time of first arrival: 0
   Time between arrivals: 1 day
   Number of arrivals: Infinite

Define Variables
   LoadsWaiting  // Number of loads to ship
   NLoads: Integer  // Integer number of loads to ship

Process Daily Begin
   Set LoadsWaiting += Triag 20, 35, 65
   Set NLoads = LoadsWaiting
   Set LoadsWaiting -= NLoads
   Clone NLoads to RoundTrip
End

The process model for truck loading and load delivery, RoundTrip, consists of four time delays, one each for truck loading, movement to the customer site, time at the customer site, and return to the terminal. Then the truck goes to the inspection process. Preceding the time delays, each load acquires a truck.

Preceding truck acquisition, the model determines whether an additional unit of the truck resource should be created. If the number of truck resource units is less than a specified limit, contained in the variable MaxTrucks, and there are no free units of the truck resource, then a new unit is created. Thus, the load would not wait for a truck. Else, the load must wait for a truck to return from a delivery as well as being inspected and repaired.

Define Variables
   MaxTrucks  // Maximum number of trucks

Define Resources
   Truck  // Trucks

Process RoundTrip Begin
   If Truck/1 is Idle is FALSE then
     Begin
       // Add another truck if possible
       If Truck Units < MaxTruck then
         Increment Truck Units by 1
     End
   End
   Wait Until Truck/1 is Idle in QTruck
   Make Truck/1 Busy
   Wait for uniform 2, 4 hours  //Loading Time
   Wait for triangular 4, 12, 30 hours  //To Customer
   Wait for triangular 2, 4, 8 hours  //At Customer
   Wait for triangular 4, 12, 30 hours  //From Customer
   Send to Inspect
End

Similar logic is used to model the worker resource in the truck inspection and repair process, Inspect. After an entity acquires the worker resource, there is time delay for inspection. Ten percent of the entities also require a time delay for repair.
Define Variables
MaxWorkers // Maximum number of workers

Define Resources
Worker // Inspection and repair workers

Process RoundTrip
Begin
If Worker/1 is Idle is FALSE then
Begin
// Add another worker if possible
If Worker Units < MaxWorker then
Increment Worker Units by 1
End
Wait Until Worker/1 is Idle in QWorker
Make Worker/1 Busy
Wait for uniform 3, 1 hr //Inspection
If uniform 0, 1 < 10% then
Wait for triangular 4, 8, 12 //Repair
Make Worker/1 Idle
Make Truck/1 Idle
End

The worker shift process is as was discussed in chapter 2. All units of the worker resource are put into the off-shift state after 16 hours of work and returned to the idle state after 8 hours.

Notice that this results in an approximation in the model. If a worker is inspecting or repairing a truck at the beginning of the off shift period, the inspection or repair will continue until completed. This worker will again be available for work at the beginning of the on-shift period. Thus, the number of workers required could be underestimated.

14.3.3 Identify Root Causes and Assess Initial Alternatives

The experimental strategy to determine the number of trucks and workers is as follows. First the number of trucks will be determined. After the number of trucks is established, the number of workers will be determined for that number of trucks.

The minimum number of trucks is the expected number, 68, as determined in the previous section. The maximum number will be determined through simulation by not constraining the number of units of the truck resource used, that is requiring that no load ever waits for a truck. Various values of the number of trucks between the minimum and the maximum will be simulated.

The number of workers is not constrained so that no returning truck waits for a worker.

For each of these values, 20 replicates will be made and the average number of completed round trips over the replicates computed. A graph showing the average number of completed trips versus the number of trucks can be constructed. Thus, the number of trucks to use is determined.

The experimental design for determining the number of trucks is shown in Table 14-2.

A terminating experiment of duration 1 year (8760 hours), the planning period for the logistics system is used. There is one random number stream for each time delay modeled as a random variable as well as a random number stream for determining the daily number of loads.
additional random number stream is needed to model the random choice as to whether a truck passes inspection.

The primary system performance measure is the number of round trips completed. The utilization of trucks and workers are of interest. The experiment will begin with all trucks at the terminal waiting to make a trip.

**Table 14-2: Simulation Experiment Design for Determining the Number of Trucks**

<table>
<thead>
<tr>
<th>Element of the Experiment</th>
<th>Values for This Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Experiment</td>
<td>Terminating</td>
</tr>
<tr>
<td>Model Parameters and Their Values</td>
<td>1. Number of trucks – Various values between the minimum needed and the maximum used.</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>1. Number of round trips completed</td>
</tr>
<tr>
<td></td>
<td>2. Utilization of trucks</td>
</tr>
<tr>
<td></td>
<td>3. Utilization of workers</td>
</tr>
<tr>
<td>Random Number Streams</td>
<td>1. Number of pallets each day</td>
</tr>
<tr>
<td></td>
<td>2. Truck loading time</td>
</tr>
<tr>
<td></td>
<td>3. Travel time to customer</td>
</tr>
<tr>
<td></td>
<td>4. Time at customer site</td>
</tr>
<tr>
<td></td>
<td>5. Travel time from customer to terminal</td>
</tr>
<tr>
<td></td>
<td>6. Time to inspect returning truck</td>
</tr>
<tr>
<td></td>
<td>7. Decision: Did truck pass inspection?</td>
</tr>
<tr>
<td></td>
<td>8. Time to repair truck</td>
</tr>
<tr>
<td>Initial Conditions</td>
<td>Empty buffers and idle resources</td>
</tr>
<tr>
<td>Number of Replicates</td>
<td>20</td>
</tr>
<tr>
<td>Simulation End Time</td>
<td>1 year</td>
</tr>
</tbody>
</table>

First the simulation is run with 68 trucks and then with maximum number of trucks used as determined by the simulation to be 144 with an approximate 99% confidence interval of (141.3, 146.3).

The maximum number of trucks case results in an average of 662 more round trip completions per year. This is an increase of 4.8% over case where 68 trucks are used. Furthermore, this difference is statistically significant as seen by the approximate 99% confidence interval for the difference.

Thus, it can be concluded that more than 68 trucks are needed and that the number of trucks needed is between 68 and 144.
Table 14-3: Number of Round Trips – Average Trucks and Maximum Trucks

