

## Chapter 10

### Inventory Control using Kanbans

#### 10.1 Introduction

Inventory control using kanbans was introduced in Chapter 9. Here, the discussion is extended to include simulation modeling and experimentation of inventory control using kanbans in order to establish target inventory levels. The inventory level is determined by the number of finished goods inventory tags and the number of work-in-process tags allowed. The minimum number of tags needed is proportional to the maximum number of items in the inventories (Mittal and Wang, 1992). Having too few tags causes an interruption in production flow which can lead to unmet demand. Having too many tags causes excess inventory and increases associated costs.

#### 10.2 Points Made in the Case Study

Previously, a process model has represented the physical movement of items through a system. In this application study, the model must represent both the flow of control information that specifies where and when to route items as well as the movement of those items through a system.

Often, models evolve from previously existing models. The model of the job shop with a push system orientation presented in chapter 8 is evolved into a model of the job shop with a pull orientation, including inventory management.

There is a trade-off between maximizing the service level to customers and minimizing the inventory on hand. The service level is the percent of demands that are met on time. A series of simulation experiments can be run varying the number of kanbans, and thus inventory capacity, of each type of product to help quantify this trade-off.

In push systems, inventory level is a consequence of how the system operates and can be a simulation experiment performance measure. In a pull system, the inventory level is a model parameter whose value is to be set through simulation experiments.

A high service level to customers may be achieved even though work-in-process inventory is not always available when a workstation is directed to perform its operation. In other words, a workstation may be starved. Thus, a high service level to each workstation may not be necessary.

Previous information about how a system operates, or should operate, can be combined with simulation results to draw conclusions. This technique is known as the use of **prior information**. In this case, the expected mix of item types demanded is known and is used in conjunction with performance measure estimates to set the number of kanbans. In addition, the number of kanbans for an item type could be the same in all inventories to minimize the number of inventory parameters. This number will be based on the number needed to provide the required customer service level in the finished goods inventory.

#### 10.3 The Case Study

The job shop described in chapter 8 is being converted to a pull inventory control strategy as an intermediate step toward a full lean transformation. The shop consists of four workstations: lathe, planer, shaper, and polisher. The number of machines at each station was determined in chapter 8: 3 planers, 3 shapers, 2 lathes and 3 polishers. The time between demands for each item type is exponentially distributed. The mean time between demands for item type 1 is 2.0

hours, for type 2 items 2.0 hours, and for type 3 items 0.95 hours. The items have the following routes through the shop:

Type 1: lathe, shaper, polisher

Type 2: planer, polisher

Type 3: planer, shaper, lathe, polisher

There is a supermarket following each workstation to hold the items produced by that station. Figure 10-1 shows the job shop configuration plus supermarkets, with job types in each supermarket identified. No routing information is shown. Improvements will be made at each station such that the processing times will be virtually constant and the same regardless of item type.

Planer: 1.533 hours  
 Shaper: 1.250 hours  
 Lathe: 0.8167 hours  
 Polisher: 0.9167 hours

Management anticipates changes in demand each month. The simulation model will be used as a tool to determine the number of kanbans to use in each month.

