Comparison and optimization of control policies in automobile manufacturing systems by simulation

by

Chiwon Kim

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Author . . . .
Department of Mechanical Engineering
May 7, 2004

Certified by . . . .
Stanley B. Gershwin
Senior Research Scientist, Department of Mechanical Engineering
Thesis Supervisor

Accepted by . . . .
Ain A. Sonin
Chairman, Department Committee on Graduate Students

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Abstract

This thesis studies material flow control policies for automobile manufacturing systems. Various control policies are implemented in simulations of manufacturing systems to test whether they increase the efficiencies of the systems in terms of specific performance measures of interest. Among the control policies, Control Point Policy (CPP) is deeply studied, because this policy is designed for controlling complex manufacturing system with multiple product types.

First, fundamental research in CPP is presented to understand the effects of the parameters on single product type manufacturing systems. Then, multiple product type, assembly-disassembly systems are studied with various control policies, including hybrid policies. Finally, a real automobile manufacturing system case study is presented, and various control policies are experimented on in the simulation model. Because the evaluations of performances are done by simulations, the speed of simulation becomes a very important problem. This thesis therefore presents a new approach to accelerating the speed of simulation.

Thesis Supervisor: Stanley B. Gershwin
Title: Senior Research Scientist, Department of Mechanical Engineering

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Chapter 1

Introduction

1.1 Objectives and overview

The efficiency of its manufacturing systems is usually one of the most important concerns of any company. There has been active research on the control of material flow in manufacturing systems, which has led to several well-known control policies such as MRP, Kanban, and CONWIP. Recently, a new control policy named Control Point Policy (CPP) was developed, which is a method for real-time decision-making in production systems and is derived using dynamic programming. One of the goals of this thesis is to find a systematic way to determine the values of optimal parameters in CPP as well as to develop a method to predict overall performance of the manufacturing systems as parameters vary, by using dynamic discrete-event simulation.

This thesis investigates the requirements of a good control policy in the environment of multiple product types, which is common in automobile companies. Robustness, balancing, and ease of optimization are studied. New control policies such as a hybrid of CPP and CONWIP are suggested. Since the speed of simulation is important, a general approach is developed to simplify the model of a portion of a manufacturing system. The simulation with this simplification is much faster and is accurate. Finally, a case study of PSA Peugeot Citroën, a French automobile company, is presented, and control of one of PSA's manufacturing systems is investigated based on the research presented in this thesis.

1.2 Literature Review

Analytical methods to predict the performances of manufacturing systems can be found in [7]. In this book, an analysis of discrete, exponential, and continuous time models are presented. A two-machine, one-buffer line model serves as a building block to analyze general tree structured assembly–disassembly systems. In addition, an extensive review of models and results of the manufacturing flow line literature can be found in [4]. This paper presents exact methods for obtaining quantitative measures of performance for small systems and approximate methods for large systems.

One of the most popular push control policies, Manufacturing Resource Planning (MRP II), is introduced in [10]. This book also describes Material Requirement Planning (MRP), Earliest Due Date (EDD), and Kanban. This book is a extensive reference of the dynamics of manufacturing systems.

The CONWIP control policy, which is one of the most famous pull control policies, is described in [19], [10]. Research on the comparison of pull policies with push policies is presented in [20]. This paper explains the apparent superior performance of pull systems. Another comparison of production line control mechanisms can be found in [2].

The issue of customer service in pull production systems is presented in [18]. This paper also shows that CONWIP not only has better service than a pure kanban system, but also solves certain implementation problems. In addition, [3] shows the performance of the hybrid of CONWIP and the finite buffer policy.

The CPP is introduced in [8]. This paper presents details of CPP with three alternative versions of CPP: time-based, surplus-based, and token-based. The CPP is based on a dynamic programming problem formulation of factory scheduling. An analytical solution to the dynamic programming problem for a simple factory is presented in [21]. Also, simulation experiments of CPP are investigated in [5], [9], and [22]. In particular, [9] is for the single product type manufacturing systems, and [22] is for the multiple product type systems.

Li [14] presents the overlapping decomposition method for the estimation of the production rate of a complex manufacturing system with assembly, parallel, rework, feed-forward and scrap operations. The idea in this paper is extended in the simulation substitution methodology presented in this thesis.

Discrete event simulation and Monte-Carlo simulation can be found in [15] and [13].

Various simulation algorithms, including design of experiment and variance reduction technique can be found in these books.

Kouikoglou and Phillis [12] present the method of acceleration of the simulation by separating major events from minor events. By combining analytical methods for minor events and the discrete event simulations for major events, this book shows that the speed can be improved while the accuracy is acceptable for most purposes.

Many queuing networks models assume that certain random variables are independent and exponentially distributed. In modelling manufacturing systems, it is common to assume that the mean time to failure and the mean time to repair are independent and follow exponential distributions. Inman [11] assesses the validity of two common assumptions regarding the randomness in automobile manufacturing systems with actual data collected from automotive body welding lines.

PSA Aulnay factory, which is the source of the case study in this thesis, is introduced in [16]. This paper treats the improvements of throughput with minimal capital investment and no compromise in quality.

1.3 Thesis Outline

Chapter 2 investigates the relations between parameters in CPP for single product type, serial line manufacturing systems. Chapter 3 treats an extension of the research in Chapter 2 to multiple product types and presents some hybrid control policies in order to include more performance measures such as balancing performance. Chapter 4 studies substitution approaches in order to accelerate the speed of simulation while maintaining the accuracy. Chapter 5 introduces an automobile company case study. Various control policies are implemented in a simulation model of the factory.

Chapter 2

Parameters in the Control Point Policy For Single Part Type

This chapter has two purposes. The first is to study a method of getting optimal tradeoffs between performance measures in the Control Point Policy (CPP). The other is to interpret what the parameters of CPP actually mean. A simple serial line model with single part type is explored to study the effects of the parameters. Two different due date assignment schemes are used independently for comparison. The Simul8 discrete event based simulation package is used.

The assessment of the performance of a control policy is a very important issue. In previous research on CPP, it was common to investigate the tradeoff between service level and work in process (WIP). However, in this thesis, production rate is used instead of service level. By using production rate instead of service level, we can eliminate simulation parameters which are related to service level such as a customer arrival rate in the MTO environment. In addition, there is a strong positive correlation between production rate and service level.

2.1 Model Description and Assumption

2.1.1 Serial Line Model

Figure 2-1 shows the model that is studied in this chapter. The model consists of three identical but unsynchronized machines. The parameters of the machines and buffers are in

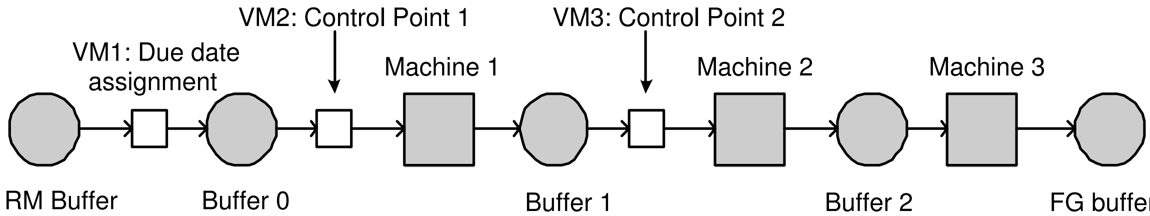

Figure 2-1: Serial Line Model

Table 2.1. There is no bottleneck in the system because of the symmetry. Often engineers try to balance the capacity of each machine in most factories, so it is reasonable to study such models that have no specific bottleneck. Note that a machine in Figure 2-1 can also represent a complex processing station.

Table 2.1: Machine Parameters

	M1	M2	M3
Processing Time	1	1	1
MTTR	10	10	10
MTTF	90	90	90

In addition, in order to provide variability, the processing time, failure time, and repair time follow the exponential distribution. The small squares in the model represent virtual machines (VM) for the implementation of CPP. These VMs have perfect reliability and zero or deterministic processing times. In particular, VM1's processing time is zero, so buffer 0 is full all the time. The rule to calculate the processing times of VMs other than VM1 is explained in the following subsections. There are five buffers in the model as follows.

- RM buffer – raw material buffer with unlimited capacity and never starved
- Buffer 0 – capacity of 50 parts waiting for the production
- Work in process buffers 1, 2 – capacities of 50 parts each
- FG buffer – finished goods buffer with unlimited capacity

2.1.2 Implementation of CPP

The implementation of the Control Point Policy can be done easily by introducing virtual machines. The first virtual machine assigns the due dates to the parts passing through. The second and the last virtual machines apply the hedging time logic to the parts. In addition, adding and removing control points at the system is equivalent to adding and removing virtual machines.

Hedging time logic The hedging time logic of the single part type CPP can be expressed in the following form.

1. Select the part in the buffer with the earliest due date.

2. Calculate the virtual machine processing time τ_{vm} for that part, where

$$\begin{aligned} \tau &= \text{Due date - Simulation running time - Hedging time} \\ \tau_{vm} &= \tfrac{|\tau|+\tau}{2} \end{aligned}$$

Proof If the part is ready, VM processing time is zero. Thus this part can pass through without delay. If the part is not ready, then just after the VM processing time calculated above, it becomes ready.

2.1.3 Due date Assignment Schemes

Due date assignment scheme 1 (DD1)

$$\text{Due date} = \text{Entry time} + \text{Expected cycle time}$$

An expected cycle time is one of the performance measures, but we should estimate it before running the simulation. Thus we can see the expected cycle time as an independent parameter to control, even though the name of this parameter implies something measured. From now on, expected cycle time is an independent parameter of this due date scheme. In a manufacturing system with this due date scheme, a part is assigned a due date that is not related to the state of the system if the expected cycle time is constant. Suppose the production is behind the target production by some random events. The system does not try to catch up the target production because the due date is not related to the state of the system, and the capacity is wasted as a result. On the other hand, we have control of the flow if the target production rate is less than the capacity of the system with this due date scheme. Parameters to optimize are hedging times and an expected cycle time. Note that cycle time in this thesis is called lead time in some literature, we use processing time to describe a single machine.

Due date assignment scheme 2 (DD2)

$$\text{Due date} = (\text{Takt time})(\text{Serial number} + \text{an offset})$$

Intuitively, this scheme is favorable in a situation in which explicit target production rate exists. As will be demonstrated, this scheme is much more robust in handling the random events in the system. In contrast to due date scheme 1, this scheme allows catching up with the target production rate, so less of the capacity is wasted. Parameters to optimize are hedging times and the takt time.

2.2 Design of Simulation Experiments

The purpose of this section is to present the design of the simulation experiments using the serial line model. First, the location and the number of control points are considered as follows.

1. Simulation with single control point (CP1) result
2. Simulation with single control point (CP2) result
3. Simulation with multiple control points (CP1,CP2) result

We can get useful insights about the CPP behavior by comparing the single control point simulation results to the results of multiple control points.

2.2.1 Single control point experiments with due date scheme 1

In the first group of simulation experiments, we activate only control point 1 with due date scheme 1. There are two parameters to tune: a hedging time for control point 1 and an expected cycle time for due date scheme 1. There are 10 sets of simulations in this group.

A set of simulations consists of 25 runs. Each set has different expected lead time values, and each run in a set has different hedging time values. See Table 2.2 and Table 2.3.

In the second group of simulation experiments, we activate only control point 2 with due date scheme 1. The design of the simulation experiments is the same as the first group except that we are using hedging times for control point 2 instead of hedging times for control point 1.

2.2.2 Single control point experiments with due date scheme 2

In the third group of simulation experiments, we activate only control point 1 with due date scheme 2. A takt time and an offset are the parameters to control as well as a hedging time. However, because the offset affects only the duration of the transient period of the system, we can fix it as a constant. Thus there are only two parameters to vary: a takt time and a hedging time. There are 10 sets of simulations in this group and each set consists of 25 runs. Each set has a different takt time, and each run has a different hedging time. These are summarized in Table 2.2 and Table 2.3.

For the experiments of control point 2 with due date scheme 2 as the last group of simulation experiments, the design is the same as the third group except that we are using hedging times for control point 2 instead of hedging times for control point 1.

Table 2.2: Design of simulation experiments: Parameters

Set number	1	2	3	4	5	6	7	8	9	10
Expected CT	0	20	40	60	80	100	120	140	160	180
Takt Time	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5

Table 2.3: Design of simulation experiments: Hedging times

Run number	1	2	3	4	5	6	7		···		21	22	23	24	25
Hedging times	0	10	20	30	40	50	60		···		200	210	220	230	240

2.2.3 Control Point 1 and 2 experiments

As we decide the values of hedging time 1 and hedging time 2, it is reasonable to assume that hedging time 1 is bigger than hedging time 2. Expected cycle time is used for each set of simulations as in Table 2.2 and 2.3 for the due date scheme 1. Similarly, takt time is used for each set of simulations as in Table 2.2 and 2.3 the due date scheme 2. Hedging times are assigned as in Table 2.4 in a set of simulations.

Table 2.4: Design of simulation experiments for Hedging times in Control Points 1 and 2

Run	1	2	3	4	5	6	7	8	9	10	11	12	13
HT1	20	40	40	40	60	60	60	80	80	80	80	100	100
HT2	10	10	20	30	10	30	50	10	30	50	70	10	30
Run	14	15	16	17	18	19	20	21	22	23	24	25	
HT1	100	100	100	120	120	120	120	120	120	140	140	140	
HT2	50	70	90	10	30	50	70	90	110	30	70	110	

2.3 Simulation Results

2.3.1 Statistical Validations

This section confirms that the results are statistically acceptable before the actual results of the sets of simulations are presented. The simulation duration of each run in a set is 1,000,000 minutes with warming up period 5,000 minutes. Table 2.5 to 2.10 gives important measures for the reliability of the data. The number of replications to get the confidence intervals is 250. Note that the C.I. ratio is defined as the ratio of the length of confidence interval (95% level) to the magnitude of the measure. For more information of confidence intervals, see [17].