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Maximum Trucks</th>
<th>Average Trucks</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14738</td>
<td>13863</td>
<td>875</td>
</tr>
<tr>
<td>2</td>
<td>14374</td>
<td>13850</td>
<td>524</td>
</tr>
<tr>
<td>3</td>
<td>14697</td>
<td>13839</td>
<td>858</td>
</tr>
<tr>
<td>4</td>
<td>14564</td>
<td>13800</td>
<td>764</td>
</tr>
<tr>
<td>5</td>
<td>14345</td>
<td>13853</td>
<td>492</td>
</tr>
<tr>
<td>6</td>
<td>14527</td>
<td>13823</td>
<td>704</td>
</tr>
<tr>
<td>7</td>
<td>14278</td>
<td>13804</td>
<td>474</td>
</tr>
<tr>
<td>8</td>
<td>14421</td>
<td>13877</td>
<td>544</td>
</tr>
<tr>
<td>9</td>
<td>14638</td>
<td>13825</td>
<td>813</td>
</tr>
<tr>
<td>10</td>
<td>14357</td>
<td>13854</td>
<td>503</td>
</tr>
<tr>
<td>11</td>
<td>14611</td>
<td>13858</td>
<td>753</td>
</tr>
<tr>
<td>12</td>
<td>14791</td>
<td>13828</td>
<td>963</td>
</tr>
<tr>
<td>13</td>
<td>14507</td>
<td>13755</td>
<td>752</td>
</tr>
<tr>
<td>14</td>
<td>14477</td>
<td>13754</td>
<td>723</td>
</tr>
<tr>
<td>15</td>
<td>14442</td>
<td>13872</td>
<td>570</td>
</tr>
<tr>
<td>16</td>
<td>14447</td>
<td>13868</td>
<td>579</td>
</tr>
<tr>
<td>17</td>
<td>14397</td>
<td>13810</td>
<td>587</td>
</tr>
<tr>
<td>18</td>
<td>14308</td>
<td>13839</td>
<td>469</td>
</tr>
<tr>
<td>19</td>
<td>14501</td>
<td>13820</td>
<td>681</td>
</tr>
<tr>
<td>20</td>
<td>14469</td>
<td>13860</td>
<td>609</td>
</tr>
<tr>
<td>Average</td>
<td>14494.5</td>
<td>13832.6</td>
<td>661.9</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>142.7</td>
<td>35.0</td>
<td>147.5</td>
</tr>
<tr>
<td>99% CI Lower Bound</td>
<td>14403.2</td>
<td>13810.2</td>
<td>567.5</td>
</tr>
<tr>
<td>99% CI Upper Bound</td>
<td>14585.7</td>
<td>13855.0</td>
<td>756.2</td>
</tr>
</tbody>
</table>

Furthermore simulation experiments are run with 68, 70, 75, …, 140, and 144 trucks. Results are shown in the following graph, Figure 14-3.

**Figure 14-3: Round Trips versus Number of Trucks**
It appears from the graph that the number of roundtrips increases significantly up to 75 trucks. The difference in round trips when 80 trucks are used instead of 75 is only 14 on the average and thus is not operationally significant. Thus, 75 trucks will be used if there is a statistically and operationally significant difference in the number of roundtrips versus when 70 trucks are used. The simulation results are summarized in Table 14-4.

Table 14-4: Number of Round Trips – 75 Trucks versus 70 Trucks

<table>
<thead>
<tr>
<th>Replicate</th>
<th>75 Trucks</th>
<th>70 Trucks</th>
<th>Difference (75 vs 70 Trucks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14268</td>
<td>14715</td>
<td>447</td>
</tr>
<tr>
<td>2</td>
<td>14197</td>
<td>14351</td>
<td>154</td>
</tr>
<tr>
<td>3</td>
<td>14238</td>
<td>14669</td>
<td>431</td>
</tr>
<tr>
<td>4</td>
<td>14198</td>
<td>14558</td>
<td>360</td>
</tr>
<tr>
<td>5</td>
<td>14235</td>
<td>14341</td>
<td>106</td>
</tr>
<tr>
<td>6</td>
<td>14222</td>
<td>14527</td>
<td>305</td>
</tr>
<tr>
<td>7</td>
<td>14104</td>
<td>14273</td>
<td>169</td>
</tr>
<tr>
<td>8</td>
<td>14258</td>
<td>14385</td>
<td>127</td>
</tr>
<tr>
<td>9</td>
<td>14208</td>
<td>14601</td>
<td>393</td>
</tr>
<tr>
<td>10</td>
<td>14169</td>
<td>14320</td>
<td>151</td>
</tr>
<tr>
<td>11</td>
<td>14226</td>
<td>14604</td>
<td>378</td>
</tr>
<tr>
<td>12</td>
<td>14212</td>
<td>14704</td>
<td>492</td>
</tr>
<tr>
<td>13</td>
<td>14123</td>
<td>14497</td>
<td>374</td>
</tr>
<tr>
<td>14</td>
<td>14174</td>
<td>14477</td>
<td>303</td>
</tr>
<tr>
<td>15</td>
<td>14276</td>
<td>14433</td>
<td>157</td>
</tr>
<tr>
<td>16</td>
<td>14262</td>
<td>14439</td>
<td>177</td>
</tr>
<tr>
<td>17</td>
<td>14189</td>
<td>14397</td>
<td>208</td>
</tr>
<tr>
<td>18</td>
<td>14231</td>
<td>14307</td>
<td>76</td>
</tr>
<tr>
<td>19</td>
<td>14191</td>
<td>14486</td>
<td>295</td>
</tr>
<tr>
<td>20</td>
<td>14239</td>
<td>14435</td>
<td>196</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>14211.0</td>
<td>14476.0</td>
<td>265.0</td>
</tr>
<tr>
<td><strong>Std. Dev.</strong></td>
<td>45.1</td>
<td>132.9</td>
<td>127.4</td>
</tr>
<tr>
<td><strong>99% CI Lower Bound</strong></td>
<td>14182.1</td>
<td>14390.9</td>
<td>183.5</td>
</tr>
<tr>
<td><strong>99% CI Upper Bound</strong></td>
<td>14239.9</td>
<td>14561.0</td>
<td>346.4</td>
</tr>
</tbody>
</table>

On the average, the number of roundtrips increases by 265, 1.9%, when 75 trucks are used versus 70 trucks. Thus, the difference is operationally significant since it is greater than 1%. The approximate 99% confidence interval for the difference is (183.5, 346.4). Thus, the difference is statistically significant.

Thus 75 trucks should be used. For this case, the truck utilization is 94.9% with an approximate 99% confidence interval of (94.1%, 95.3%). Utilization includes time spent in inspection and repair.

Given that 75 trucks should be used, the number of workers must be determined. The average maximum number of workers determined by the simulation experiments using 75 trucks is 30. This is the maximum number of workers that could be needed. The average number of workers computed with algebra was 6. The actual number of workers needed is somewhere between these two values. The simulation experiment to determine the number of workers is the same as that shown in Table 14-2 except that the model parameter is the number of workers instead of the number of trucks. Conducting this experiment is left as an exercise for the reader.
14.3.4 Review and Extend Previous Work

Management was pleased with the results as presented above and 75 trucks will be acquired.

14.3.5 Implement the Selected Solution and Evaluate

The number of completed roundtrips will be monitored. Additional trucks can be obtained and workers can be hired if needed.

14.4 Summary

This case study emphasizes a sequentially designed simulation experiment to determine the level of resources needed to operate a truck based logistics system. Minimizing the cost of the system in terms of trucks and workers trades off with the need to meet delivery targets. The idea of a level of indifference is employed. Alternatives may statistically differ significantly, but the difference may not be large enough, greater than the level of indifference, to impact system operations.

Problems

1. Validate the computation of the expected time a truck spends in repair per roundtrip.

2. Tell what the entity in each of the processes in the model discussed in this chapter represents.

3. Give verification evidence based on the information resulting from one replicate of the simulation experiment as follows:

   Number of truck round trips started: 14335
   Number of truck round trips completed: 14203
   Number of truck round trips on going at the end of the simulation: 104
   Number of trucks waiting or in inspection and repair at the end of the simulation: 28

4. Compare the modeling and experimental issues of the logistics system discussed in this chapter to those concerning the serial line discussed in chapter 7.

5. Tour the operation of the local office of an overnight delivery service. Write down a process model of their logistics system for organizing and delivering in bound packages.

