Part V
Material Handling

In previous chapters, entity movement between stations was not included in models and movement times were implicitly assumed to be negligible. However, these assumptions are not always satisfactory. Material movement or handling may be a significant component of a manufacturing system. Note that such movement and the devices required to perform it do not add value to a service or product. Thus material handling is inconsistent with the lean philosophy, increasing both capital equipment cost and lead time. Efficient and cost effective material handling is essential to successful operations.

It has been claimed that the most effective tool for evaluating the performance of material handling system designs is simulation. Alternative strategies can be evaluated. Competing equipment can be compared. The ability of a particular design to meet performance criteria such as a throughput target can be assessed.

Chapter 16 discusses transfer hubs. Such hubs are an integral part of the operations of shipping companies that transport packages. A hub provides for the sorting and routing of voluminous packages within a short time frame. This is most often accomplished using a series of conveyor systems. A transfer hub routes the inbound packages to their final destination or another hub.

Chapter 17 deals with issues concerning automated guided vehicles (AGV’s). An AGV system is used to move loads of parts along predetermined paths between workstations without manual operation. Simulation is used to confirm the operational effectiveness of an AGV system that has been designed by other means.

Chapter 18 discusses the use of an automated storage and retrieval system (AS/RS) to manage inventory. An AS/RS system provides for the high-speed storage and movement of parts and other materials. The computer system that is part of an AS/RS provides for real-time inventory management. Simulation is used to evaluate alternative AS/RS storage configurations.
Chapter 16

Transfer Hubs

16.1 Introduction

Companies such as FedEx and United Parcel Service specialize in the delivery of packages often when time is critical. The network of trucks and airplanes employed by such a company transports millions of packages to both business and personal customers each year.

The ground-based shipping methods employed by these companies typically rely on a network of terminals and hubs to move packages throughout the country. Vans are used to pick up packages from customers and deliver them to a small terminal. If a package needs to be sent outside of the terminal’s delivery area, it is loaded onto a tractor-trailer truck and sent to a hub.

Most hubs are located in major cities with hundreds of the smaller terminals located in smaller cities. Tractor-trailers containing packages to be shipped a great distance across the country can be loaded onto railcars to reduce cost. When the tractor-trailer arrives at a hub, the packages it contains are sorted by destination. Outbound packages can be loaded into vans for local delivery or sent to other hubs throughout the network.

At the heart of the hub is the material handling system usually a conveyor system. The conveyor system is used to unload, sort and transport packages throughout the hub. Hub facilities may be of enormous size, some containing 8 miles of conveyor. The hub material handling system is built up in phases. Each phase typically adds a copy of the original system as well as expanding it. Phased development reduces the financial risk associated with installing the complete system before the demand to support it exists.

The material handling structure employed by a typical hub is shown in Figure 16-1. A truck arrives to one of many docks that comprise the unload area. A large conveyor is extended into the truck. A worker manually unloads each truck and places the packages it contains on the conveyor.

A set of conveyors, usually four in number, used in truck unloading is called a bank. Typically, each pair of unload banks feeds a primary sorter, which processes packages from multiple unloading doors at once. A variety of logic is used to merge packages on to a single conveyor before reaching the primary sorter.

Each of the primary sorters routes packages to one of many secondary sorters. A secondary sorter routes each package to a particular lane and hence to an outbound truck. A worker removes each package from a lane and places it in the proper truck. A lane corresponds to a particular zip code or truck destination. A typical secondary sorter supports 20 lanes.

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1 Mr. Joel Oostdyk assisted with the development of this application study.
16.2 Points Made in the Case Study

This case study deals with modeling issues concerning conveyors. A conveyor is viewed as consisting of multiple segments. Certain segments, such as the exit points for work stations, are key. Key segments are modeled as resources with the number of units equal to the capacity of the segment. When all resource units are busy, the key segment is full and other items “back up” along preceding segments of the conveyor. The non-key segments are modeled as time delays only.

Key segments and operations are modeled similarly. A scarce system object is modeled as a resource constraining the movement of an entity. An entity uses this object for a length of time and then releases it for use by other entities.

Package travel time on a conveyor is determined from specifications of the speed of the conveyor and the distance the package must travel.

Many simulation languages have special modeling constructs for representing conveyor systems in a model. These constructs contain the logic for modeling key and other segments. Thus, this logic can be included in a model transparently to its developer.

In some cases, an operation may be performed by any of several workers or machines. In the model, this implies a choice between resources. The logic for making this choice must be specified.

Multiple individually distinguishable resources may be identified by the same name. The individual resources each have a unique ID number or index. For example a model could represent 10 workers with the resource WORKER and worker 7 could be referenced by WORKER(7).
Ergonomic considerations can be included in a model. In this case, worker walking time as well as allowances for rest and other personal time are taken into account.

Performance measures can be computed from other performance measures. In this case, the average utilization for a group of workers is computed from the utilization of each individual worker.

16.3 The Case Study

The following case study is a subset of one described by Warber and Standridge (2002). A package sorting hub is entering an expansion phase. The number of unloading banks, primary sorters and secondary sorters is increasing to support processing an increased volume of packages. Secondary sorter operations are of particular interest.

16.3.1 Define the Issues and Solution Objective

The level of staffing is a significant cost component for a transfer hub. Thus, the number of workers assigned to loading out bound trucks is at issue. Management believes that a worker can support more than one secondary sorter lane at a time. For example, a worker supporting two lanes would wait until a package arrives to one of the two lanes, walk to that lane, place the package on the truck, and return to look for the next arriving package on either lane. Note that in addition to the time to load a package into a truck, the walking time to a lane must be taken into account.

The number of workers to assign to the secondary sorter must be determined. The number of workers should be minimized to reduce costs. At the same time, loading delays are detrimental to hub operations. Thus, the time to load a package should be minimized. These two operating criteria are in conflict and a suitable balance between the two must be found.

A simulation study will be done to determine the number of workers to assign per secondary sorter. Trucks containing packages arrive to the terminal between 4:00 P.M. and 8:00 P.M. each day. It is estimated that on the average 8000 of these packages will be processed by the secondary sorter of interest. Since many packages are also sent to other secondary sorters, the time between arrivals the secondary sorter of interest is considered to be an exponentially distributed random variable with mean 4 hours / 8000 packages or 1.8 seconds.

The secondary sorter serves 20 loading lanes each leading to a loading dock. A package is equally likely to be routed to any of the loading lanes. The distance between loading lanes is 10 feet measured from the center point of one loading lane to the center point of the next. A detailed drawing of the secondary sorter of interest is given in Figure 16-2.

The distance from the secondary sorter to a loading door is 37 feet. The total length of the secondary sorter conveyor is 250 feet. Conveyor speed is 1 foot per second.

Loading time consists of two components: the time for a worker to remove a package from the end of the loading lane and place it properly in the truck and the time for the worker to walk to a loading lane. The former can be modeled as a random variable since the location of a particular package in a truck depends on the packages currently in the truck. Experience has found the loading time to be highly variable with a mean of 8 seconds. Thus, loading time is considered to be exponentially distributed.

The time for a worker to walk to a loading lane depends on how many lanes the worker serves. If the worker serves two lanes and waits halfway between them for an arriving package, the walking distance is five feet. Assuming the average walking speed is 2 miles per hour, the
average walking time is about 1.7 seconds. This time is about 21% of the average time to place a package on a truck and thus is a significant factor in determining system performance.

16-3.2 Build Models

The model of the secondary sorter operations must take into account the following system components.

1. Arrival of packages to the secondary sorter between 4 P.M. and 8 P.M. with an exponentially distributed time between arrivals with a mean of 8 seconds.
2. Package movement along the secondary sorter conveyor until the lane corresponding to the loading door is reached.
3. Package movement to the end of the lane.
4. Loading of the package on the truck.
5. Worker assignment to lanes including walking time to a lane.

Arriving entities model packages and have the following attributes.

1. Lane: Loading lane assignment, 1, 2, ..., 20.
2. TimeArriveLane: Time of arrival to the end of a lane.
3. LaneWorker: ID of the particular worker resource assigned to lane Lane.

The latter attribute allows the time a package waited for a worker for loading to be collected.

Model logic is shown in the following pseudocode. Packages arrive according to an exponential distribution with mean 1.8 seconds. The lane from which the package will be loaded is computed as a sample from a uniform distribution between 1 and 21. Thus, each of the lanes 1 through 20 is equally likely. The package moves on the secondary sorter conveyor at the rate of 1 foot per
second to the selected lane. Then the package moves down the lane to its end at the same rate. The arrival time at the end of the lane is noted. The package waits at the end of the lane for the worker serving that lane. The waiting time is collected. The worker walks to the lane in 1.7 seconds and then loads the package in an exponentially distributed time with a mean of 8 seconds. After this task, the worker becomes IDLE again.

Define Arrivals

<table>
<thead>
<tr>
<th>Time of first arrival:</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time between arrivals:</td>
<td>Exponential 1.8 seconds</td>
</tr>
<tr>
<td>Number of arrivals:</td>
<td>Infinite</td>
</tr>
</tbody>
</table>

Define Attributes

| Lane | // Loading lane assignment, 1, 2, …, 20. |
| TimeArriveLane | // Time of arrival to the end of a lane. |
| LaneWorker | // ID of the particular worker resource assigned to lane Lane. |

Define Resources

Worker(2) // Lane workers

Process SecondarySorter

Begin

Lane = Integer (Uniform 1, 21) // Select Lane
Wait for (1 sec * distance to lane in feet) // Move to lane
Wait for (1 sec * length of lane conveyor in feet) // Move to load area
TimeArriveLane = Clock
LaneWorker = (Lane+1)/2 // Select lane worker
Wait until Worker(LaneWorker)/1 is IDLE
Make Worker(LaneWorker)/1 BUSY
Tabulate (Clock-LaneArrivalTime) in WaitforWorker
Wait for 1.7 seconds // Worker walks to lane
Wait for Exponential 8 seconds // Worker loads truck
Make Worker(LaneWorker)/1 IDLE

End

Model logic for a conveyor deserves more detailed discussion. Consider a lane conveyor. The conveyor is divided into segments. Each segment can contain one package so each segment is the size of a package. The segment at the end of the lane is called a key segment. The key segment is modeled as a resource so that only one package can occupy the key segment at a time. Packages waiting for the key segment to become idle occupy the segments physically preceding the key segment. If enough packages are waiting, the lane could become full and block the secondary sorter conveyor.

When modeling a conveyor, the size of entities traveling on the conveyor and the key segments must be specified along with the conveyor speed. The use of the non-key segments as queuing space for a key segment must be included in the model. Figure 16-3 summarizes these ideas. An entity moves on the lane until it reaches the non-key segment closest to the key segment that is not occupied by another entity. Each entity waits to enter the key segment. As an entity departs the key segment, all remaining waiting entities move one non-key segment closer to the key segment.