Table 2.5: CP1 HT = 80, Due Date Scheme 1, Expected CT = 100

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.84	0.85	0.85	0.07
Cycle Time	123.79	124.05	124.32	0.21
Stdev of CT	29.69	29.82	29.96	0.45
WIP	49.67	49.92	50.18	0.50

Tables 2.5 - 2.8 show that lengths of confidence intervals are significantly small. The ratios of confidence intervals to the average of performance measures are less than 1%. Therefore, we can trust that the average values of these performance measures are in the

Table 2.6: CP1 HT = 80, Due Date Scheme 2, Takt = 1.25

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.80	0.80	0.80	0.01
Cycle Time	103.45	103.75	104.05	0.29
Stdev of CT	26.30	26.51	26.72	0.79
WIP	28.01	28.28	28.55	0.96

Table 2.7: CP2 HT = 80, Due Date Scheme 1, Expected CT = 100

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.84	0.85	0.85	0.07
Cycle Time	123.42	123.69	123.95	0.22
Stdev of CT	29.91	30.04	30.18	0.45
WIP	49.46	49.71	49.97	0.51

steady state of the system.

Tables 2.9 and 2.10 show statistical validations in situations of two control points. These tables give similar information as before, but they contain more information, including the confidence intervals of the standard deviations of the performance measures such as PR and WIP. For example, in Table 2.9, the confidence interval of the standard deviation of WIP is [1.48, 1.77] with confidence interval ratio 11.51%. The C.I. ratio seems rather high in this case, but the length of C.I. are small. This is acceptable because what we are interested in this chapter are the steady state behaviors of the average values of performance measures.

2.3.2 Control Point 1 Simulation Results

Figure 2-2 shows plots of the CP1 simulation results with due date scheme 1. In this figure, each small plot has a different expected cycle time parameter values from Table 2.2. Figure 2-3 shows the plots of all results in a single figure. In other words, all the plots in Figure 2-2 are aggregated in Figure 2-3.

In Figure 2-2, we can see that when expected cycle time is low, the hedging time parameter does not affect the steady state behavior of the system. Moreover, as expected cycle time increases, the the system gains more control over the tradeoff between the WIP and production rate. However, as shown in Figure 2-3, the set of simulations with the largest

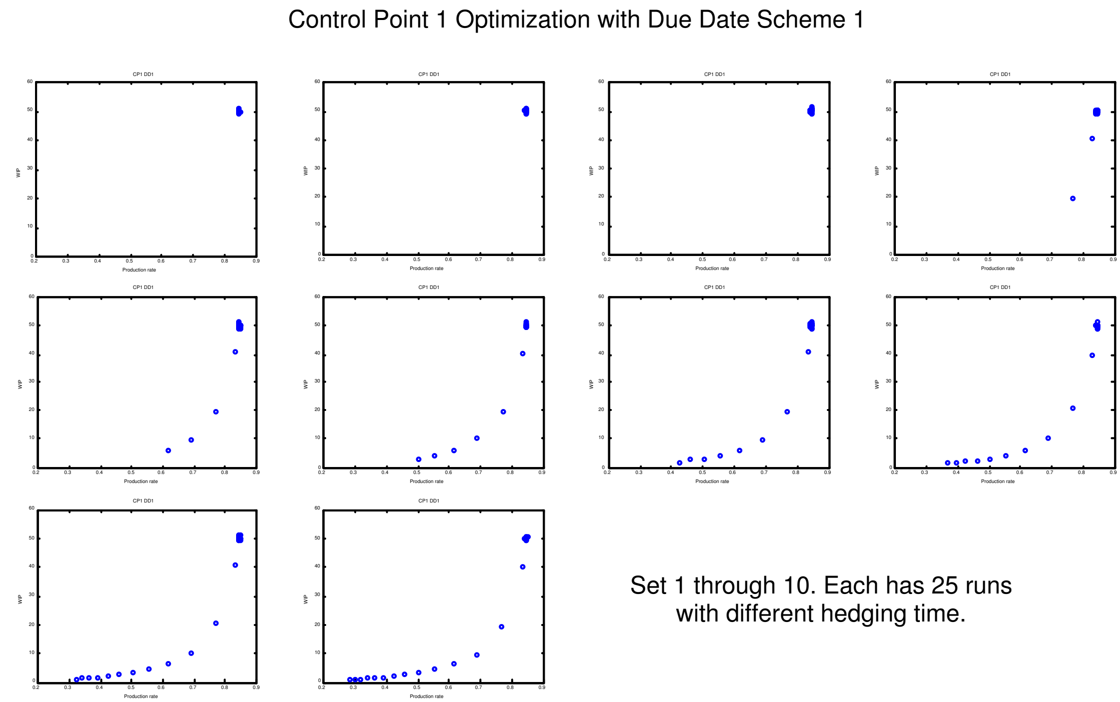

Figure 2-2: CP1, DD1, Each

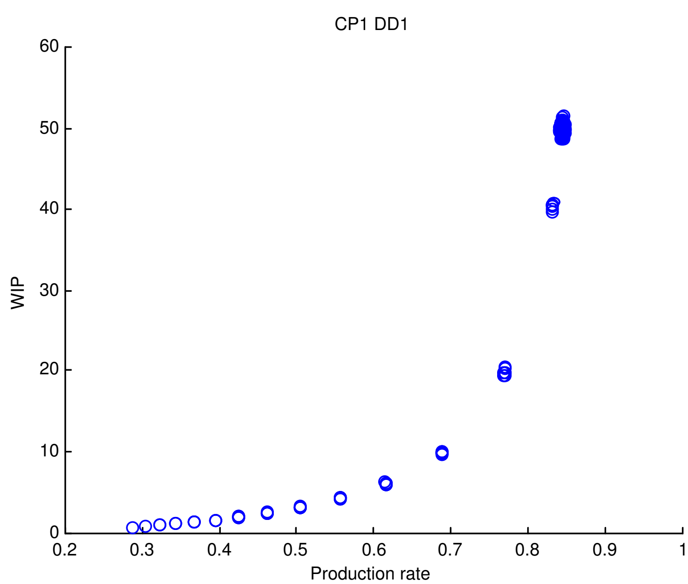

Figure 2-3: CP1, DD1, Total

Table 2.8: CP2 HT = 80, Due Date Scheme 2, Takt = 1.25

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.80	0.80	0.80	0.01
Cycle Time	130.82	131.00	131.17	0.13
Stdev of CT	25.55	25.69	25.84	0.57
WIP	49.87	50.09	50.31	0.44

Table 2.9: HT1 = 80, HT2 = 40, Due Date Scheme 1, Expected CT = 100

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.84	0.84	0.84	0.07
Stdev of PR	0.00	0.00	0.00	10.82
Cycle Time	125.26	125.52	125.78	0.21
Stdev of CT	29.55	29.68	29.81	0.45
WIP	49.87	50.11	50.36	0.49
Stdev of WIP	1.48	1.67	1.77	11.51
Buffer 1	28.99	29.11	29.23	0.42
Buffer 2	20.88	21.01	21.13	0.59
Stdev of Buffer 1	0.87	0.98	1.04	11.32
Stdev of Buffer 2	0.89	1.01	1.05	11.51

expected cycle time is a superset of all the other sets.

Figure 2-4 and 2-5 have similar structures as Figure 2-2 and 2-3. Figure 2-4 shows each plot of CP1 simulation results with due date scheme 2. In Figure 2-4, each small plot has a different takt time as in Table 2.2. Also, Figure 2-5 shows the plots of all results of Figure 2-4 in the same graph.

An important observation is that the hedging time parameter does not make any difference in the steady state behavior of the system in due date scheme 2. Only the takt time parameter affects the tradeoff between WIP and production rate. In this sense, we can say that the control policy with due date scheme 2 is less sensitive to the internal states of the system.

2.3.3 Control Point 2 Simulation Results

Figure 2-6 and 2-7 show the results for the group of simulations activating control point 2 with due date scheme 1. The structures of the figures are the same as previous section.

Similar to the results of CP1 with due date scheme 1, Figure 2-6 shows that when the

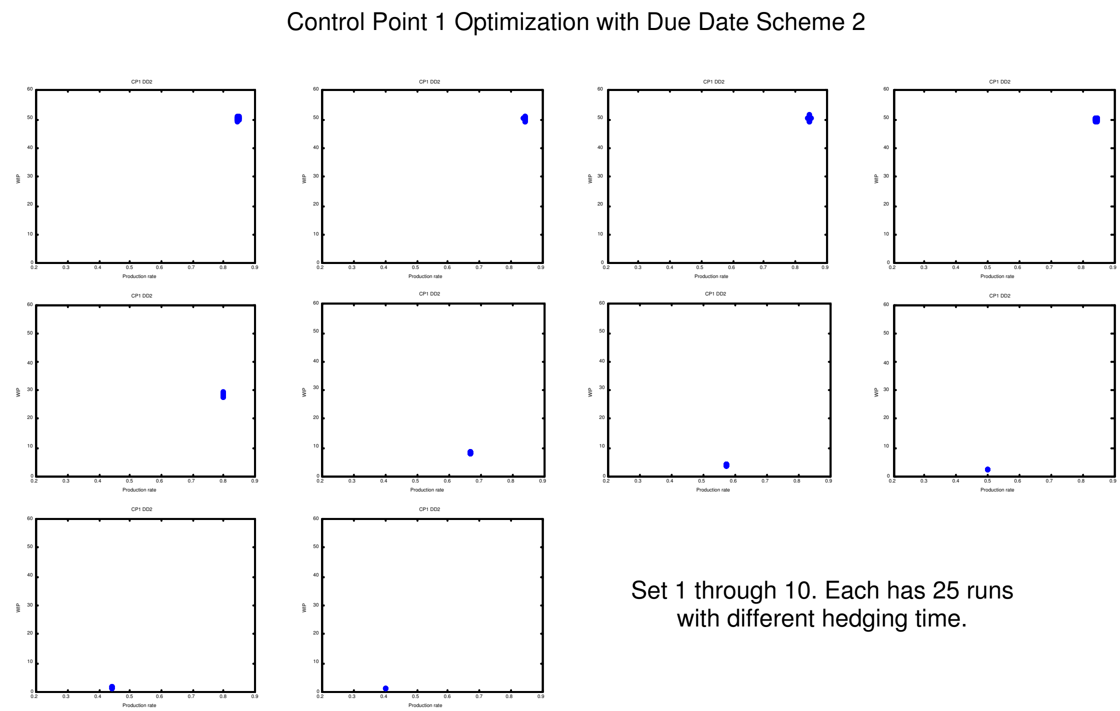

Figure 2-4: CP1, DD2, Each

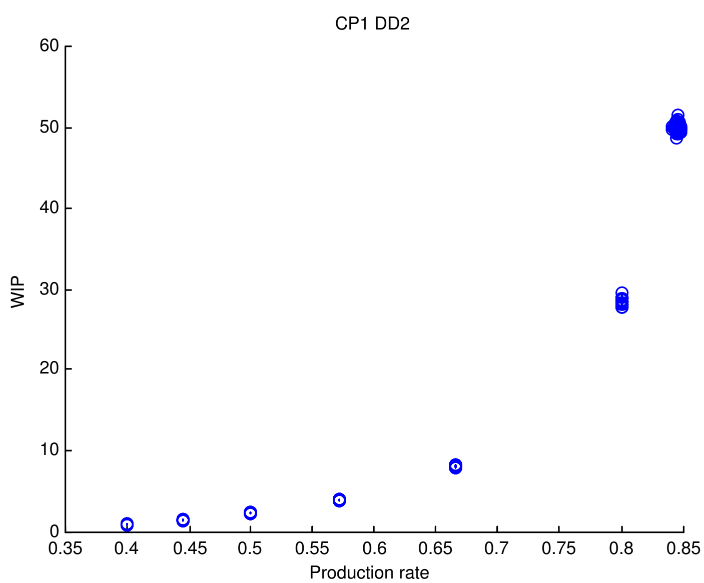

Figure 2-5: CP1, DD2, Total

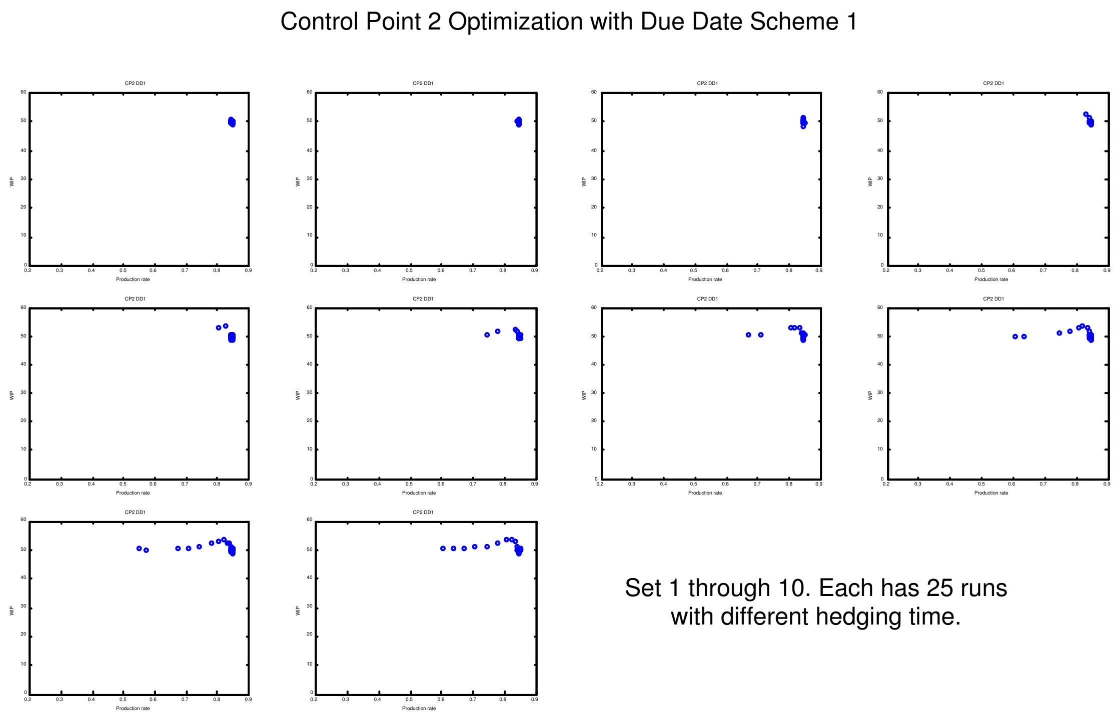

Figure 2-6: CP2, DD1, Each

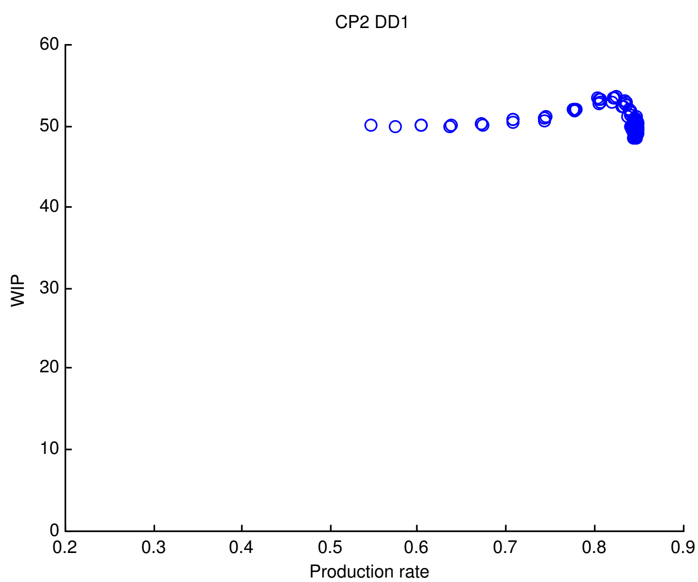

Figure 2-7: CP2, DD1, Total

Table 2.10: HT1 = 80, HT2 = 40, Due Date Scheme 2, Takt = 1.25

	95% Lower C.I.	Average	95% Upper C.I.	C.I. Ratio (%)
Production Rate	0.80	0.80	0.80	0.01
Stdev of PR	0.00	0.00	0.00	15.09
Cycle Time	121.50	121.70	121.90	0.17
Stdev of CT	24.46	24.63	24.80	0.68
WIP	41.54	41.73	41.93	0.47
Stdev of WIP	1.12	1.28	1.35	12.56
Buffer 1	28.99	29.08	29.17	0.30
Buffer 2	12.54	12.65	12.76	0.88
Stdev of Buffer 1	0.62	0.70	0.74	10.66
Stdev of Buffer 2	0.80	0.90	0.94	10.92

expected cycle time is low, the hedging time parameter does not affect the steady state behavior of the system. The system gains more control over the tradeoff between the WIP and production rate as the expected cycle time increases. Figure 2-7 shows that the set of simulations with the largest expected cycle time is a superset of all the other sets.