6. Modify the model presented in this chapter so that no worker inspects or repairs a truck during the off-shift period. Assess the effect of making the model more precise on the number of workers required.

7. Suppose that workers were available 24 hours per day but the total number of hours worked per day could not increase. That is, there would be 2/3rds of the number of workers determine above would work each shift. Use the model developed in this chapter to determine if the number of trucks needed could be lowered.

8. Modify the model and simulation experiment to estimate the needed capacity of the parking area for trucks at the terminal. Include trucks that are in inspection or repair.

9. Modify the model and simulation experiment to give a profile of truck location. Estimate the average number of trucks in each possible location: in route to the customer, at the customer, in route to the terminal, in inspection, in repair, and waiting for a load.
10. Conduct a simulation experiment to determine the number of workers needed.

**Case Study**

A new logistics system is being designed to transport one product from a factory to a terminal by rail. A simulation study is needed to estimate the following:

1. The rail fleet size.
2. The size of the rail yard at the factory.
3. The size of the rail yard at the terminal.
4. The size of the inventory needed at the terminal.

Customer demand is satisfied each day from the terminal. Demand is normally distributed with a mean of 1000 units and a standard deviation of 200 units. Production at the factory is sufficient to meet demand on a daily basis. Policy is to ship an average of 1000 units each day from the factory to the terminal. Each rail car holds 150 units. Partial rail car loads are not shipped but included with the demand for the next day.

The customer service level provided at the terminal should be at least 99%. The time period of interest is one year.

Transportation time from the factory to the terminal is triangularly distributed with a minimum of 3 days, a mode of 7 days, and a maximum of 14 days. At the terminal, a car must wait for a single unload point to unload. Unloading takes one hour. Upon return to the plant, a rail car is inspected. Inspections take 2 hours. Maintenance requires 4 days.

Embellishment: All cars leaving the factory in a day join a single train leaving at 4:00 A.M. the next morning and have the same transportation time to the terminal. A single train containing all empty cars leaves the terminal at 4:00 A.M. each morning.

**Case Study Issues.**

1. What initial conditions concerning the arrival of trains to the terminal should be used?
2. What target inventory level should be used?
3. How is the policy to ship 1000 units each day from the factory implemented if rail cars hold 150 units?
4. Embellishment: How is the requirement that all rail cars leaving the factory or terminal join a single train with a single transportation time to the other site modeled?
5. How is the unloading constraint for rail cars modeled?
6. In what order should the system parameters listed above be determined by the simulation experiments?
7. What is the primary performance measure for the simulation experiments?
8. How will verification and validation evidence be obtained?
9. How is the size of a rail yard modeled?
10. How is the size of the rail fleet modeled?
11. Computed the expected fleet size and use the result in providing validation evidence.

12. Define the processes that comprise the model.
15.1 Introduction

A supply chain integrates the efforts of geographically dispersed production and distribution facilities that acquire raw material, make intermediate or finished products, and deliver finished products to customers. Transportation links provide for product and raw material movement between facilities. Integration is accomplished by information technology that shares production, inventory, and customer demand data among the facilities.

Integration implies that the operation of each facility affects the operation of all other facilities. The volume of production at a facility is determined by the need for its products at subsequent facilities in the supply chain. The fundamental purpose of the supply chain is to meet customer demand for finished products. Thus, customer demand drives all of the work of the supply chain.

A simple two facility supply chain is shown in Figure 15-1. At the right side of the figure, customer demand is satisfied from finished goods inventory at facility B. Facility B production levels are set so that the finished goods inventory is replenished. Facility B production requires an intermediate product made by facility A that is stored in an inventory at facility B. Facility A ships the intermediate product to facility B so that just enough inventory is available to meet production requirements at facility B. Shipments are made from an inventory at facility A that is replenished by production at facility A. Thus, customer demand indirectly drives production at facility A. Facility A needs to be constantly knowledgeable about customer demand, production levels, and inventory levels at facility B to set its own production levels.

Many supply chains are much more complicated than the one shown in Figure 15-1. There are multiple kinds of facilities: some for production only and some for movement or transfer of materials like the facilities that will be discussed in a later chapter. More than one finished product may be delivered to customers. Facilities may supply products to and receive many products from many other facilities. More than one mode of transportation may be involved. The expected demand of a customer for a product may vary over time, that is be subject to seasonal variations.

Modeling an integrated supply chain involves modeling the flow of information from the end of the supply chain where product is delivered to customers to the beginning of the supply chain where the first intermediate product is produced from raw materials. The flow of product between facilities must be modeled as well as inventory management and production. Understanding and modeling of customer demand is essential.

This case study shows the simulation approach to evaluating integrated supply chain performance and how all aspects of a supply chain are integrated into one model. It is based in part on the work described in Standridge and Helte [2000].

15.2 Points Made in the Case Study

In previous chapters, emphasis has been placed on one aspect of the operation of a system. Modeling an integrated supply chain requires integrating many components in one model: shipments, inventory management, customer demand, production, and information flow. Simulation has a unique ability to provide such integration. A model integrating these components is illustrated in this case study.
Figure 15-1: Simple Supply Chain
Expected customer demand can vary by month or season of the year. At some times, demand may be far less than production capacity and at some time more. Thus, creating inventory to buffer against demand seasonality is necessary. One approach to doing this is illustrated in this case study.

The effect of the operations of one facility on the decisions made by another facility must be modeled. In this study, equations are used to compute production levels at predecessor plants in a supply chain based on inventory levels at the successor plant, customer demands, and the amount of product in route between the two plants.

The model of a complex system can be implemented using multiple processes. The processes share resources and variables to interact with each other. In this application, nine processes are used to model the supply chain. Variables and resources modeling inventory levels at plant and in route between plants as well as rail fleets are shared between them.

Decisions made within a model may be a function of time. In this application, inventory may be produced in the months prior to peak demand and used only at the time of peak demand.

Supply chain performance is best measured by the service level provided to the customers of retail products. The occasional lack of intermediate inventory for production is acceptable if the customer service level is still satisfactory.

Initial conditions in a supply chain model must include shipments between facilities. In this case, trains are scheduled to arrive at each of the production facilities each day before the expected arrival time of the first train generated by the simulation experiment as a part of the initial conditions.

15.3 The Case Study

A company owns three plants. Two of the plants, Baker and Chauncey, produce retail products for delivery to customers. A third plant, Able, produces two intermediate products for delivery to the Baker and Chauncey plants. This supply chain is pictured in Figure 15-2.

Product is shipped from the Able plant by rail. There is a separate rail fleet for Able to Baker shipments and for Able to Chauncey shipments.

Customer demand for the retail product made by the Baker plant is triangularly distributed with a minimum of 15 rail cars, a mode of 20 rail cars, and a maximum of 40 rail cars per day. Thus, the average daily demand is 25 rail cars.