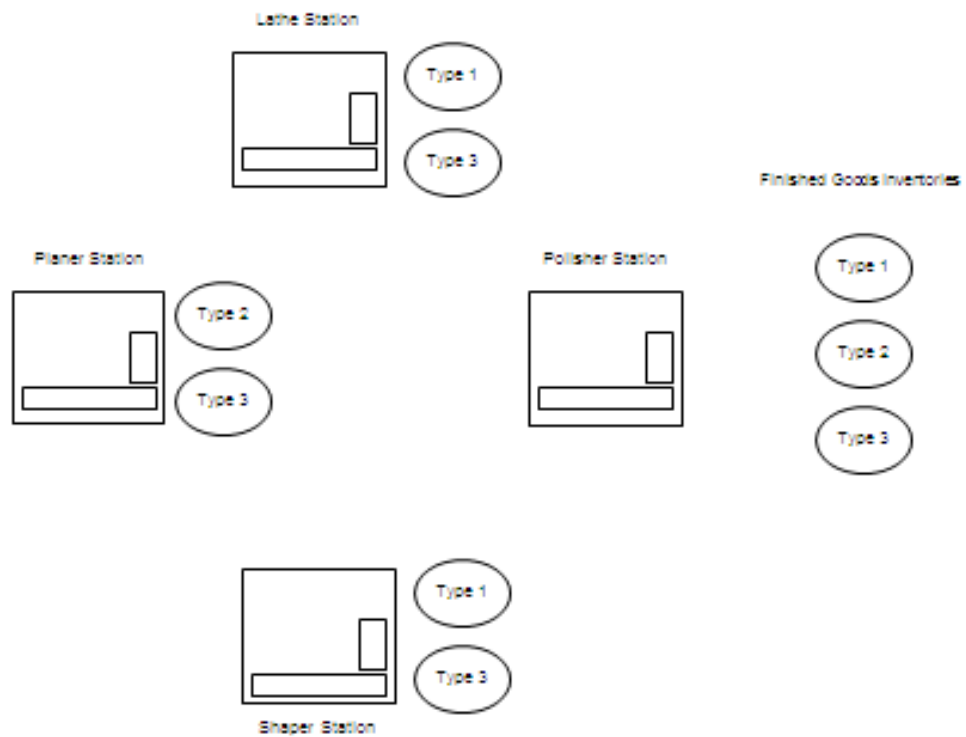


Figure 10-1: Job Shop Configuration

### 10.3.1 Define the Issues and Solution Objective

Management wishes to achieve a 99% service level provided to customers. The service level is defined as the percent of customer demands that can be satisfied from the finished goods inventories at the time the demand is made. At the same time, management wishes to minimize the amount of finished goods and in process inventory to control costs.

Thus initially, management wishes to determine the minimum number of kanbans for each item type associated with each inventory. The minimum number of kanbans establishes the maximum number of items of each type in each inventory.

### 10.3.2 Build Models

The process of the flow of control information through the job shop will be the perspective for model building. Note that the flow of control information from workstation to workstation follows the route for processing an item type in reverse order. For example, the route for type 1 items is lathe, shaper, polisher but the flow of control information is polisher, shaper, lathe.

The control information must include the name of the supermarket into which an item is placed upon completion at a workstation with the number of items of each type in the supermarket tracked. In addition, the control information should include the name of the inventory from which an item is taken for processing at a workstation. Supermarket / inventory names are constructed as follows. For the finished goods inventories, the name is INV\_FINISHED\_ItemType = INV\_FINISHED\_1 if ItemType = 1 and so forth. For the work in process inventories the name is INV\_Station\_ItemType, for example INV\_SHAPER\_1 for type one 1 items that have been completed by the shaper. Thus, the polisher places type 1 items in the inventory INV\_FINISHED\_1 and removes items from INV\_SHAPER\_1 since the shaper was the preceding station to the polisher on the production route of a type 1 item. Table 10-1 summarizes the supermarkets / inventories associated with each item type at each workstation. In the model, a distinct state variable models each of the inventories.

**Table 10-1: Inventory Names by Item Type and Station**

Supermarket / Inventory	Item Type	Output from Station	Input to Station or Customer
INV_FINISHED_1	1	Polisher	Customer
INV_FINISHED_2	2	Polisher	Customer
INV_FINISHED_3	3	Polisher	Customer
INV_SHAPER_1	1	Shaper	Polisher
INV_LATHE_1	1	Lathe	Shaper
INV_PLANER_2	2	Planer	Polisher
INV_LATHE_3	3	Lathe	Polisher
INV_SHAPER_3	3	Shaper	Lathe
INV_PLANER_3	3	Planer	Shaper

The transmission of control information via a kanban is initiated when a finished item is removed from an inventory. The station preceding the FGI, in this case the polisher for all item types, is instructed to complete an item to replace the one removed from the FGI. The polisher station removes a partially completed item from an inventory, for example INV\_SHAPER\_1 for item type 1, for processing. The item completed by the polisher is placed in the appropriate FGI. The removal of a partially completed item from INV\_SHAPER\_1 is followed immediately by processing at the shaper to complete a replacement item. This processing at the polisher and shaper can occur concurrently. Information flow and processing continues in this fashion until all inventories for the particular type of item have been replenished.

Each entity has the following attributes:

- ArriveTime: time of arrival of a demand for a job in inventory
- JobType: type of job
- Location: location of the production control information (kanban) relative to the start of the route of a job: 1..4
- Route<sub>i</sub>: station at the *i*th location on the route of a job

P\_Inv<sub>i</sub>: the name of the inventory from which a partially completed item is removed for processing at the i<sup>th</sup> location on the route of a job  
 F\_Inv<sub>i</sub>: the name of the inventory into which the item completed at the workstation is placed at the i<sup>th</sup> location on the route of a job

The arrival process for type one jobs is shown below. Arrivals represent a demand for a finished item that subsequent triggers the production process to replace the item removed from inventory to satisfy the demand.

The entity attributes are assigned values. Notice that the value of location is set initially to one greater than the ending position on the route. Thus, production is triggered at the last station on the route, which triggers production on the second last station on the route, and so forth.

The arrival process model includes removing an item from a FGI. Thus arriving entites wait for a finished item to be in inventory, remove an item when one is available, and update the number of finished items in the inventory.