There is no tradeoff between the WIP and production rate in Figure 2-7. Rather, there exists explicitly the best WIP level and production rate, which is the rightmost point. The overshoot is because WIP is piling up in front of the control point, which prevents parts to pass due to the control logic.

Figure 2-8 shows each plot of CP2 simulation results with due date scheme 2. Figure 2-9 shows aggregated plots of all results in a single figure.

As in the previous section, hedging time parameter does not make any differences in the steady state behavior of the system with due date scheme 2. Only takt time parameter affects the tradeoff between WIP and production rate. Again due date scheme 2 seems more robust to the internal states of the system. In addition, there is no change in WIP as parameters vary in Figure 2-9. Thus there exists explicit optimal set of parameters which gives us the largest production rate.

2.3.4 Control Point 1 and 2 Simulation Results

Figure 2-10 and 2-11 show the results for the group of simulations activating both the control point 1 and control point 2 with due date scheme 1. The structures of the figures

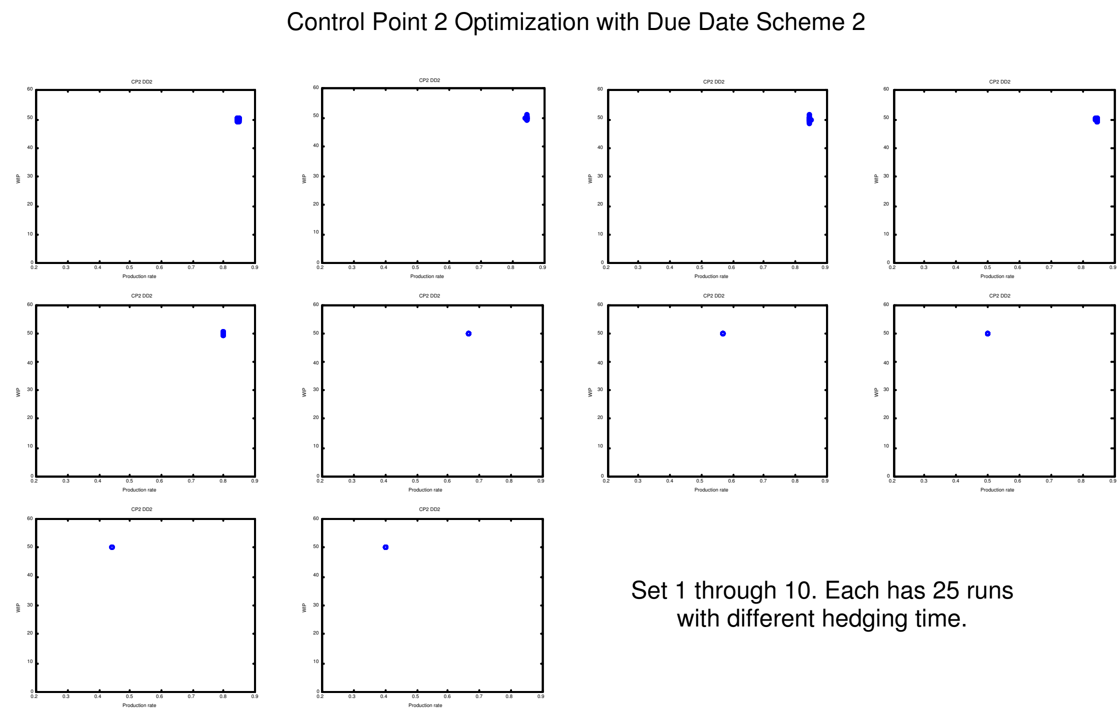

Figure 2-8: CP2, DD2, Each

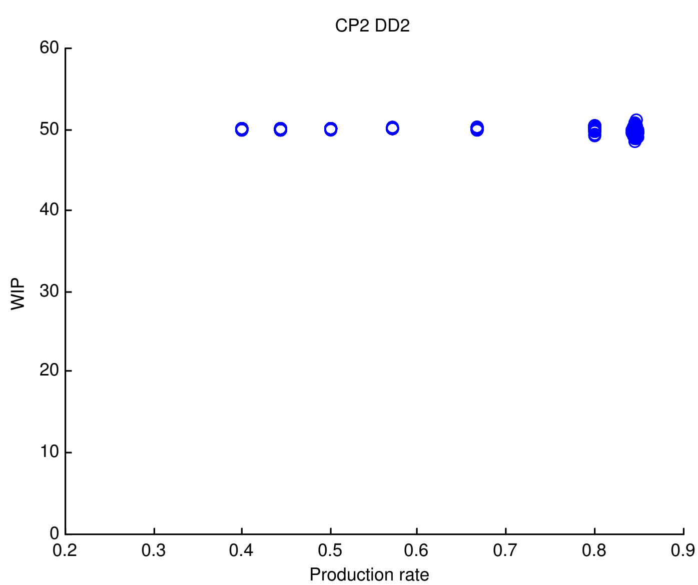

Figure 2-9: CP2, DD2, Total

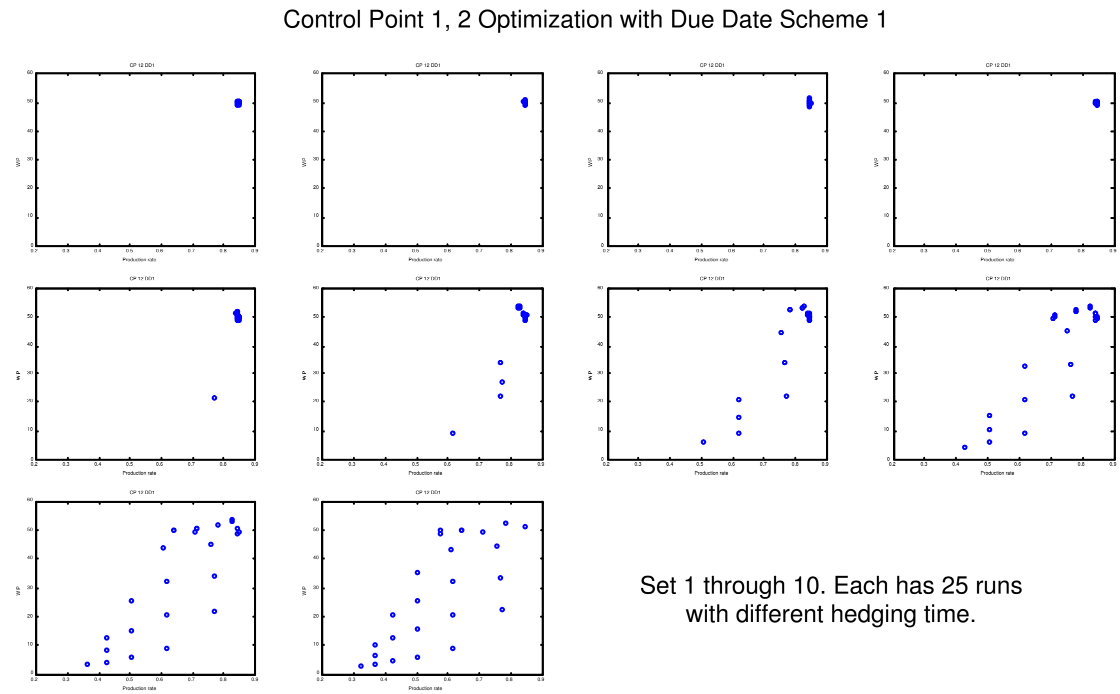

Figure 2-10: CP12, DD1, Each

are the same as in previous sections.

As we can see in Figure 2-10, when the expected cycle time is small, hedging times do not affect the behavior of the system. As the expected cycle time increases, the steady state behavior of the system has wider range of tradeoff between WIP and production rate. Furthermore, the scattered data is bounded with the boundary of the convex hull of the scattered data. We can separate the boundary into a concave part and a convex part. The relation of the convex boundary and the single control point results is suggested in the following section. Actually, it turns out that the convex part of the boundary is almost the same as the curve of the single control point cases.

In the sets using larger expected cycle times, what approximately determines the production rate is the hedging time of control point 1, while what determines the WIP level is the difference between the hedging times for the control points. As hedging time difference gets smaller, the lower WIP is observed. If the difference is big, the trajectory is similar to that of single control point 2 with due date scheme 1.

Figure 2-12 shows each plot of CP1 and CP2 simulation results with due date scheme 2. Figure 2-13 shows an aggregated plot of all results.

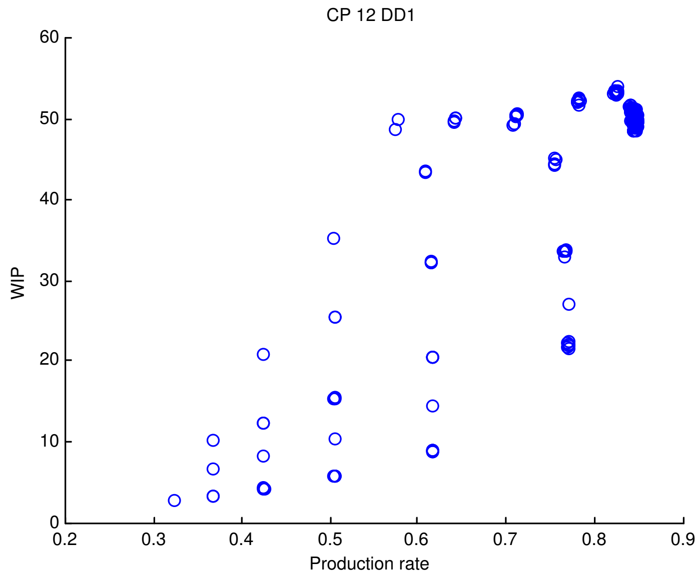

Figure 2-11: CP12, DD1, Total

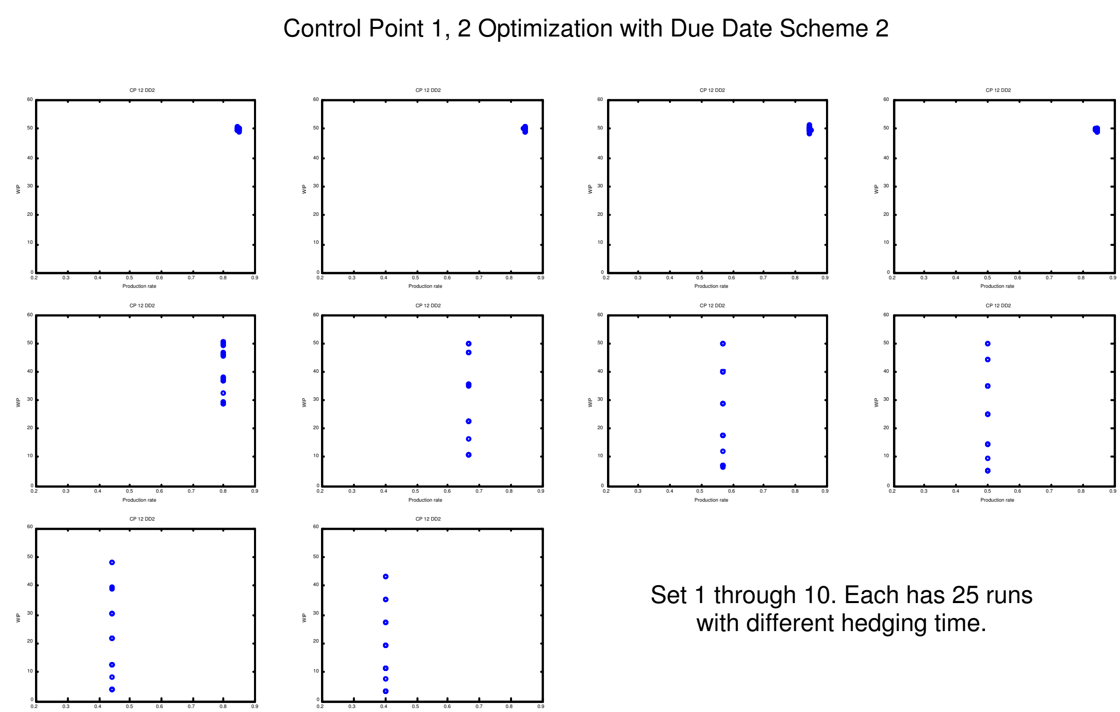

Figure 2-12: CP12, DD2, Each

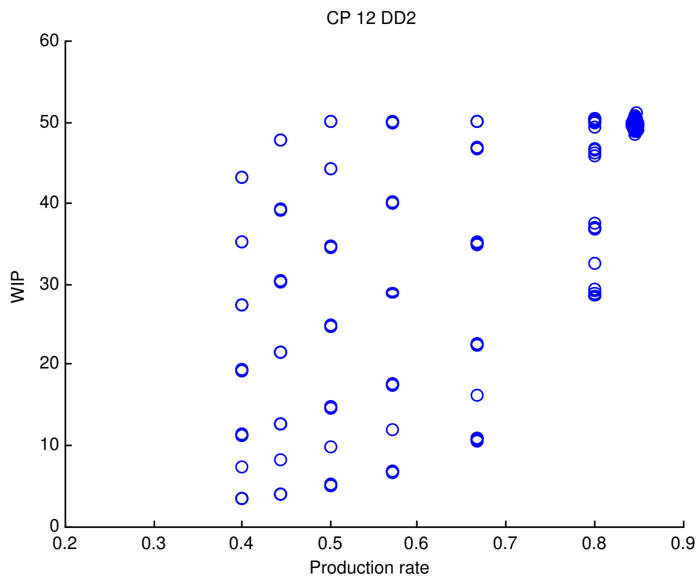

Figure 2-13: CP12, DD2, Total

In due date scheme 2 with both of the control points, the tendency is more explicit. The convex hull of the scattered data can be obtained, as in due date scheme 1, which turn out that the same shapes as single control point cases. What determines the production rate is takt time, while what determines the WIP level is the difference between the hedging times. The smaller the difference, the lower the WIP level. If the difference is big, then the trajectory is similar to that of single control point 2 with due date scheme 2.