Customer demand for the retail product made by the Chauncey plant is seasonal. The average daily demand varies by month of the year as shown in Table 15-1. This data is valid for the next year.
Figure 15-2: Application Study Supply Chain
Table 15-1: Average Demand for the Chauncey Plant Retail Product by Month

<table>
<thead>
<tr>
<th>Month</th>
<th>Average Daily Demand (Rail Cars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>17</td>
</tr>
<tr>
<td>February</td>
<td>18</td>
</tr>
<tr>
<td>March</td>
<td>18</td>
</tr>
<tr>
<td>April</td>
<td>22</td>
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<tr>
<td>May</td>
<td>23</td>
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<tr>
<td>June</td>
<td>24</td>
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<tr>
<td>July</td>
<td>22</td>
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<tr>
<td>August</td>
<td>21</td>
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<tr>
<td>September</td>
<td>21</td>
</tr>
<tr>
<td>October</td>
<td>18</td>
</tr>
<tr>
<td>November</td>
<td>18</td>
</tr>
<tr>
<td>December</td>
<td>18</td>
</tr>
</tbody>
</table>

The average of the average daily demands is 20 rail cars. The minimum demand is 70% of the average and the maximum is 130% of the average.

Daily customer demand can include a fractional number of rail cars. However, only full rail cars are shipped with the fractional demand carried over until the next day.

Production capacity at the Able plant is not an issue as sufficient quantities of each intermediate product can be made each day. Production capacity at the Baker and Chauncey plants is constrained. The Baker plant can produce only 35 rail cars per day. The Chauncey plant can produce 27 cars per day.

Production levels are determined daily. Production at the Baker and Chauncey plants can be viewed as occurring in batches equal to one rail car. A rail car of intermediate product sent from the Able plant is required before a batch can be produced. Production of a batch can be modeled as taking 24 hours / daily plant capacity.

Each day at 4:00 A.M. rail cars leave Able plant for the other two plants. There is one train to each plant. All rail cars sent to a plant travel on the same train. Arriving cars at Baker and Chauncey plants are moved into the plant railyard at 12:00 P.M for use the next day. Empty cars leave these plants for return to Able plant at 4:00 A.M. Travel time between Able plant and Baker plant is triangularly distributed with a mean of 7 days, a minimum of 3 days and a maximum of 10 days. Travel time between Able plant and Chauncey plant is triangularly distributed with a mode of 10 days, a minimum of 7 days and a maximum of 20 days. Rail car maintenance will not be modeled.

Rather than construct inventory facilities at the Baker and Chauncey plants, intermediate product remains in rail cars until needed. One rail car at a time is unloaded in preparation for the start of the next batch. Retail product is loaded directly into rail cars for shipment to customers.
Define the Issues and Solution Objective

The objective of the simulation study is to establish values for the operating parameters of the supply chain for the next year, January through December. These include:

1. The number of cars in each rail fleet: Able plant to Baker plant as well as Able plant to Chauncey plant.
2. The capacity of each inventory: Each of the two intermediate products at Able plant as well as the intermediate and retail product inventories at Baker and Chauncey plants.
3. The target retail inventories at Baker and Chauncey plants.

The primary measure of performance is the service level to customers at Baker and Chauncey plants, defined as the number of days when customer demand was met from existing inventory.

Build Models

The first step in analyzing the supply chain is to set initial target retail inventory levels. One way to do this is as follows, remembering that the simulation experiments can be used to find better values for the target inventory level if necessary.

Consider the target retail inventory level at Baker plant. Suppose there was no variation in customer demand or transportation times. The target inventory level would be equal to one day’s demand. Product to meet customer demand would be removed from the retail inventory. The day’s production would be used to replenish the inventory to meet the next day’s demand.

Because of variation, additional inventory is needed to meet customer demands to a specified service level. Suppose a 95% service level is desired. Then the target inventory can be set such that the probability that customer demand is less than the target is 95%. For Baker plant this is 35 rail cars.

For Chauncey plant, the target will vary by month as shown in Table 15-2. Note that the target inventory levels are at or above plant capacity in 4 of 12 months. This may reduce customer service levels below 95%.

<table>
<thead>
<tr>
<th>Month</th>
<th>Target Inventory Level (Rail Cars)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>21</td>
</tr>
<tr>
<td>February</td>
<td>22</td>
</tr>
<tr>
<td>March</td>
<td>22</td>
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<tr>
<td>April</td>
<td>27</td>
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<tr>
<td>May</td>
<td>28</td>
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<tr>
<td>June</td>
<td>29</td>
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<tr>
<td>July</td>
<td>27</td>
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<tr>
<td>August</td>
<td>26</td>
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<tr>
<td>September</td>
<td>26</td>
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<tr>
<td>October</td>
<td>22</td>
</tr>
<tr>
<td>November</td>
<td>22</td>
</tr>
<tr>
<td>December</td>
<td>22</td>
</tr>
</tbody>
</table>
In addition, the average customer demand at Chauncey plant exceeds the plant capacity in May and June. Thus, management has decided to increase daily production by one rail car per day in January, February, and March to prepare for May and June demand. This inventory will be set aside for use starting in April.

It seems prudent to set each of the intermediate product target inventory levels to the same value as the corresponding retail level, at least initially.

Production levels at all three plants are set using the following relationship:

\[
\text{Production} = \text{Target Inventory} - (\text{Current Inventory} + \text{Amount in production})
\]

In other words, enough units of a product are sent into production so that the sum of these units, the current inventory and the number of units still in production from previous days is equal to the target inventory.

Capacity constraints are applied at Baker and Chauncey plants. In the number of units sent into production is greater than the daily capacity, some of the units will be produced on subsequent days.

The extra production amount is added at the Chauncey plant as well to help meet customer demand in the months where the target inventory is greater than or equal to the plant capacity. This implies the need for additional intermediate inventory that must be shipped from Able plant.

Shipping volumes are set using the following relationship:

\[
\text{Shipping} = (\text{Target Inventory} - \text{Current Inventory}) + (\text{Expected customer demand in expected transportation time} - \text{Amount in route})
\]

In addition, the extra production amount is added for shipping between Able and Chauncey plants.

The model consists of nine processes as defined in Table 15-3

<table>
<thead>
<tr>
<th>Process Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Able</td>
<td>Daily operation decisions at Able Plant</td>
</tr>
<tr>
<td>Baker</td>
<td>Daily operation decisions at Baker Plant, including customer service</td>
</tr>
<tr>
<td>Chauncey</td>
<td>Daily operation decisions at Chauncey Plant, including customer service</td>
</tr>
<tr>
<td>BakerMake</td>
<td>Production at Baker Plant</td>
</tr>
<tr>
<td>ChaunceyMake</td>
<td>Production at Chauncey Plant</td>
</tr>
<tr>
<td>Move2Baker</td>
<td>Train shipment from Able Plant to Baker Plant</td>
</tr>
<tr>
<td>Move2Chauncey</td>
<td>Train shipment from Able Plant to Chauncey Plant</td>
</tr>
<tr>
<td>Move2AbleBaker</td>
<td>Train shipment from Baker Plant to Able Plant</td>
</tr>
<tr>
<td>Move2AbleChauncey</td>
<td>Train shipment from Chauncey Plant to Able Plant</td>
</tr>
</tbody>
</table>
Important variables in the model are shown in Table 15-4.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg2*</td>
<td>Average transporation time from Able plant to * plant (days)</td>
</tr>
<tr>
<td>AvgRetail*</td>
<td>Average daily customer demand</td>
</tr>
<tr>
<td>Capacity*</td>
<td>Plant capacity</td>
</tr>
<tr>
<td>Cars2Cust*</td>
<td>Number of rail cars demanded by customers currently</td>
</tr>
<tr>
<td>Cars2*</td>
<td>Number of rail cars to be shipped from Able plant currently</td>
</tr>
<tr>
<td>InRoute*</td>
<td>Number of rail cars currently in route from Able plant</td>
</tr>
<tr>
<td>ProductionAdd</td>
<td>Number of additional rail cars of retail product to produce daily at Chauncey plant to meet peak demand. The amount varies by month.</td>
</tr>
<tr>
<td>TargetInvRetail*</td>
<td>Target retail (customer) inventory</td>
</tr>
<tr>
<td>TargetInvInt*</td>
<td>Target intermediate inventory</td>
</tr>
<tr>
<td>TargetInvIntAble*</td>
<td>Target intermediate inventory at Able plant</td>
</tr>
<tr>
<td>*toAble</td>
<td>Number of rail cars currently in route to Able plant</td>
</tr>
</tbody>
</table>