Fortunately, the above logic is included in the modeling constructs of many simulation languages. Thus, the modeler is required only to specify the conveyor parameters, for example package size, conveyor speed, conveyor length, and key segment location.
Figure 16-3: Model of a Lane Conveyor
16.3.3 Identify Root Causes and Assess Initial Alternatives

Management desires that the workers be kept as busy as possible. On the other hand, ergonomic considerations require worker rest and personal time to be about 20% of the work period. Thus, an average worker utilization of 80% is sought and this quantity is one performance measure. The time a package waits for a worker before loading is also of interest.

One model parameter will be varied, the number of lanes served by a worker, either 2 or 3. Note that worker walking time to a lane will increase when 3 lanes are served. The worker will stand at the middle lane of the three being served. The walking distance to the middle lane is therefore negligible. The walking distance to each of the other two lanes is 10 feet. Thus, the average walking distance increases from 5 feet to 6.67 feet and the average walking time increases from 1.7 seconds to 2.3 seconds. Having each worker serve 3 lanes instead of 2 reduces the number of workers from ten to seven. Six of the seven workers serve 3 lanes and the seventh serves the remaining two lanes.

Since trucks arrive with packages between 4 P.M. and 8 P.M. each day, a terminating simulation experiment of duration 4 hours is employed. Twenty replicates will be made. Since there are no packages at the secondary sorter at 4 P.M., the initial conditions are all lanes empty and all workers idle.

There are three random number streams used in the model, one for package arrivals, one for lane assignments, and one for package loading time onto trucks.

The experiment is summarized in Table 16-1.

<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>Number of lanes served by one worker (2 or 3)</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>1. Average utilization over all workers</td>
</tr>
<tr>
<td></td>
<td>2. Waiting time for a worker</td>
</tr>
<tr>
<td>Random Number Streams</td>
<td>1. Time between arrivals</td>
</tr>
<tr>
<td></td>
<td>2. Lane assignment for a package (1-20)</td>
</tr>
<tr>
<td></td>
<td>3. Loading time</td>
</tr>
<tr>
<td>Initial Conditions</td>
<td>Empty and idle</td>
</tr>
<tr>
<td>Number of Replicates</td>
<td>20</td>
</tr>
<tr>
<td>Simulation End Time</td>
<td>4 hours</td>
</tr>
</tbody>
</table>

Simulation results for the cases where a worker serves 2 and 3 lanes are shown in Table 16-2. Average worker utilization is the average utilization of all workers in the first case and of only those workers serving 3 lanes in the second case.
Table 16-2: Average Worker Utilization and Package Waiting Time for a Worker at the Secondary Sorter

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Worker Serves Two Lanes</th>
<th>Worker Serves Three Lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Package Waiting Time (sec)</td>
<td>Average Worker Utilization</td>
</tr>
<tr>
<td>1</td>
<td>3.1</td>
<td>0.533</td>
</tr>
<tr>
<td>2</td>
<td>2.8</td>
<td>0.520</td>
</tr>
<tr>
<td>3</td>
<td>2.9</td>
<td>0.529</td>
</tr>
<tr>
<td>4</td>
<td>2.9</td>
<td>0.535</td>
</tr>
<tr>
<td>5</td>
<td>2.8</td>
<td>0.529</td>
</tr>
<tr>
<td>6</td>
<td>2.9</td>
<td>0.528</td>
</tr>
<tr>
<td>7</td>
<td>2.9</td>
<td>0.527</td>
</tr>
<tr>
<td>8</td>
<td>3.0</td>
<td>0.527</td>
</tr>
<tr>
<td>9</td>
<td>3.0</td>
<td>0.535</td>
</tr>
<tr>
<td>10</td>
<td>3.1</td>
<td>0.538</td>
</tr>
<tr>
<td>11</td>
<td>3.0</td>
<td>0.530</td>
</tr>
<tr>
<td>12</td>
<td>2.9</td>
<td>0.527</td>
</tr>
<tr>
<td>13</td>
<td>3.1</td>
<td>0.533</td>
</tr>
<tr>
<td>14</td>
<td>3.2</td>
<td>0.546</td>
</tr>
<tr>
<td>15</td>
<td>2.9</td>
<td>0.537</td>
</tr>
<tr>
<td>16</td>
<td>2.9</td>
<td>0.530</td>
</tr>
<tr>
<td>17</td>
<td>2.9</td>
<td>0.536</td>
</tr>
<tr>
<td>18</td>
<td>3.1</td>
<td>0.536</td>
</tr>
<tr>
<td>19</td>
<td>2.9</td>
<td>0.534</td>
</tr>
<tr>
<td>20</td>
<td>3.0</td>
<td>0.526</td>
</tr>
<tr>
<td>Average</td>
<td>3.0</td>
<td>0.532</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.096</td>
<td>0.00560</td>
</tr>
</tbody>
</table>

99% CI Lower Bound

|           | 2.9                      | 0.528                      | 10.2                       | 0.839                      |

99% CI Upper Bound

|           | 3.0                      | 0.535                      | 10.7                       | 0.851                      |

Note that in neither case does the approximate 99% confidence interval contain the target utilization of 80%. Package average waiting time increases by about 3.5 times when a worker serves three lanes instead of 2.

16.3.4 Review and Extend Previous Work

Management was disappointed that neither assigning 2 or 3 lanes to a worker produced the desired utilization of 80%. The slightly higher utilization of 84.5% on the average was deemed unacceptable since upper bound of the 99% confidence interval was 85.1%. A worker utilization of 53.2% was deemed too low and thus too costly.

The following alternative was proposed. Each worker would serve 2 lanes alone plus sharing the responsibility for a third lane with another worker. This would increase the number of workers from seven serving 3 lanes each to eight serving 2.5 lanes each. Thus, the simulation project process was restarted at the Build Models step.
16.4.1 Build Models

The average walking time when a worker serves two lanes and shares responsibility for a third lane was computed as follows. A worker stands in the same position as when serving 2 lanes. Thus, the average walking time is 1.7 seconds for 80% of the package loading operations. For the other 20% of the package loads, the walking distance is 15 feet, which requires 5.1 seconds on the average. Thus, two walking times must be included in the model.

A new version of the model was created to model two workers sharing responsibility for every third lane. The shared lanes are 3, 8, 13, and 18. No changes to model logic are required for non-shared lanes. For shared lanes, the changes to model logic are as follows.

1. Wait for either lane worker to perform the loading operation, whichever one becomes IDLE first.
2. Use the walking time to a shared lane, 5.1 seconds.
3. Free whichever worker performed the loading operation.

16.4.2 Identify Root Causes and Assess Initial Alternatives

The experiment is the same as the one define in Table 16-1 except for the performance measures. Waiting time for each of two types of packages is required: those using lanes served by one worker alone and those using lanes servered by two workers.

Simulation results comparing the two cases are shown in Table 16-3.

In the shared lanes scenario, all workers serve the same number of lanes, 2.5. The average worker utilization is 66.4%, less than the desired 80% target but more than in the case where each worker serves only two lanes. Average package waiting time is about half of that in the workers serve 3 lanes case. Average package waiting time is less on the shared lanes than on the lanes that do not share a worker.

16.4.3 Implement the Selected Solution and Evaluate

Management was disappointed that the target worker utilization of 80% could not be achieved but satisfied with the using eight workers instead of the ten required by the case in which a worker servers two lanes only. Average package waiting time was deemed satisfactory.

16.5 Summary

This chapter discusses the modeling and analysis of a package transfer hub. Specifically techniques for modeling conveyor systems have been presented. The choice between alternative resources for performing an operation has been illustrated. Ergonomic considerations have been included in the model. The number of workers to serve a loading operation was determined.
Table 16-3. Average Worker Utilization and Package Waiting Time for a Worker at the Secondary Sorter – Shared Lanes Case

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Worker Serves Three Lanes</th>
<th>Worker Serves Two Lanes Plus a Shared Lane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Package Waiting Time</td>
<td>Average Worker Utilization</td>
</tr>
<tr>
<td>1</td>
<td>10.7</td>
<td>0.843</td>
</tr>
<tr>
<td>2</td>
<td>9.8</td>
<td>0.832</td>
</tr>
<tr>
<td>3</td>
<td>10.3</td>
<td>0.839</td>
</tr>
<tr>
<td>4</td>
<td>10.8</td>
<td>0.845</td>
</tr>
<tr>
<td>5</td>
<td>10.4</td>
<td>0.845</td>
</tr>
<tr>
<td>6</td>
<td>10.4</td>
<td>0.842</td>
</tr>
<tr>
<td>7</td>
<td>10.4</td>
<td>0.837</td>
</tr>
<tr>
<td>8</td>
<td>10.1</td>
<td>0.839</td>
</tr>
<tr>
<td>9</td>
<td>10.3</td>
<td>0.844</td>
</tr>
<tr>
<td>10</td>
<td>10.6</td>
<td>0.855</td>
</tr>
<tr>
<td>11</td>
<td>10.2</td>
<td>0.841</td>
</tr>
<tr>
<td>12</td>
<td>9.9</td>
<td>0.835</td>
</tr>
<tr>
<td>13</td>
<td>10.4</td>
<td>0.844</td>
</tr>
<tr>
<td>14</td>
<td>11.3</td>
<td>0.870</td>
</tr>
<tr>
<td>15</td>
<td>10.8</td>
<td>0.853</td>
</tr>
<tr>
<td>16</td>
<td>10.3</td>
<td>0.843</td>
</tr>
<tr>
<td>17</td>
<td>10.7</td>
<td>0.852</td>
</tr>
<tr>
<td>18</td>
<td>11.4</td>
<td>0.858</td>
</tr>
<tr>
<td>19</td>
<td>10.7</td>
<td>0.849</td>
</tr>
<tr>
<td>20</td>
<td>10.3</td>
<td>0.836</td>
</tr>
<tr>
<td>Average</td>
<td>10.5</td>
<td>0.845</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>0.398</td>
<td>0.00903</td>
</tr>
<tr>
<td>99% CI Lower Bound</td>
<td>10.2</td>
<td>0.839</td>
</tr>
<tr>
<td>99% CI Upper Bound</td>
<td>10.7</td>
<td>0.851</td>
</tr>
</tbody>
</table>

Problems

1. Explain how sampling from the continuous uniform distribution with minimum 1 and maximum 21 gives equal probability to the integers 1 through 20 and no probability to the integer 21 when samples from truncated to integer values.

2. Why is the time between the arrival of a package to the secondary sorter and completion of loading on a truck not a good performance measure? Supply an improved definition for this performance measure.