---

Define Arrivals:

Type1

Time of first arrival: 0  
 Time between arrivals: Exponentially distributed with a mean of 2 hours  
 Number of arrivals: Infinite

Type2

Time of first arrival: 0  
 Time between arrivals: Exponentially distributed with a mean of 2 hours  
 Number of arrivals: Infinite

Type3

Time of first arrival: 0  
 Time between arrivals: Exponentially distributed with a mean of 0.95 hours  
 Number of arrivals: Infinite

Define Resources:

Lathe/2 with states (Busy, Idle)  
 Planer/3 with states (Busy, Idle)  
 Polisher/3 with states (Busy, Idle)  
 Shaper/3 with states (Busy, Idle)

Define Entity Attributes:

ArrivalTime // part tagged with its arrival time; each part has its own tag  
 JobType // type of job  
 Location // location of a job relative to the start of its route: 1..4  
 Route(5) // station at the i<sup>th</sup> location on the route of a job  
 ArriveStation // time of arrival to a station, used in computing the waiting time  
 F\_Inv(4) // the name of the inventory into which a completed item is placed // at the i<sup>th</sup> location on the route  
 P\_Inv(4) // the name of the inventory from which an item to be completed // is taken at the i<sup>th</sup> location on the route

```

Process ArriveType1
Begin
    Set ArrivalTime = Clock           // record time job arrives on tag
    Set JobType     = 1               // type of job
    Set Location    = 4               // job at start of route

    // Set route
    Set Route(1) to P_Lathe
    Set Route(2) to P_Shaper
    Set Route(3) to P_Polisher

    // Set following inventories
    Set F_Inv(1) to I1Lathe
    Set F_Inv(2) to I1Shaper
    Set F_Inv(3) to I1Final

    // Set preceding inventories
    Set P_Inv(1) to NULL              // NULL is a constant indicating no inventory
    Set P_Inv(2) to I1Lathe
    Set P_Inv(3) to I1Shaper

    // Get and update inventory
    Wait until I1Final > 0
    Set I1Final --

    // Record service level
    If (Clock > ArrivalTime) then
    Begin
    // Arrival waited for inventory
        tabulate 0 in ServiceLevel1
        tabulate 0 in ServiceLevelAll
    End
    Else
    Begin
    // Arrival immediately acquired inventory
        tabulate 100 in ServiceLevel1
        tabulate 100 in ServiceLevelAll
    End

    Send to P_Router
End

```

---

The process at a station includes requesting and receiving items in inventory from preceding stations, processing a item, and placing completed items in inventory at the station. All stations follow this pattern but differ somewhat from each other.

As shown in Figure 10-1, no operations precede the planer station for any item type. Thus information triggering additional production at other stations is unnecessary. Upon completion of the planer operation, a job is added to the inventory whose name is the value of entity attribute F\_INV[Location], for example INV\_PLANER\_1.

The process model of the shaper station is like the process model of the planer station with the retrieval of partially completed items from preceding workstations added. As soon as a partially completed item is retrieved, the routing process is invoked to begin generating the replacement for the item removed from inventory.

The lathe station model is similar to the shaper station model, except that it is the first station on the route for items of type 1. The polisher station model is similar to the shaper station model. Developing the process models of the lathe and polisher stations is left as an exercise for the reader. The shaper and planer station models are shown below.

---

```

Process Shaper
// Shaper Station
Begin
    // Acquire Preceding Inventory
    Wait until P_Inv(Location) > 0 in Q_Shaper
    Set P_Inv(Location) --
    Clone to P_Router

    // Process item on Shaper
    Wait until Shaper is Idle in Q_Shaper
    Make Shaper Busy
    Wait for 1.25 hours
    Make Shaper Idle
    Set F_Inv(Location)++
End

Process Planer
// Planer Station
Begin
    // Acquire Preceding Inventory
    If P_Inv(Location) != NULL then
        Begin
            Wait until P_Inv(Location) > 0 in Q_Planer
            P_Inv(Location) --
            Clone to P_Router
        End

    // Process item on Planer
    Wait until Planer is Idle in Q_Planer
    Make Planer Busy
    Wait for 0.9167 hours
    Make Planer Idle
    Set F_Inv(Location)++
End

```

---

The routing process is shown below. The attribute Location is updated by subtracting one from the current value. If the control information has been processed by the first workstation on a route, Location is equal to zero and nothing else needs to be done. Otherwise, the control information is sent to the preceding workstation on the route.

---

```

Process Router
Begin
    Location - -
    If Location > 0 then send to Route(Location)
End

```

---

Note the evolution of the model presented in chapter 8 into the model presented in this chapter. The routing process has been modified to send control information through a series of workstations in the reverse order of item movement for processing. This is how the model of the push system orientation was modified to represent a pull system orientation.