2.4 Interpretations

In this section, the results of previous section are interpreted, and the due date schemes are analyzed and compared. This section is completed by representing insights from the simulation experiments of the Control Point Policy.

2.4.1 Criteria of a good policy

There are several requirements for a good control policy. Though the criteria of a good policy are restricted to single part type manufacturing systems in this chapter, the requirements below are quite general.

- **WIP-PR Tradeoff curve**

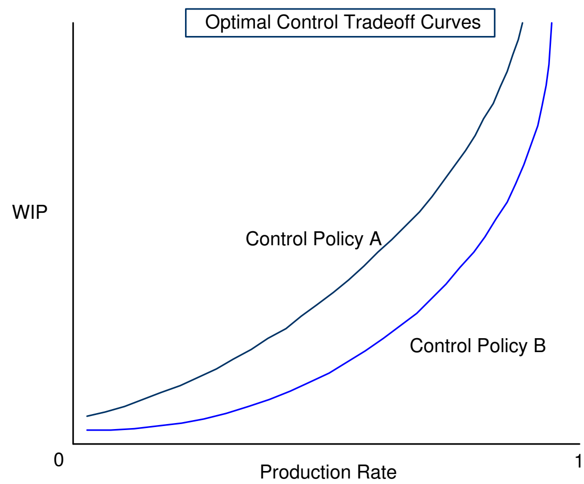

Figure 2-14: Two Different Policies

An optimal performance curve can be obtained by the boundary of convex hull of the data from many sets of simulations. For example, in Figure 2-11, we can get an approximately optimal curve from the convex part of the boundary of the convex hull.

Optimal performance curves of two different policies, which are operated with optimal parameter values, are shown in Figure 2-14. Control policy B is a better policy than control policy A because control policy B has lower level of inventory for each value of the production rate. Furthermore, the average queuing time in the system is lower in control policy B than control policy A from Little's Law ([6]).

- **Robustness and Sensitivity**

  The policy should be robust to the random events of the system. For example, if a machine failure occurs, a better policy will somehow compensate for the bad effects of the failure. On the other hand, a good policy should be sensitive to the parameters of the policy. For example, in the due date scheme 2 as Figure 2-5, the hedging time parameter has no role in the control policy. In this case, we can get rid of the hedging time parameter from the policy itself.

- **Ease of optimization**

  Generally, the optimization of a control policy is difficult and time-consuming. Even though a company uses a very fast simulation model of a manufacturing system, the number of simulation experiments to find the optimal set of parameters grows exponentially in the number of parameters. Therefore, to find the optimal parameters, the number of parameter should be small.

- **Ease of implementation**

  The implementation of the policy should be easy. For example, the implementation of multiple control points would be more complex than the implementation of a single control point. In principle, the implementation of control policy should not involve any actual change in the machines for ease of implementation of a control policy.

2.4.2 Capacity and target production rate

The capacity of the model can be obtained by running the simulation without any control logic. The capacity of the model is 0.85 parts/min, and at that capacity, the average WIP is 50. In due date scheme 1, expected cycle time determines the target production rate for the system. From the Little's law, low expected cycle time means higher production rate while keeping the average inventory constant. Also, in due date scheme 2, the takt time parameter directly determines the target production rate.

Intuitively, if the target production rate is greater than the capacity, then the system should be at its capacity point. In case of the simulation sets 1 through 4, where the expected cycle time and takt time are lower than or equal to 40 and 1 respectively, the target production rate is greater than the capacity. Therefore, as in Figures 2-2, 2-4, 2-6, 2-8, 2-10 and 2-12, the first four small plots just have one big aggregated point each, which is actually 25 points with different hedging time values.

As a conclusion, if the target production rate is greater than capacity, control logic becomes less useful. Note that this is not a disadvantage of that control policy. Rather, a bad control policy will remain effective and reduce the flow to less than capacity even though the target production rate is greater than the capacity.

2.4.3 Due date assignment scheme comparison

Figure 2-15 shows all the simulation results which makes use of only Control Point 1. In other words, it is a figure that Figures 2-3 and 2-5 are added. Similarly, Figure 2-16 shows all the simulation results of single control point 2 regardless of due date schemes. Therefore, it is a figure that Figures 2-7 and 2-9 are added. Finally, Figure 2-17 is for the simulation

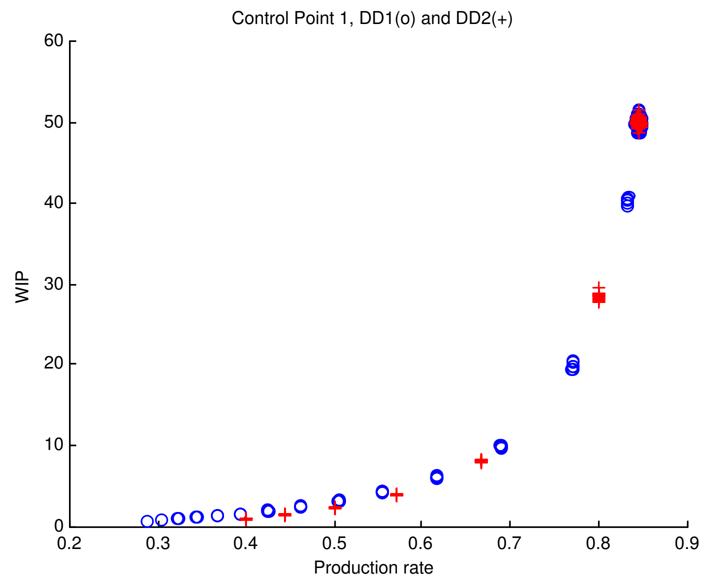

Figure 2-15: Control Point 1, Due date schemes 1 and 2

results of both control points utilization, which is a figure that Figures 2-11 and 2-13 are added. A circle is used for each data point from due date scheme 1, while a plus sign is used for each data point from due date scheme 2.

In Figure 2-15, the curve of due date scheme 2 is only slightly lower than, or almost the same as the curve of due date scheme 1. Therefore the first criterion of Section 2.4.1 cannot be applied. In terms of robustness, due date scheme 2 is better, because it is not affected by the hedging time parameters. Furthermore, there is no reason to keep a hedging time parameter as a parameter for the control policy because due date scheme 2 is not sensitive to the control parameter at all. Therefore, due date scheme 2 has only a single parameter that is a takt time parameter, while due date scheme 1 has a expected cycle time and hedging time parameters. Thus, due date scheme 2 is a better policy in terms of ease of optimization.

In Figure 2-16, the optimal parameter sets are explicit, and they are coincident with each other. Further, the optimal parameter set gives the same performance as when there is no control logic. In Figure 2-17, two results from each due date scheme share almost the same region. Therefore the abilities of two due date schemes with two control points are almost the same.

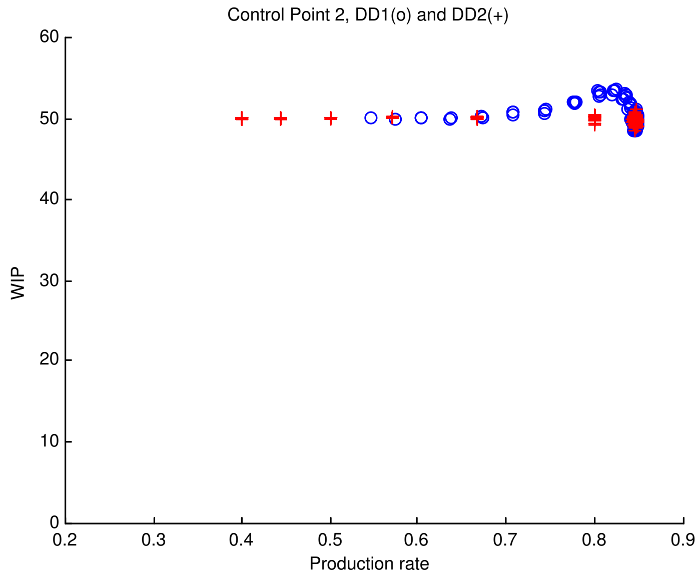

Figure 2-16: Control Point 2, Due date schemes 1 and 2

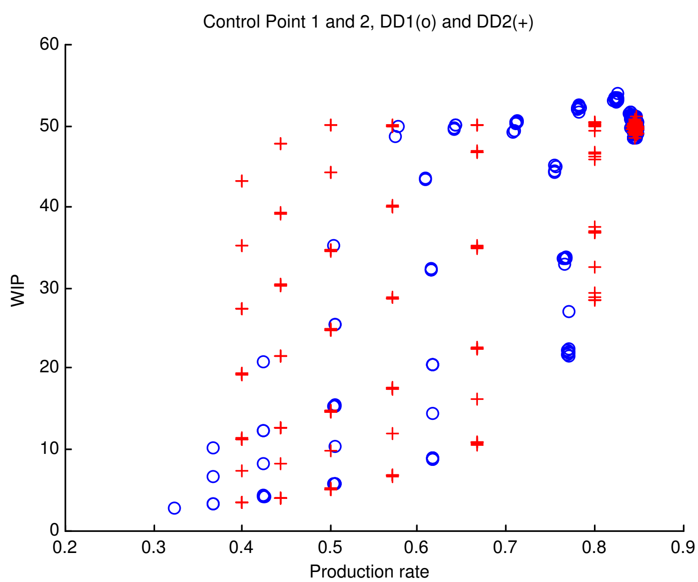

Figure 2-17: Control Point 1, 2, Due date schemes 1 and 2

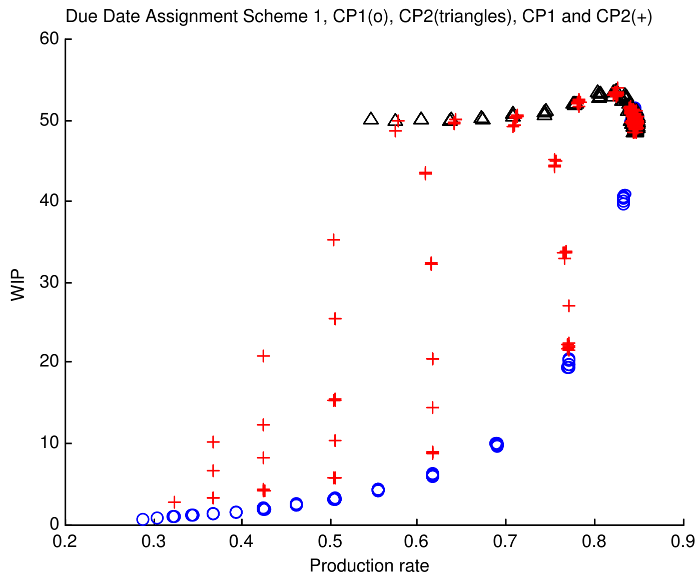

Figure 2-18: Due Date Scheme 1, all results

2.4.4 Control Point Locations and Policy Performance

Figure 2-18 aggregates all the simulation results done with due date scheme 1. In other words, it is a figure that Figures 2-3, 2-7, and 2-11 are added. Similarly, Figure 2-19 aggregates all the simulation results done with due date scheme 2. Thus Figure 2-19 is a figure that Figures 2-5, 2-9, and 2-13 are added. Control point 1 results are marked with circles, and control point 2 results are marked with triangles, while two-control-point results are marked with pluses.

As in the Figures 2-18 and 2-19, the results of control point 1 simulation experiments serve as a lower bound of the region covered by the results from both of the control points. At the same time, the results of control point 2 simulation experiments serve as a upper bound of the region covered by the results from two control points.

As a conclusion, the locations of control points are important. Furthermore, control point 1 is enough for the best performance of CPP implemented into the single part type, serial line manufacturing systems.

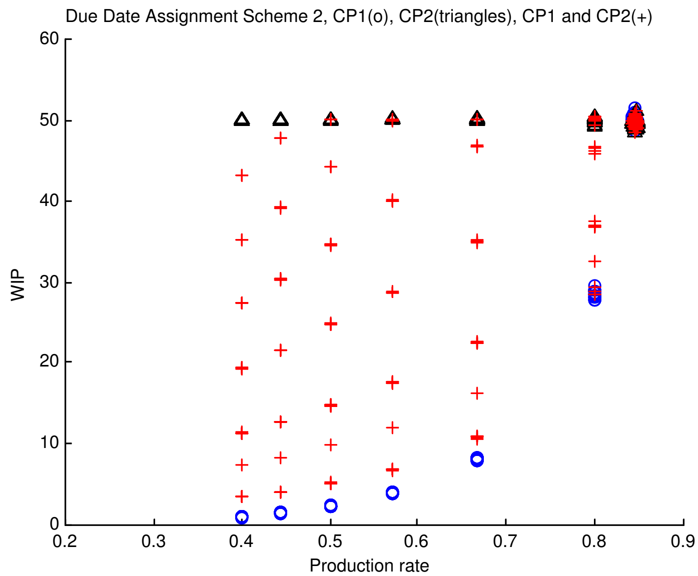

Figure 2-19: Due Date Scheme 2, all results

2.5 Conclusions and Insights

2.5.1 Summary

In this chapter, a single part type, serial line manufacturing system simulation model is developed and tested. The implementation of the Control Point Policy into a simulation is done easily by introducing virtual machines. Two different due date assignment schemes are explored. Each due date assignment scheme and the CPP control logic have parameters such as expected cycle time, takt time, and hedging times. Sets of simulations are designed and the results are collected. Confidence intervals for the results are obtained for several sets of simulations.