3. Develop a model for a lane served by either of two workers.
4. Perform a formal statistical analysis using paired confidence intervals and the data in Table 16-3 to confirm that package waiting time is less in the workers share lanes case than in the case where a worker serves 3 lanes.

   a. Compare average package waiting time with each worker serving 3 lanes (2nd column) with the average waiting time for lanes served by only one worker, the non-shared lanes (4th column).

   b. Compare average package waiting time in the shared lines (5th column) and the non-shared lanes (4th column).

5. Explain why the average waiting time for packages for a shared lane served by two workers (5th column) is less than for lanes served by one worker (4th column) as seen in Table 16-3.

6. Perform a formal statistical analysis using paired confidence intervals and the data in Tables 16-2 and 16-3 to compare the average package waiting time between the worker serves two lanes scenario (2nd column) and the shared lanes scenario (5th column).

7. Explain why average package waiting time increases in a non-linear fashion as the utilization of the workers increases.

8. Go to a manufacturing lab, transfer hub, or a local manufacturing plant to observe a conveyor system in operation. List the number of different conveyor types found.

9. Embellish the model to make package loading time a function of how many packages are on a truck. Assume 8 seconds is the mean time to load the package in the center of the truck and each truck holds 200 packages. The mean loading time varies linearly from 12 seconds for a completely empty truck to 4 seconds for the last package on a truck. After the 200th package is loaded on a truck, the fully loaded truck swaps positions with an empty truck in 3 minutes. No package loading can occur during this time. Determine the number of workers needed under these conditions.

10. Suppose that packages are not uniformly distributed across final destinations but the distribution by destination is shown in the following table. Use simulation to assign the package destinations to lanes as well as workers to lanes. The destinations may be assigned to lanes in any way that is helpful.

<table>
<thead>
<tr>
<th>Package Destination</th>
<th>Percent of Packages</th>
<th>Package Destination</th>
<th>Percent of Packages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.48%</td>
<td>11</td>
<td>5.24%</td>
</tr>
<tr>
<td>2</td>
<td>0.95%</td>
<td>12</td>
<td>5.71%</td>
</tr>
<tr>
<td>3</td>
<td>1.43%</td>
<td>13</td>
<td>6.19%</td>
</tr>
<tr>
<td>4</td>
<td>1.90%</td>
<td>14</td>
<td>6.67%</td>
</tr>
<tr>
<td>5</td>
<td>2.38%</td>
<td>15</td>
<td>7.14%</td>
</tr>
<tr>
<td>6</td>
<td>2.86%</td>
<td>16</td>
<td>7.62%</td>
</tr>
<tr>
<td>7</td>
<td>3.33%</td>
<td>17</td>
<td>8.10%</td>
</tr>
<tr>
<td>8</td>
<td>3.81%</td>
<td>18</td>
<td>8.57%</td>
</tr>
<tr>
<td>9</td>
<td>4.29%</td>
<td>19</td>
<td>9.05%</td>
</tr>
<tr>
<td>10</td>
<td>4.76%</td>
<td>20</td>
<td>9.52%</td>
</tr>
</tbody>
</table>
Case Study

Some packages that pass through a primary sorter cannot be routed to a secondary sorter for a variety of reasons and must be manually processed. Suppose such packages are routed to a circular conveyor as shown in Figure 16-4. Packages proceed around the conveyor to a workstation. There is no package waiting area or buffer at a workstation. If a package arrives to a station that is processing another package, it stays on the conveyor to the next station. If the package is not processed by the last station, it recirculates to the first station.

The purpose of the simulation study is to specify the parameters of the manual system to minimize package lead time. There may be either 1, 2, 3, or 4 workstations employed. In addition, waiting areas for up to three packages may be placed in any fashion among the workstations. Cost considerations make more buffer spaces and fewer workstations the preferred design. Determine the number of workstations, the number of buffer spaces, and the location of the buffer spaces.

Relevant information is as follows:

Time between package arrivals: Exponentially distributed with mean 1.6 minutes.
Package processing time: Exponentially distributed with mean 4.0 minutes.

Conveyor Segments (Assuming a Four Workstation Configuration).

<table>
<thead>
<tr>
<th>Conveyor Segment</th>
<th>Conveyor Distance (Feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival Point to First Work Station Exit</td>
<td>18</td>
</tr>
<tr>
<td>Station Exit Segment</td>
<td>2</td>
</tr>
<tr>
<td>Inter-Station Segment (to Exit Segment)</td>
<td>13</td>
</tr>
<tr>
<td>Last Station to Arrival Point (4 stations case)</td>
<td>45</td>
</tr>
</tbody>
</table>

Assume that conveyor speed is 0.25 feet / second and that packages are 2 feet in length. The time period of interest is 40 hours.
Case Problem Issues

1. Count the number of possible alternatives. Is it reasonable to simulate all of these?

2. Which alternatives should be simulated to make sure the best or at least a good alternative is identified?

3. What performance measures in addition to package lead time are of interest?

4. What operating rules could be added to the system to guard against excessive lead times for individual packages?

5. What is the minimum number of workstations required by the system?

6. Discuss how verification and validation evidence can be obtained.

7. What is the purpose of having buffer space in front of workstation?

8. How is the arrival of a package to a workstation modeled if:
   a. There is no buffer space at the workstation.
   b. There is at least one buffer space at the workstation.

9. What is your initial guess as to the best placement for the buffer spaces? Does the simulation study confirm your guess?

10. Tell how to compute the lead time for a package as a function of the number times it travels completely around the conveyor within the simulation.

11. What is the radius of the conveyor: \( \text{radius} = \frac{\text{circumference}}{2 \pi} \)?
Chapter 17
Automated Guided Vehicle Systems

17.1 Introduction

An automated guided vehicle (AGV) system can transport material between a finite number of pre-defined locations at work stations with little or no human assistance. Barrett Electronics Corporation invented the world's first AGV for industrial applications in 1954. In the United States there have been over 3,000 AGV systems installed during the last 50 years. These systems range from one vehicle to well over 100 vehicles.

An AGV system consists of vehicles that move along predetermined paths to move loads between workstations and storage areas. Vehicles operate without the need for an onboard operator or driver, pick up loads at designated pick-up points and transport them to designated drop-off points. Each workstation has a pick-up point and a drop-off point. These two points can be the same.

There are several major categories of vehicles:

1. **Tow Type** vehicles that pull carts, trailers, dollies and the like.
2. Self-contained **Unit Load Type** vehicles that carry products on their built-in load decks.
3. **Fork Type** vehicles that utilize a fork/mast lift mechanism for interfacing with loads at various elevations.
4. Smaller **Commercial/Office Type** vehicles that have capacities of less than 500 pounds.
5. **Heavy Carrier Type** vehicles designed to transport large or very heavy loads such as dies, rolls, coils, ingots weighing in excess of 250,000 pounds.

Vehicles move between work stations by traversing control segments. Each control segment is relatively short. The intersection point between control segments is a control point. Pickup and dropoff points are control points as well.

Vehicles in most existing systems follow an inductive guide path consisting of a wire embedded in the floor carrying alternating current that induces a magnetic field detected by antenna mounted on the bottom of the vehicles. Other control mechanisms include surface mounted magnetic or optical strips as well as inertial or laser guidance. Vehicles have controllers that respond to instructions and ensure safety.

AGV systems must be able to perform routing, traffic control and communications functions. Routing is the method by which an AGV determines how to go from its current location to a designated destination. Different approaches to routing logic can be implemented such as shortest time, shortest distance and fixed pattern. Traffic control assures that AGVs do not collide with each other. Either fixed or variable distances between vehicles can be used.

Communication is needed between vehicles, between a vehicle and a central device or for local interfaces. The communication mechanism provides the means by which vehicles are informed of routing and traffic control decisions.
A simple AGV system is shown in Figure 17-1. There are four control segments that form a loop in the shape a rectangle with rounded corners. Rounded corners allow the AGV to continue at full speed instead of stopping to make a 90 degree turn as would be the case if square corners were used. There are four stations each with its own control point indicating the place where loads are picked up or dropped off. AGV’s move in only one direction, clockwise, around the loop.

Requests come to move loads from one workstation to another. In response, an idle AGV moves from the parking area to the pickup point of the workstation where the load currently resides. The AGV moves from this pickup point to the drop off point of the destination workstation. After unloading, the AGV remains idle at the dropoff point.

Figure 17-1: Simple AGVS Layout.
17.2 Points Made in the Case Study

Simulation can be used to assess the operational behavior of a system designed by other means. In this case, the AGV system is designed using standard, analytic methods. Simulation is used to assess the behavior of the system as designed relative to operational performance criteria as well as to determine the number of vehicles the system needs.

The structure of a system can be described using data inputs to a model. This allows changes in system structure to be assessed without changing the model. In this case, the control segments and control points are defined by input data. This data input most often takes the form of a graphical drawing.

The models originally developed for operations can be directly applied to material handling situations as well. This illustrates how models developed for one domain may be directly applied to another domain where system components behavior and interact in an analogous way. In an AGV system, the control points constrain the movement of the vehicles to assure that there are no collisions at interactions. Thus, control points can be modeled as a single machine station where the processing time is the time to traverse the control point.

Increasing the number of resources that can perform an activity, such as the number of machines at a workstation, normally lessens entity waiting time for that activity. Thus, it might be assumed that increasing the number of vehicles in an AGV system would increase the responsiveness to movement requests. This might not be the case since the contention between the AGV’s for control segments, intersections, and control points will increase.

17.3 The Case Study

The case study has to do with confirming the operational effectiveness of the design of a new AGV system as well as determining the number of vehicles needed. Load movement requests can be modeled as having a constant time between arrivals. However, the origin and destination points are stochastic. That is not all requests for material movement can be predetermined. The discussion and examples of AGV systems in Askin and Standridge (1993) form the basis for this case study.

17.3.1 Define the Issues and Solution Objective

The design of a new AGV system to serve nine workstations as shown in Figure 17-2. Each shorter edge corresponds to 50 feet and each longer edge to 100 feet. AGV's move in one direction only on each bold edge as indicated by the arrows. There is no AGV movement on dashed edges. The letters in the center of a square are the work station ID's. The numbers near the edges are the control segment ID's. Idle AGV's wait where at the dropoff point of their last load.

The pickup and dropoff points for each workstation are indicated using the letters P and D respectively. Note that stations 5 and 6 share these points.

Table 17-1 gives the average number of material moves between workstations per 16 hour day. This information forms the distribution of pickup point to dropoff point AGV movements. Each individual movement can be determined as a random sample from this distribution. The time between material moves is a constant 90 seconds (57600 seconds per day / 640 moves).

A material move requires an AGV to move from it current location to the pickup point and then from the pickup point to the dropoff point. Each AGV moves at the rate of 5 feet per second and takes 30 seconds for each drop-off and each pick-up.

---

1 Todd Frazee assisted with the development of this case study.
The design shown in Figure 17-2 was developed using analytic methods. The following principles were applied.