Arrivals are interpreted as demands for an item from a finished goods inventory instead of a new item to process. Processing of a new item is triggered via the routing process when a demand is satisfied from the inventory.

Inventory management is added to the model for FGI's for each type of item as well as inventories of partially completed items.

### 10.3.3 Identify Root Causes and Assess Initial Alternatives

The design of the simulation experiment is summarized in Table 10-2. Management has indicated that demand is expected to change monthly. Thus, a terminating experiment with a time interval of one month is employed. There are three random number streams, one for the arrival process of each item type. Twenty replicates are made. Since stations are busy only in response to a demand, all stations idle is a reasonable state for the system and thus appropriate for initial conditions.

**Table 10-2: Simulation Experiment Design for the Just-in-Time Job Shop**

Element of the Experiment	Values for This Experiment
Type of Experiment	Terminating
Model Parameters and Their Values	Initial number of items of each type in each inventory 1. Infinite 2. Number needed to provide a 99% service level for the average time to replace an item in the finished goods inventory
Performance Measures	1. Number of items of each type in each buffer 2. Customer service level
Random Number Streams	Three, one for the arrival process of each item type.
Initial Conditions	Idle stations
Number of Replicates	20
Simulation End Time	184 hours (one month)

The experimental strategy is to determine a lower and an upper bound on the inventory level and thus the number of kanbans. First, the minimum inventory level needed for a 100% service level will be determined. This is the maximum inventory level that would ever be used that is the upper bound. The lower bound is the number of items in finished goods inventory needed to achieve a 99% service level for the average time to replace an item taken from the finished goods inventory. The service level in this case will likely be less than 99% since the time to replace some units will be greater than this average.

Prior information is information known before the simulation results are generated that is used along with these results to reach a conclusion. In this case, the following prior information is available.

1. For each item type, the number of kanbans associated with each inventory (finished goods and work in process at each station) should be the same by management policy.
2. All inventories for an item type should be the same as the finished goods inventory level.
3. The finished goods inventory level for a product relative to the other products should be proportional to the arrival rate of the demand for that product relative to the arrival rate of the demand for all products together, at least approximately.

The first piece of prior information makes the kanban control system simpler to operate since the number of kanbans depends only on the product, not the workstation as well. The second point recognizes that the service level depends on the availability of items in a finished goods inventory

when a customer demand occurs. The service level does not depend on the availability of partially completed items in other inventories when requested by a workstation for further processing.

The third point recognizes that the number of kanbans should be balanced between products with respect to customer demand. Table 10-3 show the computations necessary to determine the percent of the customer demand that is for each product. The demand per hour is the reciprocal of the time between demands. The sum of the demand per hour for each item is the total demand per hour. Thus, the percent of the demand for each item is determined as the demand per hour for that item divided by the total.

**Table 10-3: Percent of Demand from Each Product**

Item	Time Between Demands	Demand per hour	% of Demand
1	2.00	0.50	24%
2	2.00	0.50	24%
3	0.95	1.05	52%
Total	0.49	2.05	100%

The upper bound on the number of kanbans associated with each inventory, equal to the number of items in each inventory in this case, is estimated as follows. The initial number of items in an inventory is set to infinite. In other words, the state variable modeling the inventory is initially set to a very large number. Thus, there will be no waiting for a needed item because it is not in inventory. The inventory level will be observed over time. The minimum inventory level observed in the simulation represents the number of units that were never used and thus are not needed.

Setting the inventory level as discussed in the previous paragraph implies that the service level would be 100% since by design there is always inventory to meet a customer demand.

The simulation results for the infinite inventory case are shown in Table 10-4. These results can be interpreted using the prior information discussed above. In this way, the number of kanbans in each inventory for each item is the same as the finished goods inventory for that item. Thus, the upper bound on the number of items need in each inventory is 4 for item type 1, 4 for item type 2 and 6 for item type 3. Thus, a total of 44 items are needed in inventory.

Note that the percent of the total finished goods inventory for each item is near the percent demand shown in Table 10-3: Type 1, 29% from the simulation versus 24% of the demand; Type 2, 29% versus 24% and Type 3, 44% versus 52%. Further, the percent of the total for type 1 and type 2 are equal to each other as in Table 10-3. Thus, validation evidence is obtained.