2.5.2 Conclusions and Insights

The following is the conclusions to this chapter. Note that the conclusions are confined to the single part type, serial line manufacturing systems.

- If the target production rate is higher than the capacity, a good control policy should behave like a simple push policy. The Control Point Policy has this property.
- In due date scheme 1 with a single control point, the hedging time logic affects the

steady state behavior of the system only when the target production rate is smaller than capacity.

- In due date scheme 2 with a single control point, hedging time has no meaning. Therefore we can modify the policy so that hedging time is no longer a parameter. Then the policy becomes easier to optimize.

- If both control points are activated, and the target production rate is less than the capacity, the difference between the hedging times affects the steady state behavior of the system. If the gap is small, then the behavior approaches that of the case in which only control point 1 is activated. On the other hand, if the gap is large, then the behavior approaches that of the case in which only control point 2 is activated.

- The location of control points is one of the most important factors that affects the performance of the control. Single control point 1 shows best performance than any other combination.

Finally, we can get some insights from the conclusions above.

- The hedging time parameter has its meaning only in some special cases.

- It is better to use only single control point. This provides the best performance, and it is easiest to optimize and implement.

- It is better to put the control point as far upstream as possible.

- Due date scheme 2 is potentially better in terms of robustness and ease of optimization, because we can have one fewer parameter.

Chapter 3

Comparison of control policies for two part types

In this chapter, a two part type manufacturing system is explored. In particular, each part type shares one resource which is a machine or a processing station. Various control policies are applied to this system, and compared. The goal of this chapter is to see the behaviors of this system. By using this system as an example, we can get useful and practical insights for lager scale multiple part type manufacturing systems.

The main performance measures are production rate, average level of work in process(WIP), and cycle time. In the multiple part type manufacturing environment, it is often important to balance the flows between two part types. For example, in some automobile manufacturing systems, there is no preference between models, and any model can not be less important because of marketing reasons. Therefore the degree of unbalance is included as one of performance measures. The definition of the degree of unbalance in this chapter is defined as

$$\frac{|Pr_A - Pr_B|}{Pr_A + Pr_B}$$

where Pr_A is the production rate of part type A, and Pr_B is the production rate of part type B.

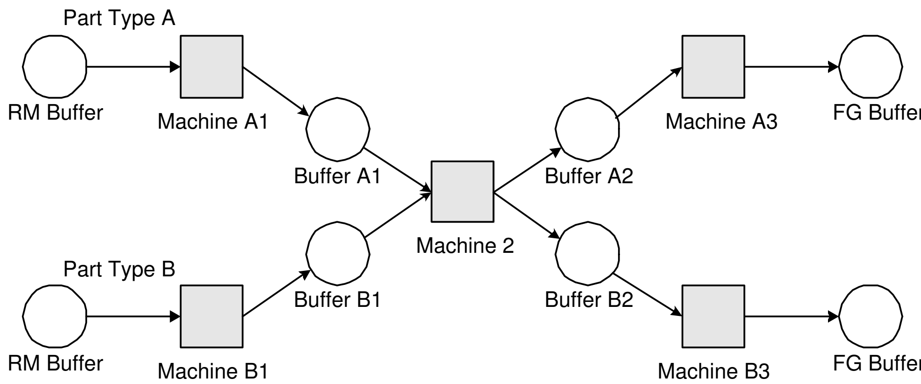

Figure 3-1: Multiple parts type manufacturing system

3.1 Model description

Figure 3-1 is the basic model that is investigated with several control policies. Table 3.1 shows the parameters of the machines in the model. Each processing time, MTTR, and MTTF follows an exponential distribution. RM buffers are raw material buffers and they are never starved by assumption. Also, FG buffers are finished goods buffers for each part type. FG buffers are never blocked. Every other buffer has finite capacity of 25.

Table 3.1: Machine Parameters

	M-A1	M-B1	M2	M-A3	M-B3
Processing Time	2	2	1	2	2
MTTR	10	10	10	10	10
MTTF	90	90	90	90	90

The machine 2 (M2) should make decision which part to load whenever both buffer A1 and buffer B1 are not empty, and buffer A2 and B2 are not full. The simplest rule is giving static priority to one part type. This chapter shows many alternative rules. It is assumed that part type A has higher priority if we use static priority.

3.1.1 BBS assumption

Blocking before service (BBS) assumption means that a machine loads a part only when the downstream buffers are not full. Therefore, if the downstream buffers are full, the machine remains idle. Blocking after service (BAS) assumption means that a machine loads a part whenever it is possible. Therefore, though downstream buffers are full, the machine loads a part into it, and holds it until a space is available in the downstream buffers.

In case of serial line manufacturing systems with single part type, BBS or BAS assumption is not so important, because the difference of the two assumptions is less than a change in the downstream buffer size by 1. However, in the multiple part type cases, the effect of BBS assumption is not clear. In this section, the effect of BBS assumption is presented.

See Figure 3-2. The production rates of part type A are the same regardless of whether we assume BBS or BAS. In other words, the production rate of the higher priority part type A is not affected by this assumption. However, the production rate of the lower priority part type B is severely affected by the BBS assumption.

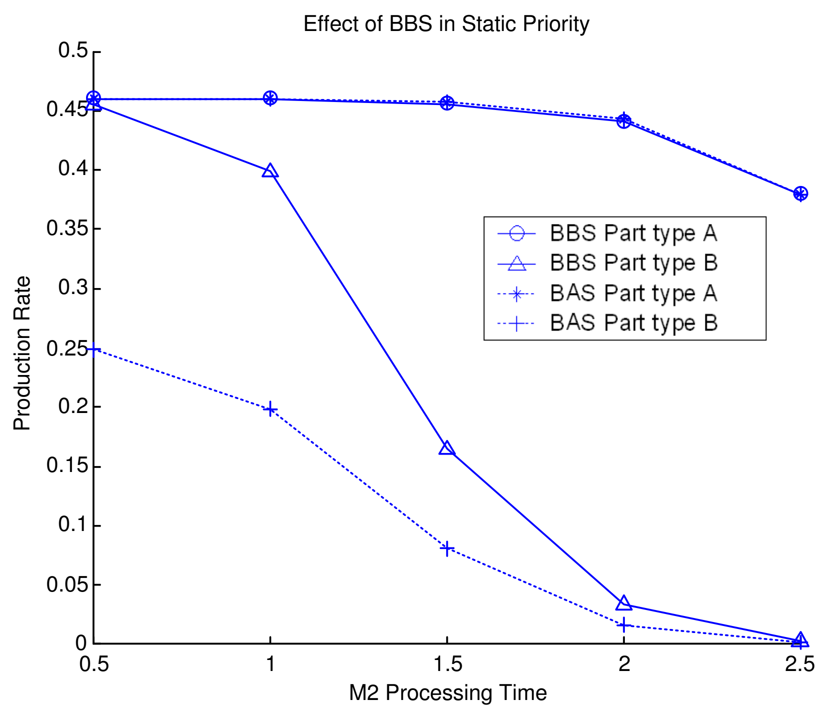

Figure 3-2: Effect of BBS assumption on Static Priority

This can be interpreted as follows. Assume BAS, and suppose that machine M-A2 is down. Then buffer A2 may become full. At the same time, if the buffer A1 is not empty, M2 will try to load a part of type A, even though part type A is blocked downstream. Moreover, the loading of a part of type A into M2 will block of the route of part type B, though part type B is not blocked downstream, and not starved upstream. This inappropriate blockage never happens the system with BBS control logic. Therefore, in the following simulations in this chapter, BBS logic is implemented in every model.

3.1.2 Static Priority Rule Results

Table 3.2 shows the simulation results of the basic model with the static priority rule. The data in this table will be the basic result to be compared throughout the chapter. Note that the C.I. ratio means the ratio of the length of confidence interval (95% level) to the magnitude of the measure.

The production rate of part type A is higher because the higher priority is given to part type A. The total production rate is about 0.860 parts/minute, and the degree of unbalance in production is about 7%.

Table 3.2: Static Priority Results

	Average	C.I. ratio(%)
Production Rate A	0.459	0.19
Production Rate B	0.399	0.35
Cycle Time A (min)	59.807	1.90
Cycle Time B (min)	67.988	0.76
Buffer A1	8.041	3.38
Buffer B1	15.582	0.81
Buffer A2	16.917	1.51
Buffer B2	9.236	1.26
Buffer A	24.958	2.11
Buffer B	24.818	0.97
Unbalance(%)	7.012	3.21

3.2 Earliest Due Date Policy

In this section, the model in Figure 3-1 will be operated with Earliest Due Date Policy.

3.2.1 EDD implementation

There are two virtual machines required to implement EDD policy, and these virtual machines assign due dates. Machine 2 selects a part with earliest due date in buffer A1 and

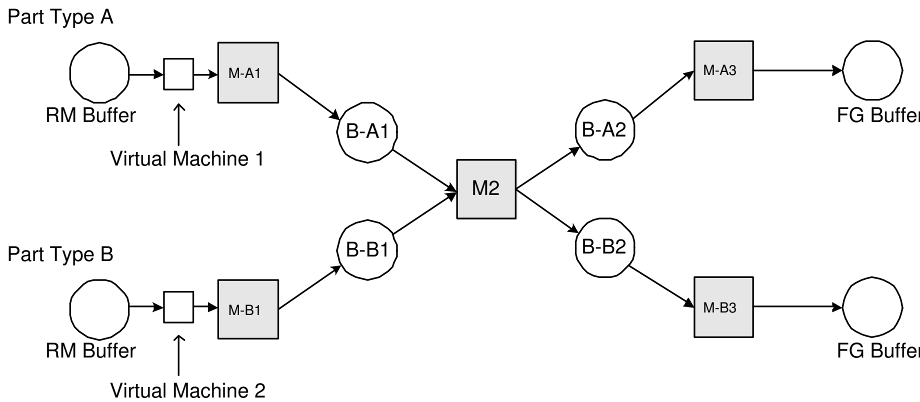

Figure 3-3: Earliest Due Date Policy applied to the model

buffer B1. Each virtual machine has zero processing time. The EDD policy gives priority to the part type that has the earliest due date. Note that the EDD policy is involved only when both of the two part types are available.

There are two ways to assign due dates. One is that due date = entry time + expected cycle time (due date scheme1). Because the control logic just compares due dates in EDD policy, we may set the expected cycle time any value. The other due date assignment scheme is using the takt time (due date scheme2). Due date = takt · (number of each part type produced + offset). The number of parts passed the entry of the system is counted independently for each part type. In addition, the takt time can be set to 1 without loss of generality in the EDD policy, because EDD compares the due dates between different part types, and takt is just a scaling factor of due dates in this policy. In addition, it is safe to set the offset to any constant in this due date assignment scheme.

3.2.2 EDD results

Table 3.3 shows the results of EDD with due date scheme 1. Table 3.4 shows the results of EDD with due date scheme 2. The total production rates are about 0.870 in both due date schemes, and 0.870 is only slightly higher than the total production rate of static priority simulation. However, the balance is improved significantly.

As shown in the tables, the performances of two due date schemes are very similar. Thus we can conclude that how the due date is assigned is not important, provided that the due date is assigned fairly between the two part types. From now on, EDD will be simulated only with due date scheme 2 (DD2) which makes use of the takt time.

Table 3.3: EDD with due date scheme 1 results

	Average	C.I. ratio(%)
Production Rate A	0.436	0.21
Production Rate B	0.436	0.20
Cycle Time A	68.905	1.01
Cycle Time B	68.655	0.87
Buffer A1	15.801	1.09
Buffer B1	15.763	1.03
Buffer A2	10.809	1.89
Buffer B2	10.734	1.63
Buffer A	26.611	1.41
Buffer B	26.497	1.28
Unbalance(%)	0.247	27.04

Table 3.4: EDD with due date scheme 2 results

	Average	C.I ratio(%)
Production Rate A	0.435	0.16
Production Rate B	0.435	0.16
Cycle Time A	65.215	1.19
Cycle Time B	65.006	1.05
Buffer A1	14.756	1.60
Buffer B1	14.701	1.38
Buffer A2	10.206	2.14
Buffer B2	10.170	1.88
Buffer A	24.962	1.82
Buffer B	24.871	1.58
Unbalance(%)	0.025	36.59

3.3 Constant Work In Process Policy: CONWIP

In this section, the CONWIP policy is experimented on to control multiple part type manufacturing systems.

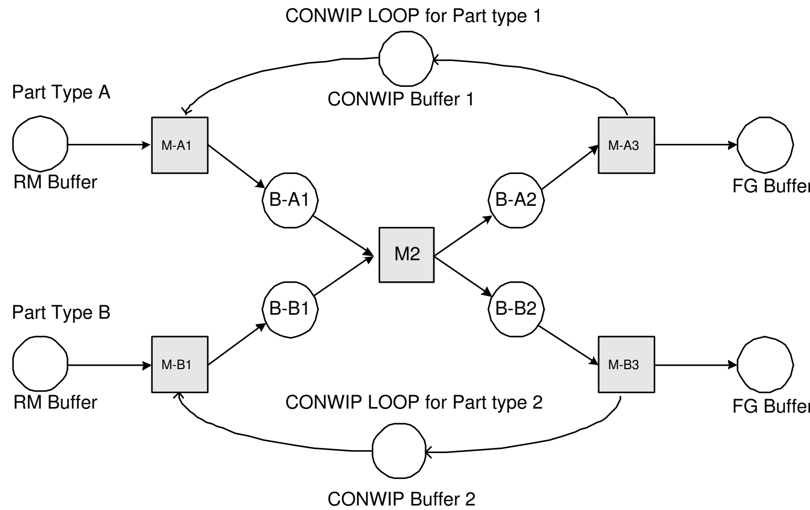

Figure 3-4: CONWIP Policy applied to the model

3.3.1 CONWIP Implementation

Two independent CONWIP loops for each part type are applied to the model. Figure 3-4 shows the model with the CONWIP policy. Each CONWIP loop has two parameters: the invariant and the size of CONWIP buffer. Here, we assume that the size of CONWIP buffer is infinite, or bigger than the invariant. Because balance is also an important performance measure, we set the invariants to be equal. Therefore, this policy has only one actual parameter.