1. Vehicles move in only one direction on path.
2. The dropoff point for a station should precede the pickup point with respect to vehicle movement.
3. Dropoff and pickup points should be placed on control segments with low utilization to avoid other vehicles waiting for dropoffs and pickups to be completed.
4. Movement of empty vehicles should be minimized. Thus after a dropoff is completed, the vehicle should wait on the same control segment for a possible pickup on that segment.

Other analytic methods were used to estimate that 2 AGV’s would be needed in the system. These analytic methods were used to compute each of the five components of total vehicle utilization time: loaded travel time, travel time while empty, blocked time, load time, and unload time. These computations are based on knowledge of the number of loads to be moved between each pair of workstations (the information shown in Table 17-1) as well as AGV travel speeds and the shortest path between each pair of workstations.

Loaded travel time, load time, and unload time are straightforward to compute. A lower bound on travel time while empty can be computed using an optimization algorithm. Blocked time was assumed to be zero for this system since the number of AGV’s need was only 2.
Table 17-1: Average Number of Material Moves between Work Stations

<table>
<thead>
<tr>
<th>From Work Station</th>
<th>To Work Station</th>
<th>Average Number of Moves</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td>40</td>
</tr>
<tr>
<td>A</td>
<td>C</td>
<td>25</td>
</tr>
<tr>
<td>A</td>
<td>D</td>
<td>30</td>
</tr>
<tr>
<td>A</td>
<td>E</td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td>F</td>
<td>10</td>
</tr>
<tr>
<td>A</td>
<td>G</td>
<td>20</td>
</tr>
<tr>
<td>A</td>
<td>H</td>
<td>5</td>
</tr>
<tr>
<td>A</td>
<td>I</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>C</td>
<td>40</td>
</tr>
<tr>
<td>B</td>
<td>E</td>
<td>30</td>
</tr>
<tr>
<td>B</td>
<td>G</td>
<td>10</td>
</tr>
<tr>
<td>B</td>
<td>H</td>
<td>10</td>
</tr>
<tr>
<td>C</td>
<td>G</td>
<td>50</td>
</tr>
<tr>
<td>C</td>
<td>I</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>B</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>C</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>F</td>
<td>10</td>
</tr>
<tr>
<td>E</td>
<td>D</td>
<td>100</td>
</tr>
<tr>
<td>F</td>
<td>D</td>
<td>60</td>
</tr>
<tr>
<td>G</td>
<td>F</td>
<td>40</td>
</tr>
<tr>
<td>G</td>
<td>I</td>
<td>40</td>
</tr>
<tr>
<td>H</td>
<td>D</td>
<td>10</td>
</tr>
<tr>
<td>H</td>
<td>F</td>
<td>5</td>
</tr>
<tr>
<td>I</td>
<td>E</td>
<td>60</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>640</td>
</tr>
</tbody>
</table>

Management wishes to confirm the operationally effectiveness of AGV system as designed. The primary performance criteria is time between the request for a load to be moved and the completion of the move. Both the maximum and average time are interest. Assessing the number of AGV’s needed is also important since blocked time was ignored and only a lower bound on travel time while empty was obtained. There is concern that 2 AGV’s are not sufficient.

17.3.2 Build Models

It is helpful to take a generic perspective to modeling AGV systems. The control segments and control points that comprise the paths taken by the vehicles between workstations can be data input, expressed most often as a graphical drawing. In this case, the graphical drawing used for input this information is the one in Figure 17-2. Other inputs include where vehicles park when they become idle and vehicle speed. Vehicles can be viewed as resources. This generic view is implemented in some simulation environments.

In addition, a process model describing the movement of loads through the AGV system, perhaps including processing at workstations, is needed. A request to move a load is the entity flowing through the process. The following are the major steps in the process model.

1. Arrival of a request for an AGV to move a load from one workstation to another.
2. Waiting for an idle AGV.
3. Selection of the idle AGV nearest to the pickup point for the load.
4. Movement of that AGV from where it is parked to the pickup point.
5. Movement of the same AGV from the pickup point to the dropoff point.
Attributes of the entity are the following:

FromStation: The station where the load is to be picked up.
ToStation: The station where the load is to be dropped off.
ArriveTime: Simulation time that the request for load movement is made.

Analytic algorithms for determining the shortest path from one workstation to another are known and can be implemented within a simulation environment that supports modeling AGV systems. In most cases, the number of feasible paths between any pair of workstation should be few in number. Otherwise, the system would be too complex to operate. For example, consider the number of paths from workstation A in Figure 17-2 to each of the other eight workstations. There is only one path to workstations B, C, E, F, and G. There are two paths to the other workstations: D, H, and I. However, one of the two paths is obviously shorter.

One issue that is unique to modeling AGV systems is contention among the vehicles for the same control segment or control point. All vehicles travel at the same speed so one cannot overtake another as long as both are moving in the same direction. Contention occurs when one vehicle is stopped at a pickup or dropoff point and another vehicle needs to pass through such a point enroute somewhere else. In this case, the second vehicle needs to stop to wait for the first vehicle to leave the pickup or dropoff point.

In addition, contention can occur when two vehicles coming from opposite directions arrive at the same intersection at the same time. One vehicle needs to stop or slow down to let the other vehicle pass. There are two such intersections in the AGV system shown in Figure 17-2. One is at the right side of the boundary between workstations G and I. The other is at the center of the upper boundary of workstation H where the path dividing workstations E and F ends.

One system performance criterion is the time between the request for moving a load and completion of the move. Thus, it may seen desirable to have as many AGV’s in the system as possible to minimize this time. This strategy is similar to increasing the number of machines at a workstation to minimize cycle time at the station that was employed in previous chapters. However, increasing the number of AGV’s also increases the contention for control points and control segments. Thus, such increases may be counter productive and must be tested using simulation.

The modeling logic described above follows in pseudo English. AGV’s are modeled as resources as are pickup and dropoff points. Each AGV has an attribute, CurrentLoc, giving its current location. Resources are also used to model intersections where vehicles can enter from more than one direction.

Travel along a path is comprised of a series of steps as modeled by Process MoveOnPath with parameters FromLoc and ToLoc. Each step represents travel between the current AGV location and the next pickup point, dropoff point, or intersection on the path. Each of these is modeled as resource that must be acquired to traverse that part of the path and freed after such movement is accomplished.

The next pickup point, dropoff point, or intersection and the distance to it are exacted from the data input describing the AGV system that was given as a graphical drawing. In this case, travel time can be modeled as distance traveled * AGV speed. It is possible to include acceleration and deceleration if desired. When the destination control point is reached, travel ends. Otherwise travel to the next pickup point, dropoff point, or intersection commences.

The process AGV System makes use of the process MoveOnPath. Arrivals to the process are requests for load movement that occur every 90 seconds in this case. Entity attributes are assigned: the workstation where the load currently resides, the workstation to which the load...
must be transported, and the simulation time the request arrives. The idle AGV closest to the workstation station where the load currently resides is chosen. If there are no idle AGV’s the movement request must wait. The AGV moves empty workstation to the where the load is residing, picks up the load, moves to the destination station, and drops off the load. The AGV become IDLE and the current location of the AGV is recorded.

Define Resources
AGV/2 // Two AGV’s
ControlPointIntersection (n)/1 // Control Points and Path Intersections

Define Attributes
FromStation // The station where the load is to be picked up.
ToStation // The station where the load is to be dropped off.
ArriveTime // Time the request for load movement is made.

Define Variables
StartTrip (NStations) // Distribution of trip starting point stations
EndTrip (NStations, NStations) // Distribution of trip end point stations by starting station
CurrentLoc(2) // Current location of an AGV

Process AGV_System
Define Arrivals
Time of first arrival: 0
Time between arrivals: 90 seconds
Number of arrivals: Infinite

Begin
Set TimeArrive = Clock
FromStation = Sample (StartTrip)
EndStation = Sample(EndTrip(FromStation))
Wait until AGV is IDLE in WaitforAGV // IDLE AGV closest to From Station is chosen
Make AGV Busy
Send to MoveOnPath (CurrentLoc, FromStation) with return
Wait for 30 seconds // Pick up load
Send to MoveOnPath (FromStation, ToStation) with return
Wait for 30 seconds // Drop off load
Make AGV IDLE
CurrentLoc (AGV) = ToStation
Tabulate Clock – TimeArrive in CompleteMovementTime

End

Process MoveOnPath (FromLoc, ToLoc)
Begin
While CurrentLoc(AGV) != ToLoc
Begin
CurrentLoc (AGV) = FromLoc
Wait for Distance*AGVSpeed to
   Next Control Point or Intersection from CurrentLoc
CurrentLoc (AGV) = Next Control Point or Intersection
Wait until ControlPointIntersection (CurrentLoc(AGV)) is IDLE
Make ControlPointIntersection (CurrentLoc(AGV)) BUSY
Wait for Distance through Control Point or Intersection * AGVSpeed
Make ControlPointIntersection (CurrentLoc(AGV)) IDLE
End
End
Identify Root Causes and Assess Initial Alternatives

The simulation experiment can be described as follows. The system operates for one 16 hour day. Thus, a terminating simulation of length one day is appropriate. The proper initial conditions are all AGV’s idle since no load movement requests occur before the work day begins. Their initial location is randomly assigned. There is one random number stream to aid in selecting the pair of workstations for pickup and dropoff. Twenty replicates are made.

Management wishes to minimize the time to complete a movement request. Thus, performance measures include this quantity as well as the utilization of AGV’s and AGV capacity lost to contention for control segments and control points. AGV congestion will be measured as the average number of AGV’s waiting due to contention for control points and intersections.

The number of AGV’s required must be determined, either the 2 previously recommend or 3 to improve the time to complete a movement request. The model parameter is the number of AGV’s to employ. Table 17-2 summarizes the experimental design.