**Table 10-4: Maximum Inventory Values from the Pull Job Shop Simulation**

Replicate	FGI Type 1	Lathe Type 1	Shaper Type 1	FGI Type 2	Planer Type 2	FGI Type 3	Lathe Type 3	Planer Type 3	Shaper Type 3
1	4	3	4	4	4	7	6	5	7
2	4	5	4	4	3	5	5	5	6
3	4	4	5	5	5	9	9	9	10
4	3	4	4	4	4	5	6	5	7
5	4	4	4	4	4	4	4	4	5
6	3	3	4	6	6	5	5	5	6
7	4	4	5	3	3	6	6	5	6
8	5	4	5	4	4	6	6	5	7
9	4	4	4	4	4	5	6	5	6
10	4	4	4	4	4	6	6	6	7
11	3	3	3	4	4	5	5	5	7
12	3	3	4	5	5	12	13	11	14
13	3	3	4	4	4	6	5	5	6
14	3	3	4	4	4	4	5	4	5
15	4	3	4	4	4	7	7	5	7
16	3	3	4	4	4	5	5	5	6
17	3	3	4	4	4	5	5	5	6
18	5	5	6	4	4	5	4	5	6
19	4	4	4	4	4	6	6	6	7
20	3	4	4	4	4	7	6	6	7
<b>Average</b>	3.7	3.7	4.2	4.2	4.1	6.0	6.0	5.6	6.9
<b>Std. Dev.</b>	0.671	0.671	0.616	0.587	0.641	1.835	1.974	1.638	1.971
<b>99% CI Lower Bound</b>	3.2	3.2	3.8	3.8	3.7	4.8	4.7	4.5	5.6
<b>99% CI Upper Bound</b>	4.1	4.1	4.6	4.5	4.5	7.2	7.3	6.6	8.2
<b>Proposed Initial Capacity</b>	4	4	4	4	4	6	6	6	6
<b>% of Total FGI</b>	29%			29%		44%			

Alternatively, the number of items in inventory, and hence the number of kanbans, will be estimated as the number required to provide a 99% service level for the average time needed to replace a product taken from inventory. In other words, for the average time interval from when a product is taken by a customer from finished goods inventory till it is replaced in the finished goods inventory by the production system, the customer service level should be at least 99%. See Askin and Goldberg (2002) for a discussion of this strategy.

The average time interval to replace a product is the sum of two terms: the amount of time waiting for the polisher and the polisher processing time. The former can be determined using the VUT equation and adjusted here for multiple machines ( $m=3$ ) as shown in equation 10-1.

$$CT_q \approx VUT = \left( \frac{c_a^2 + c_{CT}^2}{2} \right) \left( \frac{\mu^{\sqrt{2(m+1)}-1}}{(1-\mu)^* m} \right) CT \quad (10-1)$$

The V term will be 0.5. The processing time at the polisher is a constant yielding zero for the coefficient of variation. The time between demands is exponentially distributed and thus has a coefficient of variation of 1. The utilization of the polisher is the processing time (0.9167 hours) divided by the number of machines at the polisher station (3) times the total number of units demanded per hour as shown in Table 10-3. Thus, the utilization of the polisher is 91.3%.

Using these values in equation 10-1 yields 0.1747 hours for the average waiting time before processing at the polisher. The average processing time at the polisher is 0.9167 hours. Thus, the average time for the polisher to complete one item is 1.0913 hours.

The finished goods inventory needed for each product must make the following probability statement true:

$$P(\text{demand in 1.0913 hours} \leq \text{finished good inventory level}) \geq 99\%.$$

Since the time between demands for units is exponentially distributed, the number of units demanded in any fixed period of time is poisson distributed with mean equal to the average number of units demand in 1.0913 hours. The mean is computed as 1.0913 hours times the average number of units demand per hour shown in Table 10-3.

Table 10-5 shows the number of items in finished goods inventory needed to achieve at least a 99% service level for 1.0913 hours.

**Table 10-5: Finished Goods Inventory Levels for the Average Time to Replace a Unit**

Item	Expected Demand in 1.0913 Hours	Inventory Level	Service Level	Percent of Total Inventory
1	0.55	3	99.8%	30%
2	0.55	3	99.8%	30%
3	1.15	4	99.4%	40%
Total		10		100%

Note that the percent of total inventory for each product corresponds reasonably well to that given in Table 10-2, given the small number of units in inventory. Thus, validation evidence is obtained.

The lower bound on the total number of units in inventory is 31 which is 13 units less than the upper bound of 44.

Simulation results shown in Table 10-6 show the service level for each product and overall obtained when the inventory levels shown in Table 10-5 are used.