Even though the model makes use of CONWIP loops to regulate flows, a part selection scheme must exist at M2. Thus, the following sections give the results of CONWIP with the static priority scheme and CONWIP with EDD.

3.3.2 CONWIP with Static Priority Results

This section shows the results of CONWIP policy experiment with the static priority rule. Figures 3-5 and 3-6 show various tradeoffs between performance measures. The PR vs. invariant graph in Figure 3-5 shows that production rates are increasing as the invariant increases. The shape of the degree of unbalance graph seems unusual, because the difference between maximum and minimum unbalance is small. Generally, part type B has a longer cycle time and a larger buffer level while it has a lower production rate. However, the B2 buffer level is lower than that of buffer A2, because levels of buffer A2 and B2 are directly

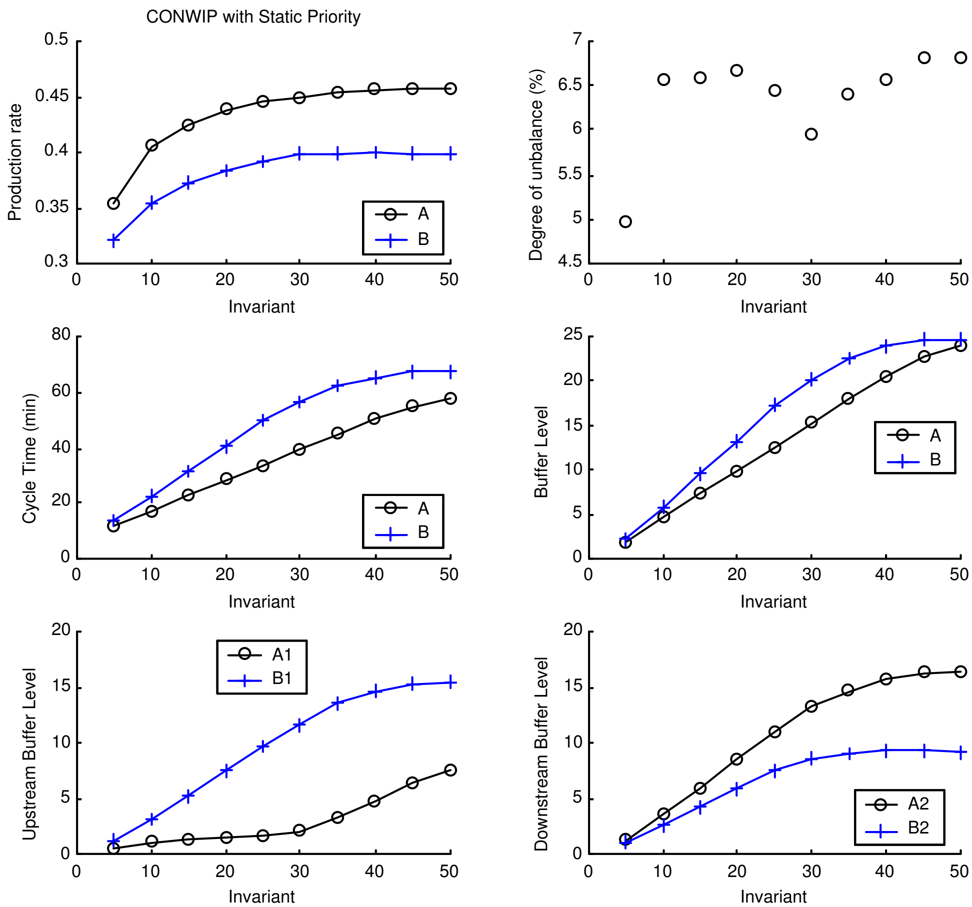

Figure 3-5: CONWIP Policy with Static Priority to Part type A

related to the production rates.

3.3.3 CONWIP with EDD (using DD2) Results

This section presents the results of the CONWIP policy with EDD using due date scheme 2 (DD2). Figures 3-7 and 3-8 show the results. Though not shown here, the results of CONWIP with EDD using DD1 are essentially the same.

Everything is symmetric between part type A and B in the results. The shape of the degree of unbalance seems scattered, but it is because the difference between maximum and minimum unbalance is small. This policy has an advantage in that the situation is symmetric between part types and we have control over the production rate. For example,

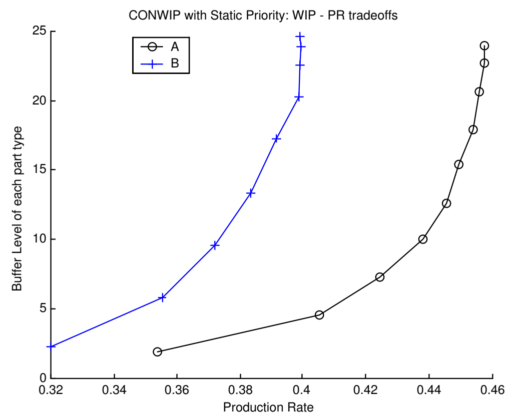

Figure 3-6: CONWIP Policy with Static Priority WIP-PR tradeoff curve

as in section 3.2, EDD can balance production between part types, but EDD alone has no control over production rate. In other words, this CONWIP–EDD policy gives us a typical WIP–PR tradeoff curve. By using this WIP–PR tradeoff curve, we can do cost–profit optimization with inventory costs and sales profit.

3.4 Control Point Policy with two part types and static priority

The Control Point Policy was originally developed for controlling multiple part-type manufacturing systems with complex routings including reentrant loops. In this section, the two part type CPP with static priority is explored.

3.4.1 CPP implementation

Figure 3-9 shows the model with CPP. Parameters of CPP for the systems with multiple part types are static buffer priority, hedging times, buffer sizes, due date assignment schemes, and locations of control points. In this model, it is assumed that the buffer sizes are fixed.

There are two kinds of due date assignment schemes as we have seen in the previous chapter. From the insights of that chapter, due date scheme 2 is easier to optimize because it has less parameters, but it still gives the best WIP-PR tradeoff curve. In other words, if the due date scheme 2 is used, it does not need to consider the hedging time values. Therefore, hedging times can be set to any constant without affecting the results. The due date

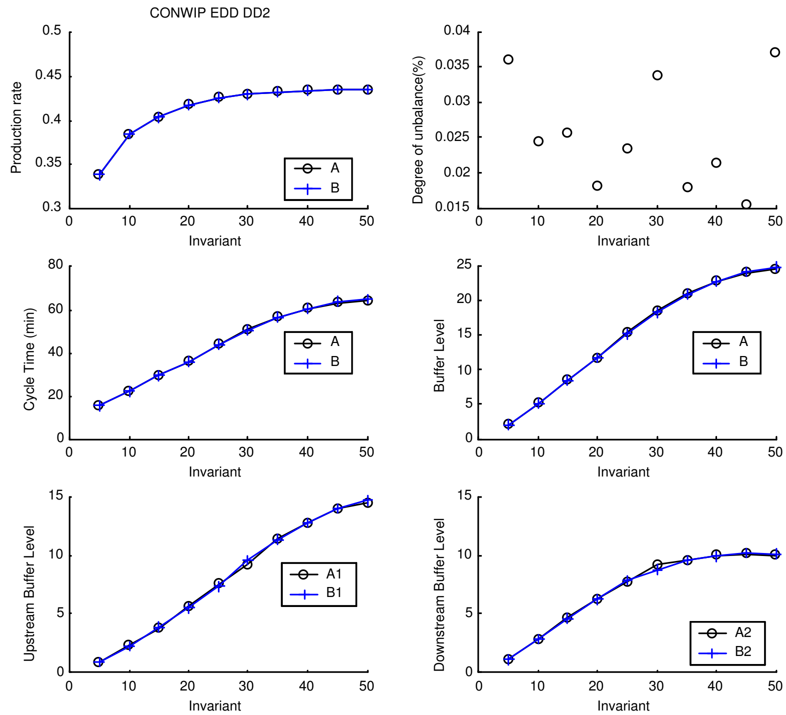

Figure 3-7: CONWIP Policy with EDD using DD2

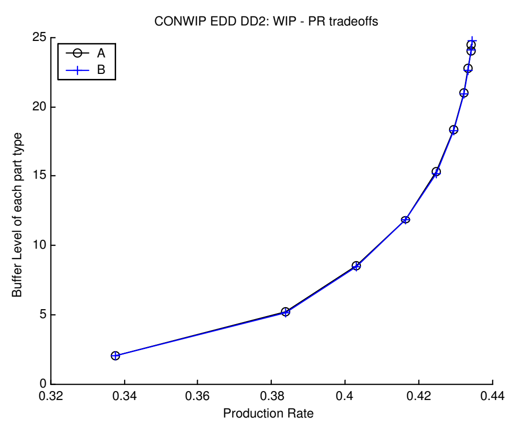

Figure 3-8: CONWIP Policy with EDD using DD2 WIP-PR tradeoff curve

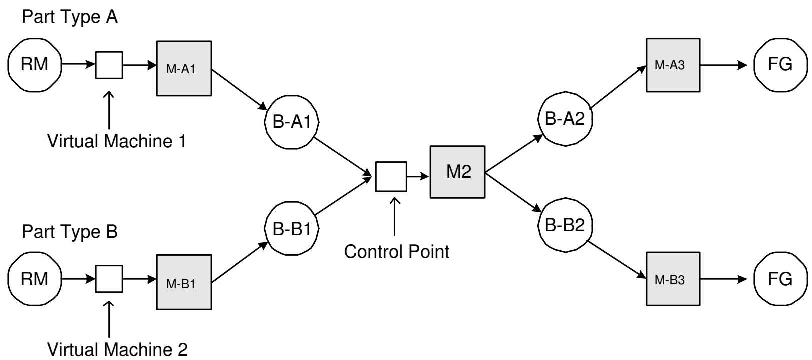

Figure 3-9: Control Point Policy applied to the model

scheme 2 says that due date = takt·(serial number of that part type + offset). Here, offset is simply set to a constant, because it does not affect the steady state behavior of the system.

The control logic is as follows. A part is *available* if it is not blocked in the downstream. A part is *ready* among available parts, if

$$\text{Current Time} + \text{Hedging Time} \geq \text{Due Date}$$

Then, the Control Point Policy says

1. Look at buffer B-A1. If there is any ready part, load it into M2. (If there are multiple ready parts, select a part by the FIFO rule.)

2. If not, then look at B-B1. If there is any ready part, then load it into M2.

3. Otherwise, let M2 be idle until there is a ready part in B-A1 or B-A2.

Note that the term *due date* is slightly generalized. A due date is an indicator related to the M2 passing time in this policy, because we can set the hedging time to any arbitrary value without affecting the steady state response of the system. Also, a static buffer priority is given to part type A, as we can see in the logic above.

Practical implementation of CPP logic In the original CPP statement in [8], there is a simple guideline how long we should wait for next CPP logic to be checked, and the decision is made by some calculation. There are two alternatives. One is to make the waiting time reasonable small, and then to regularly check the availability and readiness of parts.

The other is to make use of reliable virtual machines, and to assign their processing times some meaningful values. After the processing in the virtual machines, the parts become ready. The method with virtual machines is more intuitive and easier to implement.

3.4.2 Two part type CPP with DD2 and Static Priority results

Figures 3-10 and 3-11 show the results of the CPP with static priority. When the takt time is less than 2.2 minutes, the target production rate is greater than the capacity of the system, so CPP concentrates on the production of higher priority part type A. Therefore the production rate of part type A attains its maximum, which is the capacity of the processing line A (M-A1 – B-A1 – M2 – B-A2 – M-A3). Note that the capacity of the processing line A is around 0.46 parts/min from Table 3.2, and the production rate of part type A from Figure 3-10 is also around 0.46 parts/min if the takt time is less then 2.2 minutes. The system shows the same behavior, whenever the target production rate is higher than the capacity, or the takt time is less than a specific value related to the system capacity.

On the other hand, if the takt time is large enough, so that the target production rate is lower than the system capacity, then the production is balanced even though CPP uses the static buffer priority. Thus, if we run the manufacturing systems below the capacity limitation, CPP gives quite favorable results in terms of balance.

One thing to note is that the total buffer level is always the same. Thus, Figure 3-11 shows no tradeoff between PR and WIP, though CPP has a control over the production rate. Thus this results motivates hybrid of CPP and CONWIP in order to have a control over the total buffer level as well.