* = a plant name (Baker, Chauncey)

The Able process is given in the following pseudo-code. This process models the initiation of the shipment of railcars to Baker plant and Chauncey plant as well as the production of intermediate product at Able plant. Entities in this process represent trains and have one attribute:

CarsinTrain: The number of cars in a train

The two intermediate product inventories, one for Baker plant (IntInvAbleBaker) and the other for Chauncey plant (IntInvAbleChauncey), are modeled as resources. The units of each resource correspond to rail cars. The initial number of units of each inventory resource is equal to the target value for that inventory. The same strategy is used to model the retail inventories at Baker (RetailInvBaker) and Chauncey (RetailInvChauncey) plants.

The two rail fleets are modeled as variables: FleetBaker and FleetChauncey. The model is allowed to create as many rail cars in each fleet as needed. Thus, an estimate of the size of each fleet is obtained. The initial size of each rail fleet is zero.

First consider the shipment of rail cars to Baker plant. The number of cars that need to be shipped is incremented using equation 15-2. Suppose the inventory of intermediate product for Baker plant has at least as many cars as the number that need to be shipped. Then all cars that need to be shipped are shipped, the number remaining to be shipped is zero, and the inventory is reduced by the number of cars shipped.

Suppose more cars need to be shipped than are in inventory. Then the train consists of the cars that are in that are inventory. The number remaining to be shipped is reduce by the number in inventory and the number in inventory is set to zero.

In either case, a clone (copy) of the train entity is sent to process Move2Baker.

The modeling logic for a shipment to the Chauncey plant is identical except for the consequences of the expected customer demand varying month to month. All target inventory values for the intermediate product also vary by month.
Define Arrivals:
Time of first arrival: 0
Time between arrivals: 1 day
Number of arrivals: Infinite

Define Attributes
CarsinTrain // Rail cars in a train

Define Variables
AddInv // Number of additional rail cars needed
Avg2Baker // Average number of transit days to Baker
AvgRetailBaker // Average daily customer demand at Baker
Cars2Baker // Current number of rail cars to ship from Able to Baker
Cars2CustBaker // Current demand in rail cars at Baker
InRouteBaker // Current number of rail cars in route between Able and Baker
TargetIntlInvAbleBaker // Target intermediate inventory at Able for Baker
TargetIntlInvBaker // Target intermediate inventory at Baker

Avg2Chauncey // Average number of transit days to Chauncey
AvgRetailChauncey // Average daily customer demand at Chauncey
Cars2Chauncey // Current number of rail cars to ship from Able to Chauncey
Cars2CustChauncey // Current demand in rail cars at Chauncey
InRouteChauncey // Current number of rail cars in route -- Able and Chauncey
TargetIntlInvAbleChaunceyBaker // Target intermediate inventory at Able for Chauncey
TargetIntlInvChauncey // Target intermediate inventory at Chauncey

Define Resources
FleetBaker // Number of rail cars in the Able to Baker fleet
FleetChauncey // Number of rail cars in the Able to Chauncey fleet
IntlInvBaker // Number of rail cars in intermediate inventory at Baker
IntlInvChauncey // Number of rail cars in intermediate inventory at Chauncey
IntlInvAbleBaker // Number of rail cars in intermediate inventory at Able for Baker
IntlInvAbleChauncey // Number of rail cars intermediate inventory Able for Chauncey
ProductionChauncey // Production facility at Chauncey
RetailInvChauncey // Number of rail cars in finished goods inventory at Chauncey
SavedInvChauncey // Number of rail cars in build ahead inventory at Chauncey
Process AblePlant

Begin

Cars2Baker += TargetInvIntBaker - #IntInvBaker/IDLE +
                   (Avg2Baker*AvgRetailBaker-InRouteBaker)
If Cars2Baker <= #IntInvAbleBaker/IDLE then
Begin
   CarsinTrain = Cars2Baker
   Reduce #IntInvBaker/IDLE by CarsinTrain
   Cars2Baker = 0
End
Else
Begin
   CarsinTrain = #IntInvBaker/IDLE
   Reduce #IntInvBaker/IDLE by CarsinTrain
   Cars2Baker = CarsinTrain
End

Clone to Move2Baker

Cars2Chauncey += TargetInvIntChauncey - #IntInvChauncey/IDLE +
                          (Avg2Chauncey*AvgRetailChauncey-InRouteChauncey)
If Cars2Chauncey <= #IntInvAbleChauncey/IDLE then
Begin
   CarsinTrain = Cars2Chauncey
   Reduce #IntInvChauncey/IDLE by CarsinTrain
   Cars2Chauncey = 0
End
Else
Begin
   CarsinTrain = #IntInvChauncey/IDLE
   Reduce #IntInvChauncey/IDLE by CarsinTrain
   Cars2Chauncey = CarsinTrain
End

Clone to Move2Chauncey

Wait until Midnight
AddInv = TargetIntInvBaker - #IntInvAbleBaker/Idle
If (#FleetBaker/IDLE < AddInv) Then
   increase #FleetBaker/IDLE by (AddInv - #FleetBaker/IDLE)
Make FleetBaker/AddInv BUSY
Reduce #IntInvAbleBaker/IDLE by AddInv

AddInv = TargetIntInvChauncey(Month) - #IntInvAbleChauncey/Idle
If (#FleetChauncey/IDLE < AddInv) Then
   increase #FleetChauncey/IDLE by (AddInv - #FleetChauncey/IDLE)
Make FleetChauncey/AddInv BUSY
Reduce #IntInvAbleChauncey/IDLE by AddInv

End
After the train shipments are initiated, time is delayed until midnight when the inventories are updated. Since there is no constraint on production at Able plant, each inventory is simply reset to the target value. In addition, each unit in inventory is stored in a rail car. If there are insufficient idle rail cars at Able plant, additional units of each fleet resource are created.

The remaining discussion of the model will focus on the Chauncey plant. Baker plant operates in an identical way except that time varying average demand is not a factor.