**Table 10-6: Service Level Simulation Results for Finished Goods Inventory Levels (3, 3, 4)**

<b>Replicate</b>	<b>Type 1</b>	<b>Type 2</b>	<b>Type 3</b>	<b>Overall</b>
1	98.1	98.8	97.2	97.8
2	97.8	97.6	98.9	98.4
3	96.7	92.6	89.9	92.2
4	100.0	100.0	95.9	97.9
5	98.6	98.8	100.0	99.3
6	100.0	94.1	98.9	97.8
7	96.8	100.0	96.7	97.4
8	97.6	94.4	95.0	95.5
9	98.9	99.0	96.7	97.8
10	97.6	98.9	94.4	96.2
11	100.0	96.9	97.5	97.9
12	100.0	93.2	86.1	91.1
13	100.0	98.8	96.4	97.8
14	100.0	98.8	100.0	99.7
15	98.9	93.9	96.1	96.3
16	100.0	98.9	98.5	99.0
17	100.0	98.7	98.4	98.8
18	96.8	98.9	98.9	98.4
19	98.0	98.9	96.3	97.4
20	100.0	95.7	95.8	96.7
<b>Average</b>	98.8	97.3	96.4	97.2
<b>Std. Dev.</b>	1.26	2.41	3.32	2.17
<b>99% CI Lower Bound</b>	98.0	95.8	94.3	95.8
<b>99% CI Upper Bound</b>	99.6	98.9	98.5	98.6

The service levels are all less than the required 99% through the approximate 99% confidence interval for the service level of type 1 items contains 99%. Note in addition that the range of service levels across the replicates is small.

#### 10.3.4 Review and Extend Previous Work

Management was pleased with the above results. It was thought, however, that the service level obtained when using the upper bound inventory values should be determined by simulation and compared to the service level obtained when using the lower bound values. This was done and the results are shown in Table 10-7.



**Table 10-7: Comparison of Service Level for Two Inventory Capacities**

Replicate	Type 1			Type 2			Type 3			Overall		
	(3,3,4)	(4,4,6)	difference	(3,3,4)	(4,4,6)	difference	(3,3,4)	(4,4,6)	difference	(3,3,4)	(4,4,6)	difference
1	98.1	100.0	1.9	98.8	100.0	1.2	97.2	99.5	2.4	97.8	99.8	2.0
2	97.8	100.0	2.2	97.6	100.0	2.4	98.9	100.0	1.1	98.4	100.0	1.6
3	96.7	100.0	3.3	92.6	96.7	4.1	89.9	93.8	3.8	92.2	96.0	3.8
4	100.0	100.0	0.0	100.0	100.0	0.0	95.9	100.0	4.1	97.9	100.0	2.1
5	98.6	100.0	1.4	98.8	100.0	1.2	100.0	100.0	0.0	99.3	100.0	0.7
6	100.0	100.0	0.0	94.1	98.0	3.9	98.9	100.0	1.1	97.8	99.5	1.6
7	96.8	100.0	3.2	100.0	100.0	0.0	96.7	100.0	3.3	97.4	100.0	2.6
8	97.6	98.8	1.2	94.4	100.0	5.6	95.0	100.0	5.0	95.5	99.7	4.3
9	98.9	100.0	1.1	99.0	100.0	1.0	96.7	100.0	3.3	97.8	100.0	2.2
10	97.6	100.0	2.4	98.9	100.0	1.1	94.4	100.0	5.6	96.2	100.0	3.8
11	100.0	100.0	0.0	96.9	100.0	3.1	97.5	100.0	2.5	97.9	100.0	2.1
12	100.0	100.0	0.0	93.2	99.0	5.8	86.1	90.6	4.5	91.1	94.9	3.8
13	100.0	100.0	0.0	98.8	100.0	1.3	96.4	100.0	3.6	97.8	100.0	2.2
14	100.0	100.0	0.0	98.8	100.0	1.2	100.0	100.0	0.0	99.7	100.0	0.3
15	98.9	100.0	1.1	93.9	100.0	6.1	96.1	99.5	3.4	96.3	99.7	3.4
16	100.0	100.0	0.0	98.9	100.0	1.1	98.5	100.0	1.5	99.0	100.0	1.0
17	100.0	100.0	0.0	98.7	100.0	1.3	98.4	100.0	1.6	98.8	100.0	1.2
18	96.8	97.9	1.1	98.9	100.0	1.1	98.9	100.0	1.1	98.4	99.5	1.1
19	98.0	100.0	2.0	98.9	100.0	1.1	96.3	100.0	3.7	97.4	100.0	2.6
20	100.0	100.0	0.0	95.7	100.0	4.3	95.8	99.5	3.7	96.7	99.7	3.0
<b>Average</b>	98.8	99.8	1.0	97.3	99.7	2.3	96.4	99.1	2.8	97.2	99.4	2.3
<b>Std. Dev.</b>	1.26	0.53	1.14	2.41	0.85	1.95	3.32	2.45	1.61	2.17	1.39	1.14
<b>99% CI Lower Bound</b>	98.0	99.5	0.3	95.8	99.1	1.1	94.3	97.6	1.7	95.8	98.5	1.5
<b>99% CI Upper Bound</b>	99.6	100.2	1.8	98.9	100.2	3.6	98.5	100.7	3.8	98.6	100.3	3.0

The following can be noted from Table 10-7.