Table 17-2: Simulation Experiment Design for the AGV 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. Number of AGV’s (2 or 3)</td>
</tr>
<tr>
<td>Performance Measures</td>
<td>1. Time to complete a move request</td>
</tr>
<tr>
<td></td>
<td>2. AGV utilization</td>
</tr>
<tr>
<td></td>
<td>3. AGV congestion</td>
</tr>
<tr>
<td>Random Number Streams</td>
<td>1. From-to pair of workstations</td>
</tr>
<tr>
<td>Initial Conditions</td>
<td>AGV’s randomly assigned to control points</td>
</tr>
<tr>
<td>Number of Replicates</td>
<td>20</td>
</tr>
<tr>
<td>Simulated End Time</td>
<td>57600 seconds (one day)</td>
</tr>
</tbody>
</table>

Tables 17-3 through 17-5 give the simulation results for the above experiment, including a comparison between system operations when 2 and 3 AGV’s are used.
### Table 17-3: Simulation Results for Two AGV's

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Idle Percent</th>
<th>Congested Percent</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.7%</td>
<td>2.6%</td>
<td>80.9</td>
<td>8.7</td>
</tr>
<tr>
<td>2</td>
<td>1.4%</td>
<td>2.0%</td>
<td>60.8</td>
<td>5.9</td>
</tr>
<tr>
<td>3</td>
<td>0.5%</td>
<td>2.1%</td>
<td>114.6</td>
<td>15.5</td>
</tr>
<tr>
<td>4</td>
<td>0.4%</td>
<td>2.6%</td>
<td>92.3</td>
<td>11.5</td>
</tr>
<tr>
<td>5</td>
<td>1.6%</td>
<td>2.2%</td>
<td>99.1</td>
<td>9.8</td>
</tr>
<tr>
<td>6</td>
<td>1.4%</td>
<td>2.2%</td>
<td>71.0</td>
<td>6.8</td>
</tr>
<tr>
<td>7</td>
<td>1.3%</td>
<td>2.5%</td>
<td>88.8</td>
<td>9.0</td>
</tr>
<tr>
<td>8</td>
<td>0.6%</td>
<td>2.2%</td>
<td>100.6</td>
<td>10.0</td>
</tr>
<tr>
<td>9</td>
<td>1.2%</td>
<td>2.3%</td>
<td>75.9</td>
<td>8.4</td>
</tr>
<tr>
<td>10</td>
<td>0.4%</td>
<td>2.0%</td>
<td>120.2</td>
<td>14.4</td>
</tr>
<tr>
<td>11</td>
<td>2.8%</td>
<td>2.5%</td>
<td>43.9</td>
<td>5.1</td>
</tr>
<tr>
<td>12</td>
<td>0.5%</td>
<td>2.0%</td>
<td>105.5</td>
<td>13.0</td>
</tr>
<tr>
<td>13</td>
<td>0.4%</td>
<td>2.3%</td>
<td>94.9</td>
<td>11.3</td>
</tr>
<tr>
<td>14</td>
<td>1.9%</td>
<td>1.9%</td>
<td>45.4</td>
<td>5.5</td>
</tr>
<tr>
<td>15</td>
<td>1.9%</td>
<td>2.6%</td>
<td>60.7</td>
<td>6.0</td>
</tr>
<tr>
<td>16</td>
<td>2.5%</td>
<td>2.5%</td>
<td>24.9</td>
<td>4.4</td>
</tr>
<tr>
<td>17</td>
<td>1.2%</td>
<td>2.1%</td>
<td>125.3</td>
<td>14.3</td>
</tr>
<tr>
<td>18</td>
<td>1.2%</td>
<td>2.2%</td>
<td>52.1</td>
<td>5.8</td>
</tr>
<tr>
<td>19</td>
<td>0.9%</td>
<td>2.3%</td>
<td>93.2</td>
<td>12.9</td>
</tr>
<tr>
<td>20</td>
<td>0.4%</td>
<td>2.2%</td>
<td>79.7</td>
<td>10.4</td>
</tr>
</tbody>
</table>

**Average:**

- Idle Percent: 1.2%
- Congested Percent: 2.3%
- Maximum: 81.5
- Average: 9.4

**Std. Dev.:**

- Idle Percent: 0.7%
- Congested Percent: 0.2%
- Maximum: 27.2
- Average: 3.4

**99% CI Lower Bound:**

- Idle Percent: 0.7%
- Congested Percent: 2.1%
- Maximum: 64.1
- Average: 7.2

**99% CI Upper Bound:**

- Idle Percent: 1.6%
- Congested Percent: 2.4%
- Maximum: 98.9
- Average: 11.6

The following can be noted from Table 17-3 when 2 AGV's are used:

1. The AGV's are almost always busy.
2. There is very little congestion.
3. The average time to complete a move is 9.4 minutes with an approximate 99% confidence interval for the true average of (7.2, 11.6) minutes.
4. The maximum time to complete a move is over an hour with an approximate 99% confidence interval of (64.1, 98.9) minutes.

Thus it can be concluded from Table 17-3 that using only 2 AGV's is ineffective since the average time and maximum times to complete a move are too high. This is not unexpected since the AGV's are almost always busy. On the other hand, there is very little contention.
Table 17-4: Simulation Results for Three AGV’s

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Idle Percent</th>
<th>Percent Congested</th>
<th>Maximum</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>21.3%</td>
<td>12.8%</td>
<td>7.8</td>
<td>3.1</td>
</tr>
<tr>
<td>2</td>
<td>21.0%</td>
<td>12.0%</td>
<td>7.5</td>
<td>3.1</td>
</tr>
<tr>
<td>3</td>
<td>22.8%</td>
<td>11.7%</td>
<td>9.0</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>21.5%</td>
<td>11.5%</td>
<td>12.0</td>
<td>3.1</td>
</tr>
<tr>
<td>5</td>
<td>21.3%</td>
<td>12.1%</td>
<td>8.5</td>
<td>3.1</td>
</tr>
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**Average**

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**Std. Dev.**

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**99% CI Lower Bound**

<table>
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<th>Average</th>
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<td>21.1%</td>
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**99% CI Upper Bound**

<table>
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<th>Average</th>
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<td>22.0%</td>
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<td>9.7</td>
<td>3.1</td>
</tr>
</tbody>
</table>

The following can be noted from Table 17-4 when 3 AGV’s are used.

1. AGV utilization is near 80%.
2. Significant congestion occurs since about 1/3 of the available time of 1 AGV is lost (11.8% * 3 AGV’s = 1/3 of 1 AGV).
3. The average time to move a load is about 3 minutes.
4. The maximum time to move a load is about (8.4, 9.7) minutes with approximately 99% confidence.

Thus it can be concluded from Table 17-4 that using 3 AGV’s allows movement to occur in a sufficiently small amount of time. AGV utilization is neither too high or too low. However, contention among the three AGV’s is significant.
Table 17-5: Comparison of Simulation Results for Two and Three AGV’s

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<td>90.6</td>
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<td>91.3</td>
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</tr>
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<tr>
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<tr>
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<td>22.6%</td>
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<td>71.4</td>
<td>7.4</td>
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<tr>
<td>Average</td>
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<td>9.6%</td>
<td>72.5</td>
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<tr>
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<td>0.5%</td>
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</tr>
<tr>
<td>99% CI Lower Bound</td>
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<tr>
<td>99% CI Upper Bound</td>
<td>21.1%</td>
<td>9.9%</td>
<td>89.9</td>
<td>8.5</td>
</tr>
</tbody>
</table>

Table 17-5 shows that the difference between using 2 AGV’s and 3 AGV’s is statistically significant with approximately 99% confidence for all performance measures. AGV utilization is lowered when 3 AGV’s are used as well as the average and maximum time to move a load. Congestion increases as well.

17.3.4 Review and Extend Previous Work

Management was pleased with the results of the simulation experiment. It was decided that three AGV’s should be used.

The amount of contention between the three AGV’s was of concern. It was felt that if load volumes increased and the addition of a fourth AGV was necessary that contention might cause the AGV system to take too long to respond to and complete transportation requests.

Thus, a redesign of the AGV system was proposed. The pickup and dropoff points for each workstation would be located within the station. Workstations E and F would have distinct pickup and dropoff points.

17.4 Assessment of Alternative Pickup and Dropoff Points

The impact of alternative pickup and dropoff points was assessed as follows.
17.4.1 Identify Root Causes and Assess Initial Alternatives

The assessment of the new AGV system design can be done in the following way. Note from Figure 17-2 that there are two types of workstations. The pickup and dropoff points for workstations B, C, D, E, and F are located near each other. The pickup and dropoff points for workstations G, H, and I are separate. Workstation A has only a pickup point.

Figure 17-3 shows the redesign of the pickup and dropoff points for workstations B, C, D, E, and F. Figure 17-4 shows the redesign for the remaining stations. Note that the AGV's have a greater distance to travel to both pickup and dropoff a load since a loop of about 15 feet must be traversed into each workstation.

![Diagram showing workstations and pickup/dropoff points]

Figure 17-3: Example Workstation Layout with Pickup and Dropoff Points within the Workstation -- Style 1
A new simulation experiment can be executed. The design is the same as shown in Table 17-2 except that the operation of the modified AGV layout with three AGV’s only will be assessed. Note that the model does not need to be modified since the AGV layout is input data expressed as a graphical drawing. Simulation results for this experiment are shown in Table 17-6.

The following can be noted from Table 17-6.

1. AGV utilization is near 72%.
2. Only a little congestion occurs since about 13% of the available time of 1 AGV is lost.
3. The average time to move a load is about 3 minutes.
4. The maximum time to move a load is about (10.3, 28.1) minutes with approximately 99% confidence. The average maximum is 19.2 minutes. The range of the maximum times across the replicates is (5.3, 56.8) minutes.
Table 17-6: Simulation Results for Three AGV's with Dropoff and Pickup Points within Each Workstation

<table>
<thead>
<tr>
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</table>

Table 17-7 contains a comparison of AGV system operations using the initial system design and the new system design each employing 3 AGV's.
Table 17-7. Comparison of Simulation Results for the Original and Modified System Designs

<table>
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</tbody>
</table>

The following can be noted from Table 17-7:

1. AGV utilization increases as the average congestion increases for the new system configuration versus the original configuration. These differences are both significant with approximately 99% confidence. Note that both differences are small.

2. There is little difference in the average time to move a load between the two designs, though the difference is statistically significant.

3. The difference in the maximum time to move a load is operationally and statistically significant. The approximate 99% confidence interval is wide. The maximum difference is at least 29 minutes in 5 of 20 replicates.

17.4.2 Review and Extend Previous Work

Management rejected the new AGV system design. It was recognized that this design is more complex than the original which will require a more complex control system. AGV utilization and congestion as well as the average load delivery time were about the same for either design. The possible increase in maximum delivery time was of concern.
17.4.3 Implement the Selected Solution and Evaluate

The original system configuration with three AGV's will be implemented and the maximum time to move a load monitored.

17.5 Summary

The modeling and analysis of an AGV system design has been discussed in this chapter. The use of the graphical representation of the pathways traveled by the AGV's as data input to a simulation model has been presented. The conflict between improving response time to load movement requests and congestion by increasing the number of AGV's in the system has been examined. The need to confirm designs developed using analytic methods through simulation has been illustrated.

Problems

1. Compare and contrast the approach to modeling conveyors discussed in chapter 16 with the approach to modeling AGV systems presented in this chapter.

2. Tell why bi-directional AGV movement on a path is not desirable.

3. Tell why the dropoff point for a workstation should precede the pickup point.

4. Visit a manufacturing facility and observe the automated material handling equipment that is in use.

5. Make a list of the automated material handling equipment you have observed in the service systems you encounter regularly.

6. List the advantages and disadvantages of adding additional AGV's to a system.

7. List the advantages and disadvantages of having distinct pickup and dropoff points at each workstation versus having a single pickup-dropoff point.