The process Move2Chauncey is shown in the following pseudo-code. The number of rail cars in route to Chauncey is incremented by the number of cars in the train, CarsinTrain. The time delay for movement from Able to Chauncey is determined as a sample from the triangular distribution with minimum 7, mode 10, and maximum 20 days. All trains arrive at midnight. The number of cars in the intermediate product inventory at the Chauncey plant is recorded by increasing the number of idle units of the resource IntInvChauncey. The arriving cars are subtracted from the number of cars in route to the Chauncey plant.

```
Process Move2Chauncey
Begin
    InRouteChauncey + CarsinTrain
    Wait for Triangular 7, 10, 20 days // Train from Able to Chauncey
    Wait until Midnight
    Increase #InvIntChauncey by CarsinTrain
    InRouteChauncey -= CarsinTrain
End
```

Next consider the daily operations at the Chauncey plant. This involves determining the number of rail cars of product demanded by customers, the number of cars that can be shipped from inventory to meet this demand and the number of rail cars of the retail product to produce to replenish the inventory. Additional cars of retail product may need to be produced and saved to meet peak demand. Such cars already in inventory may or may not be available to meet current demand.

The process begins by adding the customer demand for the current day to the currently unfilled customer demand (the variable Cars2Cust). The demand is a sample from a triangular distribution whose mode depends on the month of the year, whose minimum is 70% of the mode and whose maximum is 130% of the mode and can result in a fractional number of rail cars. Only whole rail car loads are shipped so fractional demand, as well as unmet demand, is carried forward to the next day.

If the number of rail cars in the regular inventory is sufficient to meet the customer demand, then the inventory is reduced by the number of rail cars demanded and the remaining customer demand is reduced by the same quantity. If the demand is greater than the number of rail cars in regular inventory, the entire inventory is used to partially meet the demand. The inventory and demand variables are updated accordingly. If the month is April through December, the saved inventory can used to meet the remaining demand, partially or completely.

Service level observations are recorded. If all demand is met, the service level for the day is 100. Otherwise, the service level is zero.

The regular inventory is replenished to the target level by creating an order to produce more rail cars of retail product. The number of rail cars to produce is given by equation 15-1. The number of rail car loads in production is incremented by the right hand side of the same equation.
The saved inventory is built up each day by the number of rail cars depends on the month of the year and is specified in the variable \( \text{ProductionAdd}(\text{Month}) \). Thus, an order for \( \text{ProductionAdd}(\text{Month}) \) additional rail cars is created.

Each order entity corresponds to a single rail car's volume of production and has one attribute.

*IsSaved:* Whether or not the rail car is a part of the saved inventory (1 Yes; 0 No or regular inventory.)

The Chauncey plant process is given in the following pseudo-code.

```plaintext
Define Attributes

IsSaved // Is rail car part of saved inventory

Define Variables

WholeCars // Integer portion of demand in rail cars
OrderSize // How much to produce in rail cars

Process ChaunceyPlant

Begin

Cars2CustChauncey += triangular 70%*\text{Mode}(\text{Month}), \text{Mode}(\text{Month}), 130%\text{Mode}(\text{Month})
WholeCars = \text{Integer}(\text{Cars2CustChauncey})
If WholeCars <= \#RetailInvChauncey/\text{IDLE} Then

Begin // Enough Inventory to Meet Demand
Reduce \#RetailInvChauncey/\text{IDLE} by WholeCars
Cars2CustChauncey -= WholeCars
Tabulate 100 in ServiceLevel

End

Else

Begin // Not enough inventory to meet demand
WholeCars -= \#RetailInvChauncey/\text{Idle}
Cars2CustChauncey -= WholeCars
Reduce \#RetailInvChauncey/\text{IDLE} by WholeCars
If (Month is not April through December) Then tabulate 0 in ServiceLevel
Else

Begin // Try to use pre-made cars in inventory

If (WholeCars <= \#SavedInvChauncey/\text{IDLE}) Then

Begin // Enough pre-made cars to meet demand
Reduce \#SavedInvChauncey/\text{IDLE} by WholeCars
Cars2CustChauncey -= WholeCars
Tabulate 100 in ServiceLevel

End

Else

Begin // Not enough pre-made cars to meet demand
WholeCars -= \#SavedInvChauncey/\text{IDLE}
Cars2CustChauncey -= \#SavedInvChauncey/\text{IDLE}
Reduce \#SavedInvChauncey/\text{IDLE} by WholeCars
Tabulate 0 in ServiceLevel

End

Else

OrderSize = TargetInvRetailChauncey - \#InvRetailChauncey/\text{IDLE}
RetailProdChauncey += Ordersize
IsSaveInv = 0
Clone OrderSize to MakeChauncey

End

End
```

15-12
IsSaveInv = 1
Clone AddProduction(Month) to MakeChauncey

End
Chauncey plant production is modeled by process MakeChauncey, which is shown in the following pseudocode. Each entity represents an order to produce one rail car. The entity waits for one rail car sized unit of the intermediate product inventory. After the intermediate inventory is obtained, the entity waits for its turn in the Chauncey production facility. The production time is 1440 minutes (in a day) / 27 (the daily production capacity). Thus, the number of units made per day is limited to the capacity. The newly made unit is added to the appropriate inventory (regular or saved). The rail car containing the intermediate product is sent to wait for the next train to Able plant by adding one to the count of the number of rail cars on the train.

Process MakeChauncey
Begin
Wait until IntInvChauncey/1 to be IDLE
Make IntInvChauncey/1 Busy
Wait until ProductionChauncey/1 is IDLE
Make ProductionChauncey/1 Busy
Wait for 1440/27 minutes
Make ProductionChauncey/1 IDLE
Reduce #IntInvChauncey/Busy by 1
If IsSavedInv = 0 then
Begin
Increase #RetailInvChauncey/IDLE by 1
RetailProdChauncey -=1
End
Else Increase #SavedInvChauncey/IDLE by 1
Chauncey2Able +=1
End

The movement of empty cars from Chauncey plant to Able plant is modeled by process MoveChauncey2Able as shown in the following pseudocode. The number of cars in the train is the number cars containing intermediate inventory that was consumed since the last train departed. The trip is made and the train arrives at midnight to Able plant. One unit of the FleetChauncey resource is freed for each car in the train.

Define Arrivals:
Time of first arrival: 0
Time between arrivals: 1 day
Number of arrivals: Infinite

Process Move2AbleChauncey
Begin
CarsinTrain = Chauncey2Able
Chauncey2Able = 0
Wait for 7, 10, 20 days
Wait until Midnight
Make FleetChauncey/CarsinTrain IDLE
End

It is important to note when and how each process is initiated. An entity is sent to each of the plant processes: Able, Baker, and Chauncey once each day at midnight. An entity is sent to each process that moves trains to Able plant: Move2AbleBaker and Move2AbleChauncey at the time of daily train departure, 4 A.M. The MakeBaker and MakeChauncey processes are initiated by the Baker and Chauncey plant processes respectively after the number units to make to replenish the inventory has been determined. The Move2Baker and Move2Chauncey processes are initiated by the Able plant process after the number of rail cars to ship to each has been determined.
15.3.3 Identify Root Causes and Assess Initial Alternatives

The design of the initial simulation experiment is shown in Table 15-5. Since the customer demand data is valid for one year, a terminating experiment of length one year is used.

Model parameters are the inventory target levels. Establishing inventory target levels is a primary objective of the simulation study. This will be done by setting the target levels in the manner previously described and determining the resulting system performance. The performance is measured by the customer service level at Baker and Chauncey plants as well as the size of each fleet. In addition, the waiting time of orders for intermediate product at Baker and Chauncey plants so production can begin will be measured. Excessive waiting time could lower customer service levels. Only the waiting time for orders that had to wait is recorded.