1. For the upper bound inventory values, (4, 4, 6), the approximate 99% service level confidence intervals include 99%.
2. The approximate 99% confidence intervals of the difference in service level do not contain zero. Thus, it can be concluded with 99% confidence that the service level provided by the lower bound on inventory values is less than that provided by the upper bound inventory values.
3. The approximate 99% confidence intervals of the difference in service level are relatively narrow.

Based on these results, management decided that an acceptable service level would be achieved by using a target inventory of 4 units for jobs of type 1 and 2 as well as 6 units for jobs of type 3.

### 10.3.5 Implement the Selected Solution and Evaluate

The selected inventory levels were implemented and the results monitored.

#### *10.4 Summary*

This chapter emphasizes how simulation is used to evaluate the operating strategies for systems. In addition, simulation is helpful in setting the parameters of such operating strategies. The use of simulation in modeling a pull production strategy is shown. The evolution of previously existing models is illustrated.

#### **Problems**

1. Develop the process model for the lathe station.
2. Develop the process model for the polisher station.
3. Develop a process model of a single workstation producing one item type that uses a pull production strategy.
4. Find verification evidence for the model discussed in this chapter.
5. Provide additional validation evidence for the model discussed in this chapter.
6. Compare the routing process used in the model in this chapter to that used in chapter 8.
7. Compare the process at each workstation used in the model in this chapter to that in the model in chapter 8.
8. Provide a justification for using different inventory levels at different stations and the FGI for the same product.
9. Find an inventory level between the lower and upper inventory sizes that provides a 99% service level. How much inventory is required?
10. Conduct additional simulation experiments using the model developed in this chapter to determine the product inventory levels that yield a 95% service level.
11. For one customer demand, augment the model to produce a trace of the movement of the entities through the model.

### Case Problem -- CONWIP

Convert the assembly line presented in the chapter 7 application problem to a CONWIP production strategy. The assembly line was described as follows.

A new serial system consists of three workstations in the following sequence: mill, deburr, and wash. There are buffers between the mill and the deburr stations and between the deburr and the wash stations. It is assumed that sufficient storage exists preceding the mill station. In addition, the wash station jams frequently and must be fixed. The line will serve two part types. The production requirements change from week to week. The data below reflect a typical week with all times in minutes.

Time between arrivals -	Part type 1:	Exponentially distributed with mean 2.0
	Part type 2:	Exponentially distributed with mean 3.0
Time at the mill station -	Part type 1:	0.9
	Part type 2:	1.4
Time at the deburr station -	Uniform (0.9, 1.3) for each part type	
Time at wash station -	1.0 for each part type	
Time between wash station jams -	Exponentially distributed with mean 30.0	
Time to fix a wash station jam -	Exponentially distributed with mean 3.0	

Arrivals represent demands for completed products. Demands are satisfied from finished goods inventory. Each demand creates a new order for the production of a product of the same type after it is satisfied. The completed product is placed in the finished goods inventory.

Three quantities must be determined through simulation experimentation:

1. The CONWIP level, that is the maximum number of parts allowed on the line concurrently.
2. The target FGI level for part type 1.
3. The target FGI level for part type 2.

Two approaches to setting these values could be taken. Choose either one you wish.

1. Approach one.
  - a. Set the FGI inventory level for each product as described in this chapter. Set the CONWIP level to infinite (a very high number). Use an infinite (again a very high number) FGI inventory level to determine the minimum number of units needed for a 100% service level.
  - b. Determine the inventory level needed for a 99% service level during the average replacement time analytically. The average replacement time is the same for each part type. Determine the average lead time using the VUT equation for each station. Sum the results. Remember that  $c_a$  at a following station is equal to  $c_d$  at the preceding station. Hints: 1) The VUT equation assumes that there is only one part type processed at a station. Thus, the processing time to use the mill station is the weighted average processing time for the two part types. The weight is the percent of the total parts processed that each part type is of the total: 60% part type 1 and 40% part type 2. The formulas for the average and the variance for this situation are given in the discussion of discrete distributions in chapter 3. 2) The formula for the variance of a uniform distribution is given in chapter 3. 3) Ignore the downtime at the wash station for this analysis.