8. Consider the following modification to the original configuration with pickup and dropoff points on the main AGV path. All AGV's return to a parking area where maintenance and recharging is performed immediately after completing the movement of a load. Assess this design.

9. Consider the following modification to the new system configuration with pickup and dropoff points within each department. The pickup and dropoff points for each station are the same. Assess this design.

10. Reassess each design proposed in this chapter for the case where the time between request to move loads is exponentially distributed with mean 90 seconds.

11. Generate a customized trace of events and state variable values for the new design to determine why the maximum time to move a load sometimes becomes large.
Case Problem

Consider the following manufacturing system described in Askin and Standridge (1993) and shown in Figure 17-5. There are five departments. Material movement between departments is performed using an AGV system.

Material flow volumes between departments per eight hour day are shown in the following table.

<table>
<thead>
<tr>
<th>From/To</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total From</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>10</td>
<td>25</td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td></td>
<td>10</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>40</td>
<td></td>
<td>20</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>10</td>
<td></td>
<td>50</td>
<td></td>
<td>84</td>
</tr>
</tbody>
</table>

Note that each department uses the same point for dropoffs and pickups. AGV travel time is 3 feet/second. Assume that the sequence of interdepartmental moves is essentially random but that the time between move requests can be modeled as a constant value.
Each department is 30 feet by 30 feet in size except department 1 which is 30 feet by 60 feet. Pickup and dropoff times are 15 seconds.

The problem is to determine the routes taken by AGV’s between each pair of stations. In addition, the number of AGV’s required in this system as well as the effectiveness of the system as measured by the time from the request to move a load until load movement is completed must be determined. Both the average and maximum times are of interest.

If the AGV system as designed proves ineffective, it may be improved by moving pickup and dropoff points. The redesign could include having separate pickup and dropoff point. A new AGV path could be defined as well.

The simulation study should answer the following questions:
1. Is one AGV sufficient for the current demand or are two AGV’s necessary?
2. If demand increases uniformly across all stations by 20%, what adjustments to the system are necessary?

Case Problem Issues
1. Can the same model developed in this chapter be used as is or slightly modified to apply to the case problem? What would the modifications be?
2. What alternative AGV paths should be considered?
3. For each department, what pickup and dropoff point locations should be considered?
4. Are there any other performance measures besides load movement time and AGV utilization that could be important?
5. How will verification and validation evidence be obtained?
6. What is the expected number of AGV’s required?
7. How will the arrival of load movement requests be modeled?
Chapter 18
Automated Storage and Retrieval

18.1 Introduction

Much of the time that material is in a plant, it is being moved or stored. In this chapter, the dynamics of how an automated storage and retrieval system (AS/RS) organizes and maintains an inventory are examined. An AS/RS system provides the following benefits: space efficient storage of materials, high speed controlled transportation of materials, and real-time inventory control. Thus an AS/RS system helps reduce inventory, labor, floor space, and material control costs.

A typical AS/RS system has several components as is shown in Figure 18-1. A storage / retrieval (S/R) machine places pallets (or another standard carrier) having one or more standard sizes in a high rise rack system. A rack consists of a matrix of storage locations. Racks are separated by aisles. There is one S/R machine per aisle. An S/R machine moves in the horizontal direction on a track located in the floor of an aisle and rises vertically via an imbedded mechanism. Typically, vertical speed is about 1/3 of horizontal speed.

Items to be stored arrive to a pick point. Retrieved items are transported by a the S/R machine to a drop point.

A computer-based control system is an important part of an AS/RS system. The computer keeps track of the exact location of all items in the racks. The control system directs the movement of the S/R machine by providing timely instructions concerning what items to retrieve or store in the racks. These instructions are in response to external requests for storage and retrieval.

The computer-based control system can be tested using simulation. Alternative rack sizes can be assessed. Various storage and retrieval strategies can be compared. In this way, movement of the S/R machine when it is empty, as well as the capital investment in racks, can be minimized.
18.2 Points Made in the Case Study

The control algorithm for an automated system, such as an AS/RS, can be included in a simulation model. The control algorithm may be coded in a general purpose programming language and interfaced within the model.

A simulation model can consist of multiple processes. These processes can share the same resources. In this application, an S/R machine, represented by a resource, is used by both an inventory storage process and an inventory retrieval process.

A resource may have multiple BUSY states. Each BUSY state indicates that the resource is occupied in a unique way. In this application, each rack space is either empty or full of a particular type of item. BUSY states correspond to item types.

Sometimes it is necessary to select a resource to employ from a set of resources with similar or identical characteristics. A criteria for making the selection must be specified. The set of resources cannot be modeled as units of a single resource since the state of each individual resource must be tracked. In this application, the state of each individual rack storage space is important. The model must use the AS/RS control logic to select from among the storage spaces in the IDLE state when a carrier is stored. In the same way, the model must select from among items of the same type when a retrieval is required.

18.3 The Case Study

A particular manufacturing plant assembles finished goods from subassemblies that are produced in another area of the plant or delivered to the plant from external suppliers. A subassembly consists of component parts that have been joined together. Subassemblies arrive to the area preceding the final assembly operation as completed or as delivered.

Thus, a buffer before final assembly is required. The buffer is implemented using an AS/RS system. The storage area consists of two rectangular racks of bins with an aisle between them. Each bin holds one subassembly, which may be of one of four types. Subassemblies are delivered to a pick point where they are picked up one at a time by the S/R machine and placed in the nearest, with respect to S/R machine movement time, available bin.

The final assembly process requests subassemblies one at time. Each request specifies a particular type of subassembly. The S/R machine retrieves the nearest, with respect to its movement time, subassembly of the requested type and places it at the drop point. The subassembly is subsequently moved from the drop point to the final assembly area.

To minimize unproductive movements, the S/R machine remains at the bin in which it last placed a subassembly or at the drop point when it completes a task and becomes idle.

Subassemblies arrive from 6:00 A.M. to 2:00 P.M. each day. The final assembly process operates from 8:00 A.M. to 4:00 P.M. each day or until all of the subassemblies in the AS/RS have been consumed.

18.3.1 Define the Issues and Solution Objective

A fundamental issue in the AS/RS control algorithm is into what free bin to store a subassembly and from what occupied bin to retrieve a subassembly. The algorithm to select a bin is an intrinsic component of the operation of the AS/RS system and must be included in the simulation model. Each bin is in one of nine states:
1. Idle
2-5. Occupied with a subassembly of type one, two, three, or four
6-9. Occupied with a subassembly of type one, two, three, or four that is committed to the final assembly process

The selected bin is the one in the specified state that requires the least travel time for the S/R machine. The idle S/R machine waits at the pick point or at the last bin in which a subassembly was stored.

The S/R machine moves 6 feet per second horizontally and 2 foot per second vertically. Each bin is 1 foot square including the rack structure. Thus, the time to reach any bin is the sum of the number of bins traversed horizontally * 1/6 second per bin and the number traversed vertically * 1/2 second per bin. This sum is illustrated for a rack 8 bins high and 7 bins long in Figure 18-2 assuming the S/R machine starts at the pick point which is to the left of the bin structure on the floor level.

The search for a bin is performed by the AS/RS control software. Bins are searched in order of the movement time values shown in Figure 18-2, least to greatest until a bin in the state desired is located. Among bins with the same value, those closer to the floor are preferred.

The same search strategy can be applied if the S/R machine is waiting at a particular bin. The control algorithm searches in four directions, one at a time. These directions are:

1. Right and up from the current location, as shown in Figure 18-2.
2. Right and down from the current location.
3. Left and up from the current location.
4. Left and down from the current location.

After all the searches have been completed, the storage location nearest the S/R machine with respect to movement time is chosen.

The search strategy is worthy of discussion. Consider the movement time of $\frac{7}{6}$th second. This is the movement time to the seventh bin in the first row, the fourth bin in the second row, and the first bin in the third row. Thus, the bin search order for the time $\frac{7}{6}$th second is as listed previously.

Consider searching up and right from the current SR machine location in general. Bins are examined in order of movement time, least to greatest, until a bin in the desired state is found. Bins with equal movement times are searched as follows. The search begins at the bin to the right of the current location and proceeds to the bin in the next higher row and three columns preceding (since the vertical movement time is three times the horizontal movement time). This part of the search stops when either a bin in the desired state is found or the next bin to be examined would be to the left of the current location of the SR machine or the next bin to be examined does not exist.

It takes the S/R machine 6 seconds to store or retrieve a subassembly from a bin. The time between requests to store a subassembly is 20 seconds, exponentially distributed, as is the time between requests to retrieve a subassembly.

Two configurations of the AS/RS system have been proposed. In the first, each rack has 180 bins, 10 bins high and 18 bins long. In the other, each rack has 225 bins, 9 bins high and 25 bins long. Thus, extra storage space requires more floor space. The problem is to select between these two alternatives.
Figure 18-2: S/R Machine Movement Time (Seconds)

18.3.2 Build Models

The two operations performed by the AS/RS system are modeled as two separate processes. The first operation stores a subassembly in a bin. The second retrieves a subassembly from a bin.
Entities represent subassemblies to be stored or retrieved and have five attributes:

- **Type** = Type of subassembly: 1, 2, 3, 4.
- **ArriveTime** = Time of arrival to the AS/RS system.
- **Rack** = Rack in which to store the subassembly: 1 or 2.
- **Row** = Horizontal position of the bin in which to store the subassembly.
- **Column** = Vertical position of the bin in which to store the subassembly.

A state variable is used to track the state of each bin: idle, filled with a subassembly of a particular type, or filled with a subassembly of a particular type that is committed to the second manufacturing process. In addition, there is a state variable for each subassembly type modeling the number of units of that type in the racks.

A resource represents the S/R machine. The resource modeling the S/R machine has two attributes indicating its Row and Column location in the rack structure.

The storage of an arriving subassembly is handled as follows. The subassembly waits at the pick point until at least one bin is idle. Which particular idle bin to use is determined by the AS/RS control algorithm which is implemented in the model. Information identifying the location of the bin is recorded in the attributes (Rack, Row, Column) of the subassembly entity.

The subassembly continues to wait until the S/R machine is idle. The S/R machine moves from its current location to the pick point. The S/R machine picks up the subassembly, moves to the selected idle bin, and stores the subassembly in that bin. The S/R machine waits at that bin for its next assignment.

Finally, the state of the system updated. The state of the bin is changed to the type of subassembly stored in the bin. The location of the S/R machine is recorded in its Row and Column attributes. The number of subassemblies of the type just stored is incremented by one.

The process of retrieving a subassembly from a bin is similar to the storage process just described. The request for a subassembly of a particular type waits until there is a subassembly of that type in the AS/RS. The AS/RS system control algorithm selects the bin closest to the current location of the S/R machine containing a subassembly of the desired type. The S/R machines moves to that bin, retrieves the subassembly and proceeds to the drop point. The S/R machine becomes idle and remains at the drop point.