There are four random streams, two for transportation times to and from Able plant and two for customer demand at Baker and Chauncey plants. Twenty replicates will be made.

Ideally, the level of each inventory at the end of each day should be the target value. Thus, the target value is used for the initial inventory level.

Trains arrive to Baker and Chauncey plant daily on the average. However, the first shipments from Able plant will not arrive to Baker and Chauncey plants until day 7 and 10 on the average. Thus, shipments must be scheduled to arrive to Baker and Chauncey plants on the preceding days as part of the initial conditions. Shipment size is the average number of rail cars arriving to the plant per day. This is equal to the average customer demand at that plant.

**Table 15-5: Simulation Experiment Design for the Supply Chain**

<table>
<thead>
<tr>
<th>Element of the Experiment</th>
<th>Values for This Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Experiment</td>
<td>Terminating</td>
</tr>
<tr>
<td>Model Parameters and Their Values</td>
<td>1. Retail inventory target levels set to the 95% point of the customer demand distribution</td>
</tr>
<tr>
<td></td>
<td>2. Intermediate inventory target levels at Baker and Chauncey plants initially set to the same value as corresponding retail inventory target level</td>
</tr>
<tr>
<td></td>
<td>3. Intermediate inventory target levels at Able plant initially set to the same value as the corresponding inventory at Baker or Chauncey plant</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>1. Service level to customers at Baker plant</td>
</tr>
<tr>
<td></td>
<td>2. Service level to customers at Chauncey plant</td>
</tr>
<tr>
<td></td>
<td>3. Fleet size: Able to Baker</td>
</tr>
<tr>
<td></td>
<td>4. Fleet size: Able to Chauncey</td>
</tr>
<tr>
<td></td>
<td>5. Order waiting time for intermediate inventory at Baker plant</td>
</tr>
<tr>
<td></td>
<td>6. Order waiting time for intermediate inventory at Chauncey plant</td>
</tr>
<tr>
<td>Random Number Streams</td>
<td>1. Transportation time between Able plant and Baker plant</td>
</tr>
<tr>
<td></td>
<td>2. Transportation time between Able plant and Chauncey plant</td>
</tr>
<tr>
<td></td>
<td>3. Customer demand at Baker plant</td>
</tr>
<tr>
<td></td>
<td>4. Customer demand at Chauncey plant</td>
</tr>
<tr>
<td>Initial Conditions</td>
<td>1. All inventory levels set equal to their target</td>
</tr>
<tr>
<td></td>
<td>2. Intermediate inventory arrivals to Baker and Chauncey plants as discussed in the text</td>
</tr>
<tr>
<td>Number of Replicates</td>
<td>20</td>
</tr>
</tbody>
</table>
Simulation results are shown in Table 15-6.

Table 15-6: Simulation Results for the Initial Experiment

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Fleet Size (Rail Cars)</th>
<th>Service Level</th>
<th>Wait for Inventory (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baker</td>
<td>Chauncey</td>
<td>Baker</td>
</tr>
<tr>
<td>1</td>
<td>501</td>
<td>666</td>
<td>43</td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>722</td>
<td>55</td>
</tr>
<tr>
<td>3</td>
<td>502</td>
<td>671</td>
<td>49</td>
</tr>
<tr>
<td>4</td>
<td>468</td>
<td>724</td>
<td>68</td>
</tr>
<tr>
<td>5</td>
<td>467</td>
<td>700</td>
<td>85</td>
</tr>
<tr>
<td>6</td>
<td>501</td>
<td>704</td>
<td>61</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>684</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>502</td>
<td>719</td>
<td>54</td>
</tr>
<tr>
<td>9</td>
<td>494</td>
<td>724</td>
<td>39</td>
</tr>
<tr>
<td>10</td>
<td>495</td>
<td>698</td>
<td>43</td>
</tr>
<tr>
<td>11</td>
<td>486</td>
<td>732</td>
<td>61</td>
</tr>
<tr>
<td>12</td>
<td>484</td>
<td>709</td>
<td>60</td>
</tr>
<tr>
<td>13</td>
<td>481</td>
<td>749</td>
<td>64</td>
</tr>
<tr>
<td>14</td>
<td>489</td>
<td>675</td>
<td>68</td>
</tr>
<tr>
<td>15</td>
<td>534</td>
<td>717</td>
<td>61</td>
</tr>
<tr>
<td>16</td>
<td>472</td>
<td>722</td>
<td>28</td>
</tr>
<tr>
<td>17</td>
<td>501</td>
<td>737</td>
<td>54</td>
</tr>
<tr>
<td>18</td>
<td>489</td>
<td>717</td>
<td>44</td>
</tr>
<tr>
<td>19</td>
<td>488</td>
<td>736</td>
<td>52</td>
</tr>
<tr>
<td>20</td>
<td>476</td>
<td>695</td>
<td>51</td>
</tr>
</tbody>
</table>

Average 492 710 54 26 30 33
Std. Dev. 15 23 13 18 2 2
99% CI Lower Bound 482 695 46 15 29 32
99% CI Upper Bound 501 725 62 37 32 34

Service level values are unexpectably low. Order waiting time for intermediate inventory averages greater than one day at each plant. An average of 1339 orders per replicate waited for intermediate inventory at the Baker plant with an approximate 99% CI of (1152, 1526) while an average of 1094 orders per replicate waited for intermediate inventory at the Chauncey plant with an approximate 99% CI of (949, 1238).

These results lead to a second alternative. The target intermediate inventory at Baker plant is increased by the expected customer demand in one day as the waiting time for intermediate inventory averages about 1.25 days. Similarly, the target inventory at Chauncey plant is increased by the expected customer demand in two days as the waiting time for intermediate inventory is about 1.4 days. Otherwise the simulation experiment is the same as shown in Table 15-5. Results are shown in Table 15-7.
Table 15-7: Simulation Results with Higher Intermediate Inventory Targets

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Fleet Size (Rail Cars)</th>
<th>Service Level</th>
<th>Wait for Inventory (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baker</td>
<td>Chauncey</td>
<td>Baker</td>
</tr>
<tr>
<td>1</td>
<td>520</td>
<td>770</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>483</td>
<td>795</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>501</td>
<td>771</td>
<td>93</td>
</tr>
<tr>
<td>4</td>
<td>492</td>
<td>763</td>
<td>93</td>
</tr>
<tr>
<td>5</td>
<td>516</td>
<td>778</td>
<td>91</td>
</tr>
<tr>
<td>6</td>
<td>499</td>
<td>744</td>
<td>93</td>
</tr>
<tr>
<td>7</td>
<td>502</td>
<td>750</td>
<td>95</td>
</tr>
<tr>
<td>8</td>
<td>532</td>
<td>819</td>
<td>91</td>
</tr>
<tr>
<td>9</td>
<td>499</td>
<td>801</td>
<td>94</td>
</tr>
<tr>
<td>10</td>
<td>494</td>
<td>846</td>
<td>96</td>
</tr>
<tr>
<td>11</td>
<td>516</td>
<td>782</td>
<td>90</td>
</tr>
<tr>
<td>12</td>
<td>504</td>
<td>784</td>
<td>95</td>
</tr>
<tr>
<td>13</td>
<td>497</td>
<td>813</td>
<td>94</td>
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<tr>
<td>14</td>
<td>499</td>
<td>774</td>
<td>92</td>
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<tr>
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<tr>
<td>16</td>
<td>487</td>
<td>773</td>
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<td>492</td>
<td>748</td>
<td>96</td>
</tr>
<tr>
<td>18</td>
<td>524</td>
<td>808</td>
<td>93</td>
</tr>
<tr>
<td>19</td>
<td>511</td>
<td>808</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>502</td>
<td>779</td>
<td>93</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td>504</td>
<td>785</td>
<td>94</td>
</tr>
<tr>
<td><strong>Std. Dev.</strong></td>
<td>13</td>
<td>26</td>
<td>2</td>
</tr>
<tr>
<td><strong>99% CI Lower Bound</strong></td>
<td>496</td>
<td>769</td>
<td>92</td>
</tr>
<tr>
<td><strong>99% CI Upper Bound</strong></td>
<td>512</td>
<td>802</td>
<td>95</td>
</tr>
</tbody>
</table>