- c. Assess the service level for the inventory level midway between the lower and upper bound.
  - d. Pick the lowest level of inventory of three that you have tested that yields close to a 99% service level. Note average and maximum WIP on the serial line for this value.
  - e. Set the CONWIP level to the lowest value that doesn't negatively impact the service level. The minimum feasible CONWIP level is 3. Try values of 3, 4, 5, ... until one is found that does not impact the service level. Confirm your choice with a paired-t analysis.
  - f. Compare the maximum WIP before the CONWIP level was established to the CONWIP level you selected.
2. Approach two:
- a. Find the minimum CONWIP level that maximizes throughput. Set the two FGI levels to infinite (a very high number) so that the service level is 100%. The minimum feasible CONWIP level is 3. Try values of 3, 4, 5, ... until one is found such that the throughput is no longer increasing. Confirm your choice with a paired-t analysis.
  - b. Compare the maximum WIP in the serial line without the CONWIP control to the CONWIP level you select. The former could be determined by setting the CONWIP level to a large number.
  - c. Estimate the finished goods inventory level need to satisfy customer demands using the approach described in this chapter and after the CONWIP level has been established. Use an infinite (again a very high number) FGI inventory level to determine the minimum number of units needed for a 100% service level.
  - d. Determine the inventory level needed for a 99% service level during the average replacement time analytically. The average replacement time is the same for each part type: the average lead time at station  $j$  is given by the following equation discussed in Chapter 9 where  $M = 3$  stations and  $N$  is the CONWIP level you selected: 
$$\left( \frac{N - 1}{M} \right) CT_j + CT_j$$
  - e. Assess the service level for the inventory level midway between the lower and upper bound and pick the lowest level that yields close to a 99% service level.

Terminating Experiment: Use a simulation time interval of 184 hours.

#### Application Problem Issues

1. How should the CONWIP control be modeled?
2. What should the ratio of the two FGI levels be if prior information is used?
3. Should the mean or maximum WIP level on the serial line with no CONWIP control be compared to the CONWIP level?
4. Given the CONWIP control, is it necessary to model the finite buffer space between the stations on the serial line? Why or why not?
5. How will verification and validation evidence be obtained?



## Case Problem -- POLCA

Convert the assembly line presented in the chapter 7 application problem to a set of QRM Cell pairs as follows.

A QRM analysis determined that there will be three QRM cells processing two part types.

- A. Mill and deburr serving both part type 1 and part type 2
- B. Wash station 1 serving part type 1
- C. Wash station 2 serving part type 2

The wash stations jam frequently and must be fixed.

Time between wash station jams - Exponentially distributed with mean 30.0  
Time to fix a wash station jam - Exponentially distributed with mean 3.0

Production requirements change from week to week. The data below reflect a typical week with all times in minutes.

Time between arrivals - Part type 1: Exponentially distributed with mean 2.0  
Part type 2: Exponentially distributed with mean 3.0

Time at the mill station - Part type 1: 0.9  
Part type 2: 1.4

Time at the deburr station - Uniform (0.9, 1.3) for each part type

Time at wash station 1 for part type 1 - 1.7

Time at wash station 2 for part type 2 - 2.5

Arrivals represent demands for completed products. Demands are satisfied from finished goods inventory. Each demand creates a new order for the production of a product of the same type after it is satisfied. The completed product is placed in the finished goods inventory.

Three quantities must be determined through simulation experimentation:

- 4. The number of POLCA cards of each type (A-B and B-C).
- 5. The target FGI level for part type 1.
- 6. The target FGI level for part type 2.

### Approach

- 3. Determine an upper bound on the needed inventory for each part type as follows. Set the POLCA cards levels to infinite (a very high number). Use an infinite (again a very high number) FGI inventory level to determine the minimum number of units needed for a 100% service level.
- 4. Determine a lower bound on the needed inventory for each part type as follows. Determine the inventory level needed for a 99% service level during the average replacement time analytically. Determine the average replacement time separately for each part type. Remember however that the average time in QRM Cell A will be the same for each part type when determined using the VUT equation as described in items a, b, and, c. Remember that  $c_a$  at a following station is equal to  $c_d$  at the preceding station.
  - a. The VUT equation assumes that there is only one part type processed at a station. Thus, the processing time to use at the mill station is the weighted average processing time for the two part types. The weight is the percent of the total parts processed that each part type is of the total: 60% part type 1

- and 40% part type 2. The formulas for the average and the variance for this situation are given in the discussion of discrete distributions in chapter 3.
- b. The formula for the variance of a uniform distribution is given in chapter 3.
  - c. Ignore the downtime at the wash stations for this analysis.
5. Assess the service level for the inventory level midway between the lower and upper bounds.
  6. Pick the lowest level of inventory of three that you have tested that yields close to a 99% service level.
  7. Set the POLCA levels to the lowest values that don't negatively impact the service level. Confirm your choice with a paired-t analysis.

Terminating Experiment:            Use a simulation time interval of 184 hours.

#### Application Problem Issues

1.        How should the POLCA control be modeled?
2.        What should the ratio of the two FGI levels be if prior information is used?
3.        What should the ratio of the number of A-B POLCA cards to the number of A-C POLCA cards be if prior information is used?
4.        Given the POLCA control, is it necessary to model the finite buffer space between the stations on the serial line? Why or why not?
5.        How will verification and validation evidence be obtained?