Again, the state of the system is updated. The state of the bin from which the subassembly was retrieved is changed to idle. The number of subassemblies of the type just retrieved is decremented by one. The location of the SR machine is recorded.

When it becomes idle, the SR machine resource may need to choose between two jobs: storing a subassembly or retrieving a previously stored one. Management decided that it was most important to keep the second manufacturing process working. Thus, priority is given to requests to retrieve previously stored subassemblies.

The AS/RS control algorithm is shown in Figures 18-3 a, b, and c.
function SearchOne  
/* routine to search in a given direction for a bin in a given state */
inputs:
RowDir = Row Direction (1 or -1)
ColDir = Column Direction (1 or -1)
RowStart = Row Location of First Cell
ColStart = Column Location of First Cell
ColDiff = Number of columns to move before moving rows
RowMax = Number of Rows in a Rack
ColMax = Number of Columns in a Rack
Rack = Rack ID number (1 or 2)
TargetState = Required State of Location
LocState = State of each rack
outputs:
Row = Row of required bin
Col = Column of required bin */
/* Search Equivalent Bins */
Row = 0
Col = 0
RowIndex = RowStart
ColIndex = ColStart
RowBase = RowStart
ColBase = ColStart
/* Stay within the boundaries of a rack */
while RowIndex <= RowMax and RowIndex > 0 do
begin
while ColIndex <= ColMax and ColIndex > 0 do
begin
/* Stay within the boundaries of the search direction from the starting point */
while (RowIndex <= RowMax and RowIndex > 0) and
      (ColIndex <= ColMax and ColIndex > 0) and
      ((RowIndex >= RowStart and RowDir > 0) or
       ((RowIndex <= RowStart and RowDir < 0)) and
      ((ColIndex >= ColStart and ColDir > 0) or
       (ColIndex <= ColStart and ColDir < 0)) do
begin
if(LocState(Rack,RowIndex,ColIndex) = TargetState) then
begin
/* Bin in desired state found. Set attributes */
Row = RowIndex
Col = ColIndex
return
end
/* Go to next bin having same movement time */
RowIndex = RowIndex + RowDir
ColIndex = ColIndex - ColDir*ColDiff
end
/* Go to bin with next smallest movement time in the initial row */
RowIndex = RowBase
ColBase = ColBase + ColDir
ColIndex = ColBase
end
/* Go to bin in the next row with the next smallest movement time */
RowBase = RowBase + RowDir
RowIndex = RowBase
ColBase = ColStart + ColDir*ColDiff
ColIndex = ColBase
end
end

Figure 18-3a: Control Algorithm Function for Searching in One Direction
begin S_SearchRack
/* routine to search for a storage state in a given state in a given
direction in each of two racks 
inputs:
 RowDir    = Row Direction (1 or -1)
 ColDir    = Column Direction (1 or -1)
 RowStart  = Row Location of First Cell
 ColStart  = Column Location of First Cell
 ColDiff   = Number of columns to move before moving rows
 RowMax    = Number of Rows in a Rack
 ColMax    = Number of Columns in a Rack
 TargetState = Required State of Location
 LocState  = State of each rack
outputs:
 RackA = Rack ID of the required bin
 Row   = Row of required bin
 Col   = Column of required bin */
/* Search the first rack */
 Rack = 1
 RackA = 1
 call S_SearchOne
 RowTemp = Row
 ColTemp = Col
/* Search the second rack */
 Rack = 2
 RackA = 2
 call S_SearchOne
/* See if the location in the first rack is closer than the one in the
second rack */
/* return second rack info if no bin was found in the first rack */
 if(RowTemp = 0 or ColTemp = 0) then return
/* return first rack info if no bin was found in the second rack */
 if(Row = 0 or Col = 0) then begin
 Row   = RowTemp
 Col   = ColTemp
 RackA = 1
 return
 end
/* Bin found in both racks; return info for bin with shorter movement
time */
 if(abs(RowTemp-RowStart)*RowSpeed+abs(ColTemp-ColStart)*ColSpeed<
     abs(Row   -RowStart)*RowSpeed+abs(Col   -ColStart)*ColSpeed)
 then begin
/* Movement to rack one bin is shorter */
 Row   = RowTemp
 Col   = ColTemp
 RackA = 1
 return
 end
end

Figure 18-3b: Control Algorithm Function for Determining the Shortest Move Time Among
Two Racks
The control algorithm is implemented as three functions. The first searches from the current location of the SR machine given by RowStart and ColStart in any of the four directions given above as specified by RowDir and ColDir. Each of these two variables takes on the values −1 or +1 to define the search direction. The dimensions of a rack are specified in the variables RowMax and ColMax. Which of the two racks to search is specified in the variable Rack which has the value 1 or 2. The variable TargetState gives the state of interest, zero for idle or 1, 2, 3, or 4 for a subassembly of that type. The state of each bin is stored in the three-dimensional array LocState(Rack, Row, Col). The variable ColDiff stores the ratio of the horizontal speed to the vertical speed of the SR machine which is three in this case.

The entity attributes Row and Col store the location of the bin in the desired state. If no such bin is found both Row and Col have the value zero.

The other two functions use the same variables as SearchOne. The function SearchRack, shown in Figure 18-3b, searches each rack in one of the directions listed above for a bin and returns the location of the bin that is closest with respect to movement time to the current position of the SR machine. The rack ID number (1 or 2) is returned in the entity attribute RackA.

The function SearchAll, shown in Figure 18-3c, searches in all four directions from the current SR machine location to find the nearest bin in the desired state. The directions are searched one at a time using function SearchRack. After each search, the nearer location so far is determined. The nearest location is returned using the entity attributes Row, Col, and RackA.

The model also contains two processes, Arrival and Retrieval, whose steps were previously described. Pseudo-code for the two processes follows. The same variables defined above for the function SearchOne are also used in the processes. Note that in the Arrival process, the function SearchRack is used instead of SearchAll since the only search direction is up and right of the pick point.
begin SearchAll
/* routine to search for a storage state in each of two racks in all directions

inputs:
    RowStart = Row Location of First Cell
    ColStart = Column Location of First Cell
    ColDiff = Number of columns to move before moving rows
    RowMax  = Number of Rows in a Rack
    ColMax  = Number of Columns in a Rack
    TargetState = Required State of Location
    LocState = State of each rack

outputs:
    RackA = Rack ID of the required bin
    Row = Row of required bin
    Col = Column of required bin */
/* Search right and up */
    RowDir = 1
    ColDir = 1
    call S_SearchRack
    RowTemp1 = Row
    ColTemp1 = Col
    RackTemp = RackA
/* Search right and down */
    RowDir = 1
    ColDir = -1
    call S_SearchRack
/* Select which is closer */
    if(RowTemp1 = 0 or ColTemp1 = 0) then
        begin
            RowTemp1 = Row
            ColTemp1 = Col
            RackTemp = RackA
        end
    else
        begin
            if((abs(RowTemp1 - RowStart)*RowSpeed+
                abs(ColTemp1 - ColStart)*ColSpeed >
                abs(Row - RowStart)*RowSpeed+
                abs(Col - ColStart)*ColSpeed) and
                (Row > 0 and Col > 0)) then
                begin
                    RowTemp1 = Row
                    ColTemp1 = Col
                    RackTemp = RackA
                end
        end

Figure 18-3c: Control Algorithm Function for Determining the Shortest Move Time in Any Direction
/* Search left and up */
RowDir = -1
ColDir = 1
call S_SearchRack
/* Select which is closer */
if(RowTemp1 = 0 or ColTemp1 = 0) then
begin
  RowTemp1 = Row
  ColTemp1 = Col
  RackTemp = RackA
end
else
begin
  if((abs(RowTemp1 - RowStart)*RowSpeed +
     abs(ColTemp1 - ColStart)*ColSpeed >
     abs(Row - RowStart)*RowSpeed +
     abs(Col - ColStart)*ColSpeed) and
     (Row > 0 and Col > 0)) then
  begin
    RowTemp1 = Row
    ColTemp1 = Col
    RackTemp = RackA
  end
end
/* Search left and down */
RowDir = -1
ColDir = -1
call S_SearchRack
/* Select which is closer */
if(RowTemp1 = 0 or ColTemp1 = 0) then
begin
  RowTemp1 = Row
  ColTemp1 = Col
  RackTemp = RackA
end
else
begin
  if((abs(RowTemp1 - RowStart)*RowSpeed +
     abs(ColTemp1 - ColStart)*ColSpeed >
     abs(Row - RowStart)*RowSpeed +
     abs(Col - ColStart)*ColSpeed) and
     (Row > 0 and Col > 0)) then
  begin
    RowTemp1 = Row
    ColTemp1 = Col
    RackTemp = RackA
  end
end
/* return closest location */
Row   = RowTemp1
Col   = ColTemp1
RackA = RackTemp
end
Define Resources
SRMach // Storage / retrieval (S/R) machine

Define Attributes
ArriveTime // Time of arrival of subassembly
Type // Type of subassembly

Define Variables
Bin // Bins currently available
InvSA1 // Subassemblies of type 1
InvSA2 // Subassemblies of type 2
InvSA3 // Subassemblies of type 3
InvSA4 // Subassemblies of type 4
RowStart // Current location of S/R machine – row
ColumnStart // Current location of S/R machine – column
RowDirection // Direction of row search
ColumnDirection // Direction of column search
TargetState // State of requested bin
Rack // Rack with bin in requested state
Row // Row of bin in requested state
Column // Column of bin in requested state
VerticalSpeed // Vertical (column) speed of S/R Machine
HorizontalSpeed // Horizontal (row) speed of S/R Machine
LocState // State of each bin
ColumnMax // Number of columns in a rack

Process SubAssembly_Arrivals
Define Arrivals
Time of first arrival: 0
Time between arrivals: Exponential 20 seconds
Number of arrivals: Infinite

Begin
Set ArriveTime = Clock
Set Type = Integer Uniform (1, 4)
Wait until Bin > 0
Increment Bin by 1
Wait until SRMachine is IDLE
Make SRMachine BUSY
Wait for RowStart*VerticalSpeed + ColumnStart*HorizontalSpeed
// Move SRMachine to Pick Point
Set RowStart = 1
Set ColumnStart = 1
Set RowDirection = 1
Set ColumnDirection = 1
Set TargetState = 0
Call SearchRack returning Rack, Row, Column
Wait for Row*VerticalSpeed + Column*HorizontalSpeed
// Move SRMachine to Selected Bin
Wait for 6 seconds // Store Carrier in Bin
Make SRMach IDLE
LocState (Rack, Row, Column) = Type
Increment InvSA<Type> by 1

End
Process SubAssembly_Retrievals
Define Arrivals
  Time of first arrival: 2 hours
  Time between arrivals: Exponential 20 seconds
  Number of arrivals: Infinite

Begin
  Set ArriveTime = Clock
  Set Type = Integer Uniform (1, 4)
  Wait until InvSA<Type> >0
  Decrement InvSA<Type> by 1
  Set TargetState = Type
  Call SearchAll returning Rack, Row, Column
  Set LocState (Rack, Row, Column) = Type +4
  Wait until SRMachine is IDLE
  Make SRMachine BUSY
  Wait for abs ((Row - RowStart)*VerticalSpeed) +
    abs ((Column-ColumnStart)*HorizontalSpeed
    // Move SRMachine to Select Bin
  Wait for 6 seconds  // Remove Carrier from Bin
  Wait for abs (Row-1)*VerticalSpeed + abs (Column-ColumnMax)*HorizontalSpeed
  // Move SRMachine to drop point
  Make SRMach IDLE
  Set RowStart = 1
  Set ColumnStart = ColumnMax
  Set LocState(Rack, Row, Column) = 0

End
18.3.3 Identify Root Causes and Assess Initial Alternatives

Table 18-1 gives the design for the AS/RS system simulation experiment. The final assembly process consumes all subassemblies stored in the rack each day. Thus, a terminating experiment with the simulated time interval equal to the time each day that the subassemblies arrive to the AS/RS system is appropriate. The dynamics of how the final assembly process consumes the subassemblies remaining in the storage racks after all subassemblies have arrived will not affect the choice of configurations. Thus, this part of the system need not be included in the experiment.