3.5 Control Point Policy with two single part type control points: Hybrid CPP/EDD

From the insights of the previous chapter, it is essential for the performance of a manufacturing system to locate control points as far upstream as possible. Generally, in the original multiple part type CPP, control points are located at locations into where two or more flows are merging. The only such location is M2, and by selecting M2 as a control point, we lose

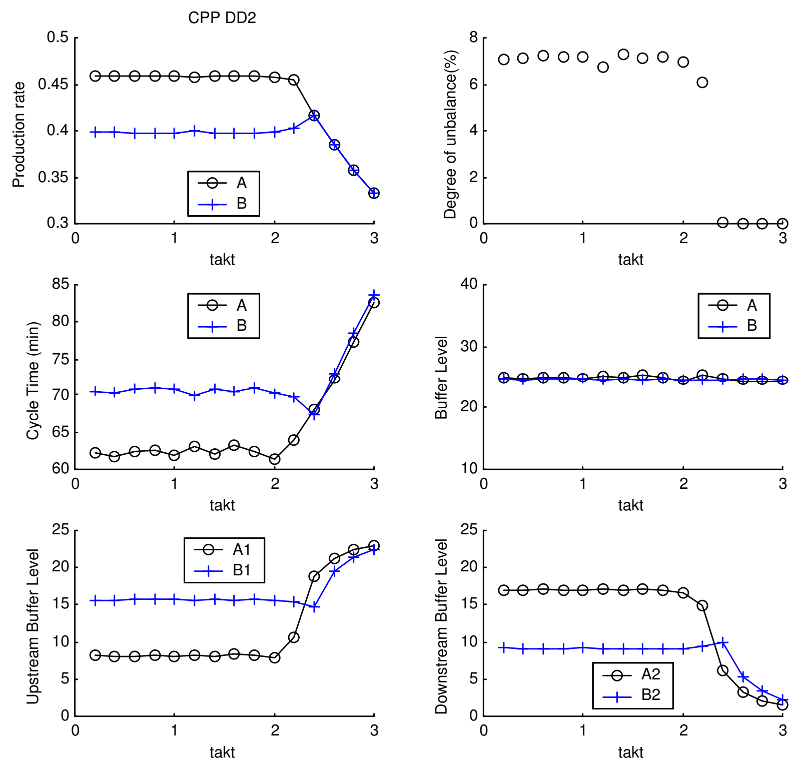

Figure 3-10: Control Point Policy with DD2 and Static Priority

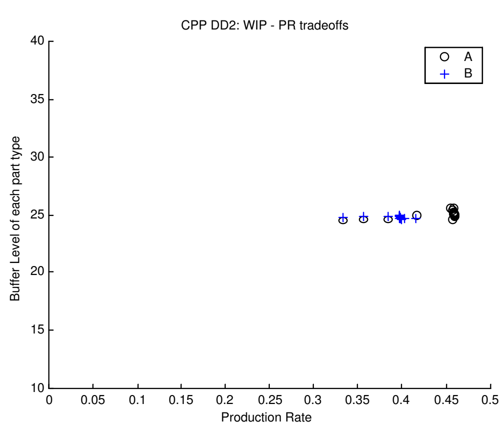

Figure 3-11: Control Point Policy with DD2, SP; WIP-PR tradeoff curve

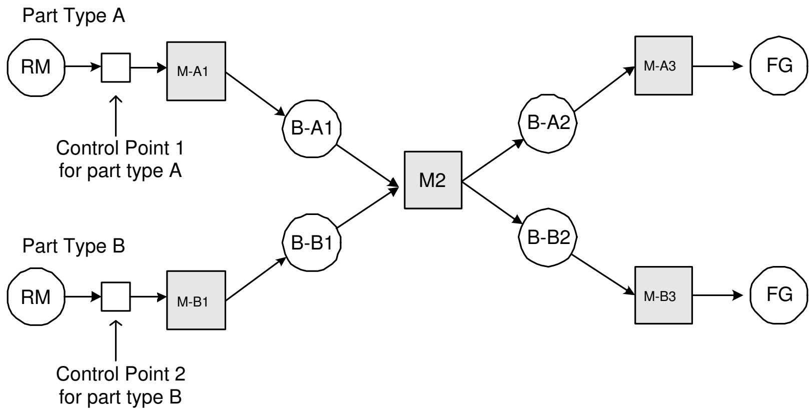

Figure 3-12: Modified Control Point Policy applied to the model

controls of the buffers B-A1, B-A2. Therefore, a slightly modified CPP is applied to the system in this section.

3.5.1 Hybrid CPP/EDD implementation

This section studies the use of two control points which are for different part types, and are located as far upstream as possible. See Figure 3-12. One more advantage of due date assignment scheme 2 is that, because the due date is not related to the entry time, the due date assignment and the control logic can be implemented at the same virtual machines. Therefore, in Figure 3-12, a control point assigns a due date to a part, and then it applies the control logic to regulate the flow. The modified logic is as follows.

A part is *available* if it is not blocked in the downstream. A part is *ready* among available parts, if

$$\text{Current Time} + \text{Hedging Time} \geq \text{takt} \cdot (\text{Serial number} + \text{Offset})$$

Note that hedging time and offset does not affect the steady state results of the system. Thus they can be set to arbitrary constants if we use due date scheme 2.

Practical implementation of CPP logic into simulation Similarly, if we make use of reliable virtual machines with appropriately assigned processing times, the implementation of CPP becomes easier.

3.5.2 Hybrid CPP/EDD results

See Figures 3-13 and 3-14. In contrast to section 3.4.2, even if the takt time is small or the target production rate is large, the production is perfectly symmetric. The system is fully utilized, because the system behaviors are not changed when the takt time is smaller than a specific value.

When the takt time is large or the target production rate is smaller than the capacity, the production rate behavior is also in symmetric, and we have control over the performance measures. Figure 3-14 shows tradeoff between PR and WIP, which we cannot see in Figure 3-11. Thus, under the same takt time or target production rate, hybrid CPP/EDD shows better performance than CPP with static priority. Note that this better performance of CPP/EDD should be interpreted only with our current performance measures. For example, if the balance ratio is changed to other than 1, we cannot say anything from our observations. In addition, we may try CPP with static priority at all three points to see better performance of CPP with static priority.

3.6 Hybrid CPP/CONWIP

In attempts to get the most benefit out of CPP and CONWIP, hybrids of the two are presented and simulated in this section.

3.6.1 Hybrid CPP/CONWIP Implementation

Figure 3-15 shows the structure of a hybrid policy. There are two kinds of hybrid policy. One is using CPP with static priority, and the other is using CPP with dynamic priority. The main advantage of using this hybrid is that we can eliminate or compensate for the bad effects of the static buffer priority rule. In other words, we can implement CPP with dynamic buffer priority with help of CONWIP loops. In addition, we can have control over the buffers in the system.

Hybrid CPP/CONWIP Logic

1. **Dynamic Priority**

   There are three candidates for the dynamic priority assignment scheme.

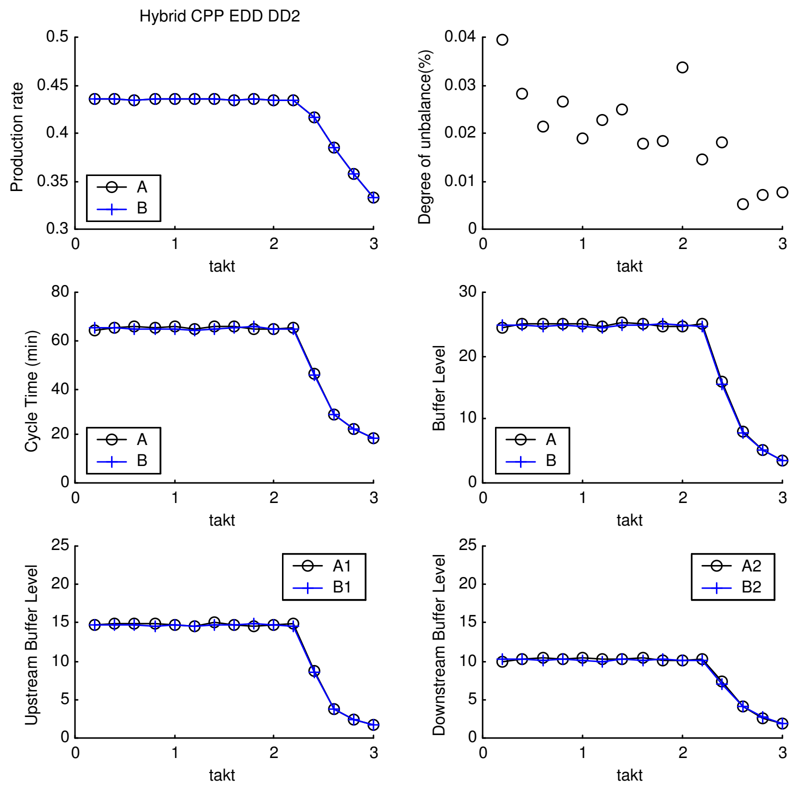

Figure 3-13: Control Point Policy with EDD (DD2)

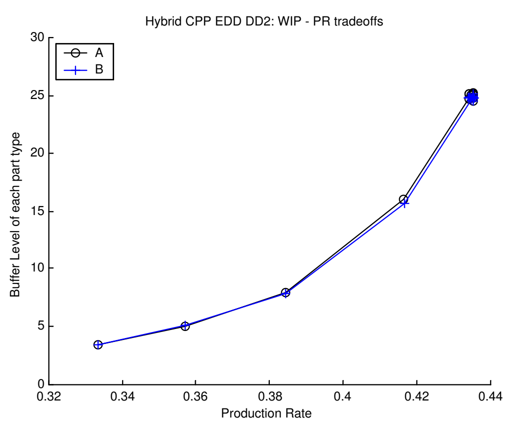

Figure 3-14: Control Point Policy with EDD (DD2); WIP-PR tradeoff curve

- Compare the levels of B-A2 and B-B2. The part type with lower buffer level has higher priority. If equal, give priority to part type A. The rationale is to minimize the probabilities of starvation for the machines M-A3 and M-B3.

- Compare the levels of B-A1 and B-B1. The part type with higher buffer level has higher priority. If equal, give priority to part type A. The rationale is to minimize the probabilities of blockage for the machines M-A1 and M-B1.

- Compare the levels of CONWIP buffers 1 and 2. The part type with higher buffer level has higher priority. If equal, give priority to part type A. The rationale is to balance the number of parts in the system.

In this section the dynamic priority is assigned by comparing the levels of B-A2 and B-B2 (the first candidate).

2. **Control Logic**

   The following logic can be applied to both of static and dynamic priority rules, once priority is set before loading a part into M2.

   - First look at the higher priority buffer between B-A1 and B-B1. If there is any ready part, load it into M2.
   - If not, look at the other buffer. Load a ready part into M2, if any.
   - Else, wait for a while.

Simpler Dynamic Priority Schemes There can be simpler dynamic priority schemes. For example, priority can be given to the part type such that the cumulative production up to that moment is smaller. However, with this scheme, we have no control over buffers B-A1 and B-B1. In addition, by some random events, once the gap becomes huge, it will behave like static priority scheme. Thus, in some sense, it is less dynamic.

3.6.2 Hybrid CPP/CONWIP results

Figures 3-16 to 3-19 are for the results of hybrid control policy with the static priority scheme, and Figures 3-20 to 3-23 are for the results of hybrid control policy with the dynamic priority scheme. When takt = 1.4, the target production rate is higher than the

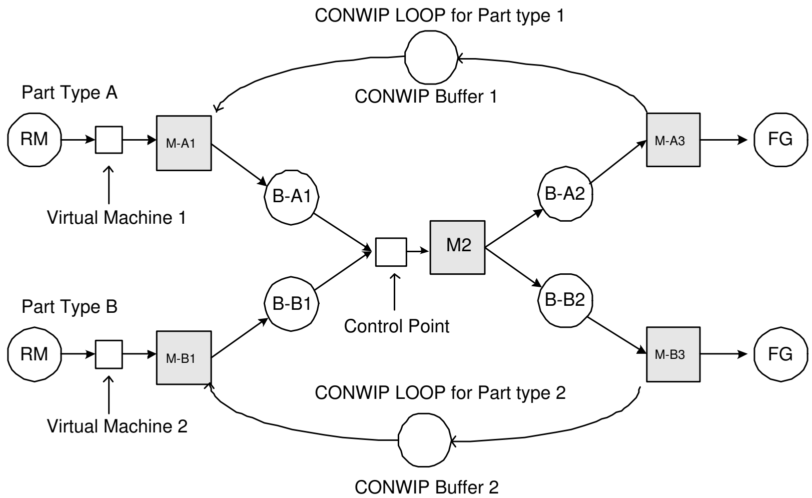

Figure 3-15: Hybrid CPP/CONWIP applied to the model

capacity. On the other hand, if takt = 2.4, the target production rate is less than the capacity.

Figures 3-16 and 3-17 show the results of hybrid CPP/CONWIP with static priority rule and takt = 1.4, as the invariant of CONWIP varies. We can observe that the degree of unbalance is not improved by changing the value of invariant. If we assign different invariant values to each CONWIP loops, the degree of unbalance may be improved, but it introduces one more parameter to consider. Though the production is not balanced, the buffer levels are better than the results of section 3.4.2.

Figures 3-18 and 3-19 shows the results of hybrid CPP/CONWIP with static priority rule and takt = 2.4, as the invariant of CONWIP varies. Though the system capacity is greater than the target production rate, if the invariant is small, the degree of unbalance is significant. One thing to note is that, as in Figure 3-19, the higher priority part type A can achieve high production rate while reducing inventory significantly. In addition, this policy has control over lower part type B, though the tradeoff curve between WIP-PR is worse than that of higher priority part type A.

Figures 3-20 and 3-21 show the results of a hybrid CPP/CONWIP policy with the dynamic priority rule and takt = 1.4, as the invariant of CONWIP varies. The production

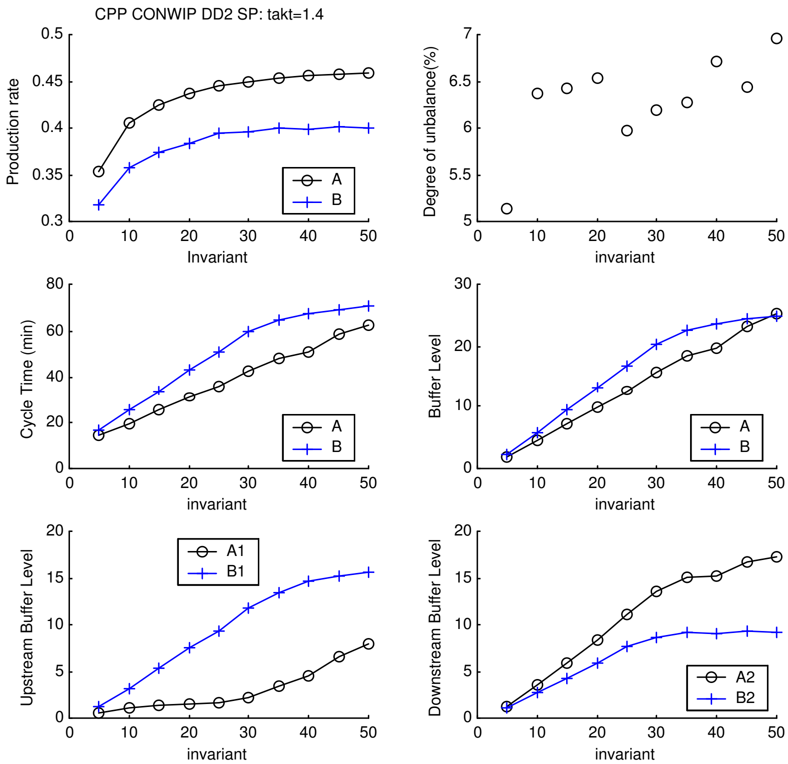

Figure 3-16: Hybrid CPP/CONWIP with Static Priority and Takt=1.4

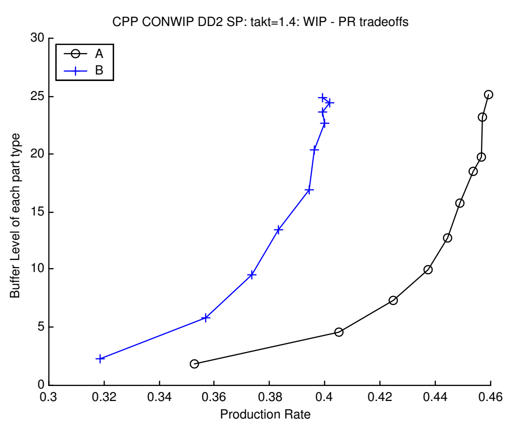

Figure 3-17: Hybrid CPP/CONWIP with Static Priority and Takt=1.4; WIP-PR tradeoff curve