Results show that the approximate 99% confidence intervals for the service level at both the Baker plant and the Chauncey plant contain the target service level of 95%. The fleet size required for the Chauncey plant is 785 cars and the fleet size required for Baker plant is 504 cars. An average of 122 orders per replicate waited for intermediate inventory at the Baker plant with an approximate 99% confidence interval of (83, 161) while an average of 124 orders per replicate waited for intermediate inventory at the Chauncey plant with an approximate 95% confidence interval of (100, 148). Note that number of orders waiting at each plant has dropped by about an order of magnitude.

Since service levels are acceptable for this alternative, inventory capacity can be examined. The retail inventories at Baker and Chauncey plant can by design not exceed the target. The same is true for the intermediate inventories at Able plant. Thus, only the inventory capacities to be set are the intermediate inventories at Baker and Chauncey plant. The approximate 99% confidence interval for the maximum number of rail cars in the intermediate inventory at Baker plant is (135, 145) with an average of 140. The approximate 99% confidence interval for the same quantity at Chauncey plant is (155, 170) with an average of 162.

15.3.4 Review and Extend Previous Work

Management was willing to except a slightly less than 95% service level at Baker plant. Fleet sizes of 504 for Able to Baker and 785 for Able to Chauncey will be used. The number of orders waiting for intermediate inventory as well as the average waiting time were felt to be acceptable.
The target inventory levels are as follows. Note that target inventory values associated with Chauncey plant vary by month.

**Retail inventories:** 35 at Baker plant, the 95% point of the demand distribution as shown in Table 15-2 at Chauncey plant.

**Intermediate inventories:**
- 60 (35 + 25 = the expected demand in one day) at Baker plant
- and for the Baker plant intermediate inventory at Able plant
- 35 + 2 * the monthly value shown in Table 15-1 for the Chauncey plant

Inventory capacities were set as follows.

**Customer inventories:** Same as target inventories.

**Intermediate inventories:**
- Able plant – Same as target inventories.
- Baker plant – Same as the average maximum of 140 rail cars
- Chauncey plant – Same as the average maximum of 162 rail cars

### 15.3.5 Implement the Selected Solution and Evaluate

The supply chain will be operated with the above parameters. Service level performance will be monitored.

### 15.4 Summary

This chapter discusses the use of simulation to analyze complex systems in general and supply chains in particular. Some components of such systems have time varying characteristics such as the expected customer demand for products. The behavior of one component may depend on the behavior of other components. Customer demand at one facility is a factor in determining shipping quantities at another facility.

Models can be constructed by viewing the complex system as a set of semi-independent processes that share information using modeling constructs such a variables and resources. Simulation experiments include initial conditions that specify time dynamic behavior such as the arrival of shipments over time at a facility. A variety of simulation results can be collected and the behavior of many of aspects of such a system can be assessed.
Problems

1. Distinguish the integrated supply chain approach from the automated inventory management approach discussed in chapter 13.

2. Compare the flow of information in an integrated supply chain to the flow of work in a kanban system such as the one discussed in chapter 10.

3. What other factors should be taken into account in setting the initial target inventory levels for the intermediate products at each plant in addition to the variation in customer demand?

4. What information would be lost if two models were used instead of the one model in this chapter? One model would represent the supply chain between Able plant and Baker plant and the other between Able plant and Chauncey plant.

5. State the model for each of the following processes:
   a. Baker
   b. BakerMake
   c. Move2Baker
   d. Move2AbleBaker

6. Instead of scheduling daily train arrivals at Baker and Chauncey plants as a part of the initial conditions, discuss the effects of simply increasing the initial inventory at each plant by an amount equal to the total volume arriving due to the initially scheduled shipments.

7. Why is the fleet size larger for Chauncey plant than Baker plant when the customer demand is smaller?

8. Modify the model discussed in this chapter to determine how many rail cars would be saved if there was only one rail fleet used to ship product from the Able plant.

9. Evaluate the policy of shipping an amount equal to the expected customer demand from Able plant to each of the other two plants each week. For Chauncey plant this means the expected time of train arrival should be used in determining which expected demand to use.

10. Modify the model in this chapter to estimate the rail yard size needed at Able plant.

11. Suppose that the capacity of Able plant is 62 rail cars per day in sum total over all products produced. Analyze the supply chain for this case. Generate additional inventory needed to support Chauncey plant ahead of time if needed.

12. Analyze the supply chain for the following case: Allow the saved inventory at Chauncey to be used to meet demand during the first three months of the year. Replace all saved inventory that is used in this way.

13. Modify the model so that the size of each rail fleet can be constrained to a pre-specified upper limit. Find the smallest rail fleet size that results in an acceptable service level.

14. Currently the model described in this chapter assumes that customers will accept backorders and late deliveries. Modify the model so that demand which can not be met on time results in lost sales. Conduct simulation experiments to estimate the volume of lost sales and reset the operating parameter values of the supply chain to minimize lost sales.
15. Modify the model described in this chapter so that fractional demand is met if inventory is available.

16. Rerun the simulation model to collect verification and validation evidence. This evidence could include:
   a. One table for each inventory. The rows of the table correspond to days. There is one column for each of the following: Level at the beginning of the day, additions, removals, and level at the end of the day.
   b. The number of orders at each plant that way for intermediate inventory.
   c. Month by month service levels at Chauncey plant

Case Problem

A company supplies a customer product for which daily demand, expressed in truck loads, is normally distributed with a mean of 10 and a standard deviation of 2. Production capacity is 14 truck loads per day. Delivery time is equally distributed between one day and two days that is it takes either one or two days for the truck to travel to the customer, deliver the load, and return to the company site.

There is one truck load of raw material per truck load of final product. Raw material is obtained from a supplier. Travel time from the company site for each truck is as follows: one day to the supplier, one day (80%) or two days (20%) at the supplier, and one day to return to the company site.

The same truck fleet is used for both product delivery and raw material acquisition.

Determine the size of the truck fleet. In addition, determine the target inventory level for raw material and the inventory target level for the consumer product needed for a 95% service level for delivery to customers.

The time period of interest is one year (365 days).

Case Problem Issues


2. How could a lower bound on the target inventory for the consumer product be set?

3. How could a lower bound on the target inventory for the raw material be set?

4. How could a lower bound on the truck fleet size be computed?