Table 18-1: Simulation Experiment Design for the AS/RS 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>Rack configuration -- (10X18 and 9X25)</td>
</tr>
</tbody>
</table>
| Performance Measures      | 1. Number of bins in non-IDLE states  
2. Time subassemblies wait for a bin  
3. Time subassemblies and final process requests wait for the SR machine. |
| Random Number Streams     | 1. Type of subassembly to store  
2. Time between arrivals of subassemblies to the AS/RS system  
3. Type of subassembly requested by final assembly  
4. Time between arrivals of requests from final assembly |
| Initial Conditions         | The bins empty and the SR machine idle |
| Number of Replicates      | 20                          |
| Simulation End Time       | One eight hour day (time in seconds) |

The initial conditions are the daily start-up conditions for the system: all bins empty and the SR machine idle. Twenty replicates will comprise the experiment. There are four random number streams, one each to determine the type of subassembly delivery to the AS/RS and requested by the final assembly process as well as one each for the time between arrivals of subassemblies and requests from the final assembly process.

The model parameter is the rack configuration with the two alternatives proposed by management tested. Performance measures have to do with the utilization of bins, subassembly waiting time for an empty bin, and waiting time for the SR machine to move subassemblies.

Results of this experiment are shown in Table 18-2. The average percent of bins occupied is 16% less for the 9 X 25 rack configuration with an approximate 95% confidence interval of 15% to 18% for the true percent difference. The 9 X 25 rack is 25% bigger than the 10 X 18 rack. Thus, some use is made of the extra bin space. This is reflected in the fact that there is no waiting for an empty bin when the larger rack is used. However, the average waiting time for the smaller rack is only 2.5 seconds with an approximate 95% confidence interval of 0.7 to 4.3 seconds for the true mean waiting time. The average waiting time for the SR machine increases when the larger rack size is used, though the average difference is only 2.4 seconds.
Table 18-2: Results of the AS/RS System Simulation Experiment

<table>
<thead>
<tr>
<th>Replicate</th>
<th>Percentage of Full Bins</th>
<th>Average Time Waiting for an Empty Bin (Seconds)</th>
<th>Average Time Waiting for the SR Machine (Seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 X 18</td>
<td>9 X 25</td>
<td>Diff</td>
</tr>
<tr>
<td>1</td>
<td>70%</td>
<td>92%</td>
<td>22%</td>
</tr>
<tr>
<td>2</td>
<td>72%</td>
<td>92%</td>
<td>20%</td>
</tr>
<tr>
<td>3</td>
<td>71%</td>
<td>92%</td>
<td>20%</td>
</tr>
<tr>
<td>4</td>
<td>67%</td>
<td>93%</td>
<td>27%</td>
</tr>
<tr>
<td>5</td>
<td>65%</td>
<td>92%</td>
<td>27%</td>
</tr>
<tr>
<td>6</td>
<td>72%</td>
<td>92%</td>
<td>19%</td>
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<tr>
<td>7</td>
<td>68%</td>
<td>94%</td>
<td>26%</td>
</tr>
<tr>
<td>8</td>
<td>72%</td>
<td>93%</td>
<td>21%</td>
</tr>
<tr>
<td>9</td>
<td>73%</td>
<td>91%</td>
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18.3.4 Review and Extend Previous Work

The smaller rack configuration seems preferable since it would be less costly and require less floor space as long as system performance is not significantly improved by using the larger rack. While the larger rack does eliminate waiting for an empty bin, it increases waiting time for the SR machine. However, no waiting time is very long for either configuration. The bin utilization is relatively high for both rack sizes (92% versus 70%).

18.3.5 Implement the Selected Solution and Evaluate

The AS/RS system with the 10 X 18 configuration of two racks of bins will be implemented. Subassembly waiting at the pick point will be monitored and sufficient buffer space provided as needed.

18.4 Summary

This case study shows how system operational algorithms can be included in models. The use of modeler defined resource states is included. Inventories and other resources are shared between processes in the model. The simulation experiment compares alternative system configurations.

Problems

1. Based on the process steps in the simulation model, tell why the bin states: occupied with a subassembly of type one, two, three, or four that is committed to the final assembly process are necessary.

2. Validate the function SearchOne by searching from rack location row 2 column 2 as shown in Figure 18-2 in the right and up direction. List the first ten values of RowIndex and CollIndex computed in SearchOne, including the infeasible bin location values that cause the loops in SearchOne to end.

3. In the Arrival process model, why is it not necessary to check if the function SearchRack located a bin in the IDLE state?

4. Tell why the quantity: Number of final assembly process requests waiting for a subassembly is not an effective performance measure for the simulation experiment in this chapter.

5. What impact would running the simulation experiment until all subassemblies had been moved to the final assembly process have on the validity of the performance measure estimates?

6. Explain why the average waiting time for the SR machine increases when the larger rack size is used especially considering that there is no waiting for an empty bin.

7. Would you expect the utilization of the SR machine to increase or decrease when the larger rack size is used? Justify your answer.

8. Use Little’s Law to estimate the average number of subassemblies waiting at the pick point. How much buffer space would you use at the pick point?

9. Compute the expected time to store a carrier in a bin after the SR machine is obtained.

10. Visit a manufacturing facility and observe the automated material handling equipment that is in use.
11. Make a list of the automated material handling equipment you have observed in the service systems you encounter regularly.

12. How much improvement is there in the AS/RS system if the speed of the SR machine increases by 100%.

13. How much improvement is there in the AS/RS system if the time between requests from the second manufacturing process is uniformly distributed between 10 and 30 seconds?

14. Perform additional simulation experiments to find the smallest difference between the starting time of the storage process (current 6:00 A.M.) and the retrieval process (current 8:00 A.M) for which the system can effectively operate.

15. The current rack configurations are about one story high. Suppose a two story high configuration was preferred, specifically 18 bins high and 10 bins wide. Compare system performance using this configuration to the 10 bins high and 18 bins wide configuration.

16. Embellish the model in this chapter with acceleration and deacceleration of the SR machine. Assume the acceleration (deacceleration) distance is one bin in either direction and the average time to traverse this bin is twice that of other bins.

Case Problem

The benefits of AS/RS technology have been effectively realized in libraries. The amount of floor space required for books and periodicals has been reduced by ten-fold or more. The number of librarians required was reduced as well. Reshelving errors were eliminated. The location of each item while in the library is known with certainty. Despite these benefits, it is estimated that a few (less than 12) mini-load AS/RS systems have been installed in libraries.

This case problem involves determining the saturation point for a mini-load AS/RS system installed in a particular library. This is done by creating a graph of the cycle time for retrieving a book or periodical versus the arrival rate for such requests. The arrival rate resulting in the longest acceptable retrieval time is the saturation point. The smallest arrival rate of interest is 10 requests per hour. Assume that the arrival rate for retrievals is the same as the arrival rate for returns.

The mini-load AS/RS system installed in one particular library has a capacity of 250,000 books and periodicals. There is a single aisle with identical racks on each side. The system is installed inside a secured vault for safety and security reasons.

Books and periodicals are stored in carriers that are 4 feet deep and 2 feet wide. Each carrier row is one of three heights: 10, 12, or 15 inches. Each item is stored in the shallowest carrier in which it can stand. Thus, vertical space is used most efficiently. Assume that the number of books and periodicals of each height is the same.

There are 36 carrier rows on each side of the single aisle. The height of the first row is 10 inches, the second 12 inches, the third 15 inches, the fourth 10 inches and so forth. There are 60 carriers in each row.

The S/R machine travels at a high rate of speed: 12.6 feet/second horizontally and 4.3 feet/second vertically. Assume that the S/R machine must travel either horizontally or vertical but not diagonally.

The process of retrieving a book or periodical is the following. A patron makes a request using the electronic library catalog system. The AS/RS fills one request at a time. The location of the
item is completely random. The S/R machine moves from its idle location to the required carrier, extracts the carrier in 3 seconds, and places the carrier in the pick and delivery station. A librarian must remove the desired item from the carrier and record its status in the information system. This takes 7 seconds. The S/R machine remains idle at the pick and delivery station.

Next the librarian determines whether any item that needs to be returned to storage is of the same size as the carrier. If so, the item’s new carrier location is recorded in the information system and the item placed in the carrier. Both steps combined take 7 seconds.

Assume the library is open 16 hours per day, 7 days per week.

Embellishment: The AS/RS system tests the carrier for weight restrictions. One in 100 tests fail. In this case, the librarian must remove the item as well as the newly entered location from the information system in 7 seconds. In either case, the S/R machine replaces the carrier and returns empty to its idle location.

Embellishment: Find the saturation point when the following procedure is used. The S/R machine does not replace a carrier that is at a pick and delivery station until the next retrieval request is made. At that time, a carrier is first stored and then the next carrier retrieved.

Embellishment: Limit the number of carriers stored at the pickup/dropoff station to a total of three. When the fourth carrier arrives, it is immediately returned to the same storage location by the AS/RS machine.

Case Problem Issues:

1. How should carriers be modeled?
2. How should the location of the carrier containing the book or periodical requested be determined?
3. How should S/R machine travel time be computed?
4. Specify the process for book and periodical returns.
5. What are good initial conditions for this simulation experiment?
6. What performance measures, other than cycle time, would be of interest?
7. What is the expected utilization of the SR machine?
8. How should verification and validation evidence be obtained?