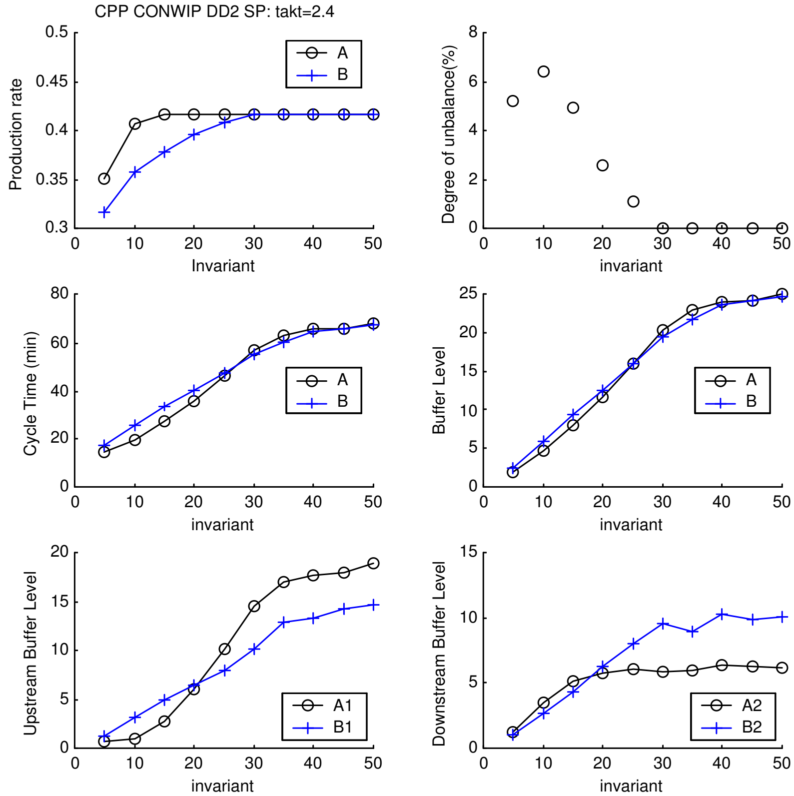

Figure 3-18: Hybrid CPP/CONWIP with Static Priority and Takt=2.4

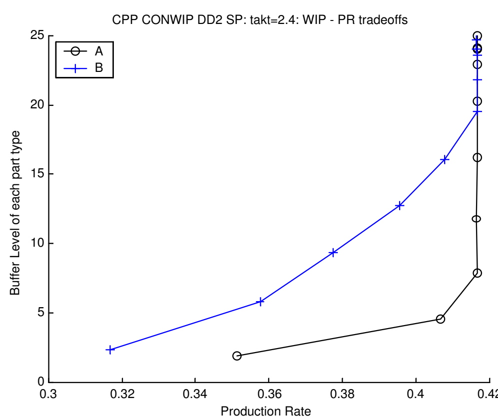

Figure 3-19: Hybrid CPP/CONWIP with Static Priority and Takt=2.4; WIP-PR tradeoff curve

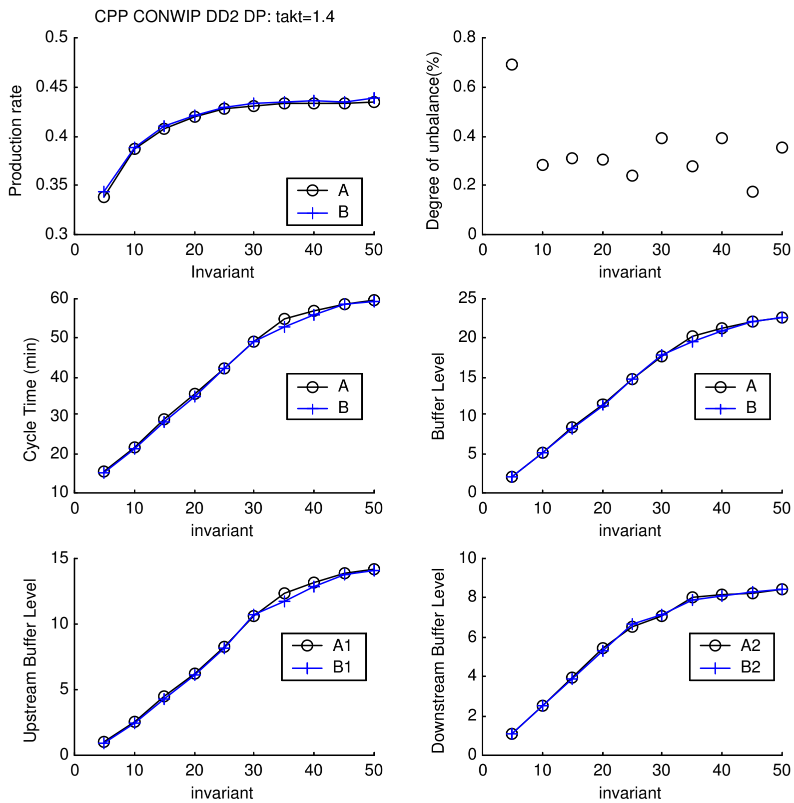

Figure 3-20: Hybrid CPP/CONWIP with Dynamic Priority and Takt=1.4

rates are in balance and we have control over the production rate and inventory, even though the takt time is fixed and the target production rate is higher than the capacity. The behavior of the system with this policy is very similar to the behavior of the system with CONWIP/EDD. Note that the shape of degree of unbalance seems scattered, because the difference between maximum and minimum unbalance is small.

Figures 3-22 and 3-23 show the results of hybrid CPP/CONWIP with dynamic priority rule and takt = 2.4, as the invariant of CONWIP varies. First, the production rates are in balance and the degree of unbalance is small. Though there exists small gaps between upstream buffer levels as well as between downstream buffer levels, the total buffer levels for each part type are also in balance. Because the takt = 2.4, the system is not fully loaded. Thus, the tradeoff curve in Figure 3-23 is blocked by the vertical line where the production rate is about 0.42. The rest of the tradeoff is very similar to that of takt = 1.4. This suggests that we can drop off the takt time parameter once we set it to desired target

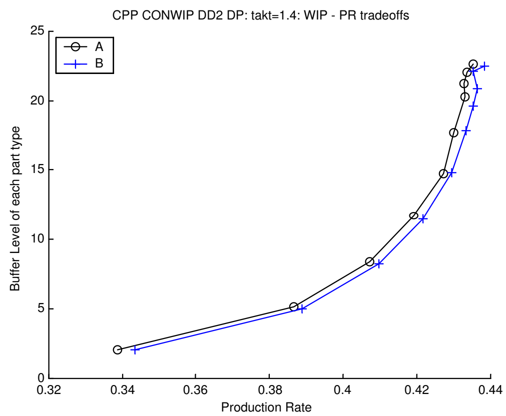

Figure 3-21: Hybrid CPP/CONWIP with Dynamic Priority and Takt=1.4; WIP-PR tradeoff curve

production rate or simply set to system capacity. Then we can lower the WIP by tuning invariants in CONWIP loops.

3.7 Conclusions and Insights

This section gives summary of this chapter and presents some insights of choosing a policy for multiple part type manufacturing systems.

3.7.1 Summary

A multiple part type manufacturing system is studied in this chapter. Each part type has its own route but along its route, a resource is shared with the other part type. This kind of system can be seen commonly in automobile manufacturing systems. The model is devised that there is no specific bottleneck, but behaviors of the the machines are quite volatile, so that the model can have ample randomness. Consequently, choosing the right control policy is very important.

First of all, the effect of blocking before service assumption is studied and it is observed that the BBS logic should be implemented whenever possible. Then, several control policies are experimented on in the model. They are as follows.

- Simple static priority rule

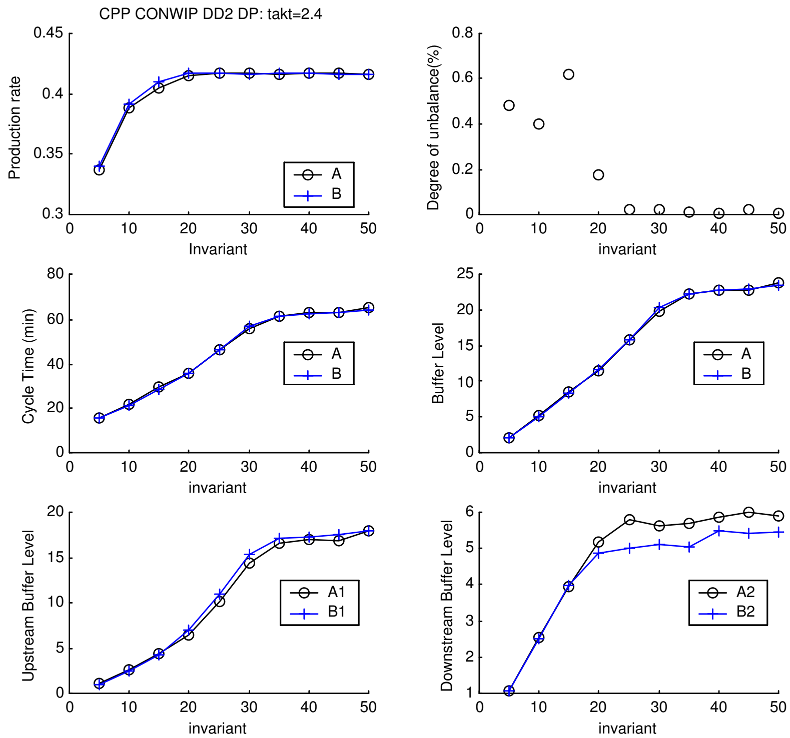

Figure 3-22: Hybrid CPP/CONWIP with Dynamic Priority and Takt=2.4

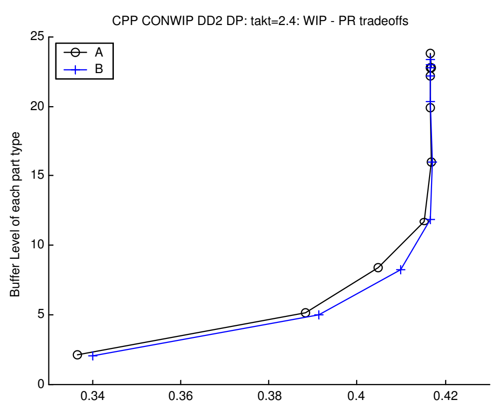

Figure 3-23: Hybrid CPP/CONWIP with Dynamic Priority and Takt=2.4; WIP-PR trade-off curve

- Earliest due date policy(EDD) with two different due date assignment schemes
- Constant work in process policy(CONWIP) with static priority rule or EDD
- Control point policy(CPP) with static priority rule
- Hybrid CPP/EDD
- Hybrid CPP/CONWIP with static priority rule or dynamic priority rule

Performance measures include production rate, cycle time, WIP, and the degree of unbalance between part types. Each control policy shows its own behavior and tradeoffs between performance measures.

3.7.2 Conclusions and Insights

In a single part type serial line manufacturing system, the assumption about blocking before or after service is not significant, but in a multiple part type manufacturing system case, blocking before service assumption is better, because it seriously affects the production of the lower priority part type. The other conclusions from the simulations of control policies listed above are listed below.

1. When the balance between multiple part types is considered, EDD, CONWIP/EDD, CPP/EDD, and CPP/CONWIP with dynamic priority show satisfactory performances.
2. When the system should concentrate on producing one of the part types, CONWIP with static priority and CPP/CONWIP with static priority rule show best performance. CPP with static priority rule does not have control over WIP, thus CPP is not so competitive as CONWIP/SP or CPP/CONWIP.
3. When the production rate of higher priority part type is important and WIP is not important, then CPP and CPP/CONWIP with static priority show best performance.
4. CONWIP, CPP/EDD and CPP/CONWIP have control over WIP levels, by sacrificing production rate, but EDD and CPP with static priority do not have control over WIP.

If dynamic priority is employed, the balance is generally improved, and this is well suited with our intuition. However, when the target production rate is lower than the capacity, CPP with static priority is able to balance the production quite well.

In order to draw tradeoff curve between WIP and production rate, it is important to place all buffers in the system under the control of the policy. For example, the CPP with static priority does not have any control over the buffers A1 and B1, while CONWIP has the control of all the buffers.

By combining the behaviors observed by using various control policies in this chapter, optimal control of larger scale systems of multiple merging points can be done more easily and effectively.

Chapter 4

Simulation simplification by substitution

Sometimes, even a simulation model of moderate size is slow. If we want to optimize a simulation model with several control parameters, the simulation requires huge number of runs. Thus, the speed of simulation becomes one of the most important problems.

Generally, if someone wants a more accurate simulation model, he or she describes more details in the simulation model. In other words, there is a positive relationship between *the degree of details* and *the degree of accuracy*. However, as we increase the degree of details, the simulation becomes bigger and slower, because there is a tradeoff between the degree of details and the speed of simulation.

This chapter will present a systematic approach to find a suitable simulation model to substitute for a complex assembly line, and a general approach to find a model for a portion of the main line. This processes are based on the knowledge of the behavior of a specific manufacturing system. After the substitution, the simulation becomes much faster than before, but it gives us enough accuracy.

4.1 Situations that fast simulations are required

Making a slow simulation model is easy. For example, a company may already has built detailed simulation models for different subsystems of a manufacturing system. If the company wants to see the behavior of the whole system, the model can be built simply by connecting the detailed simulation models of the subsystems. However, this model of the whole system will be generally huge and slow. Once a simulation model is built, the size of the model tends to increase as more functionalities are required, or as higher accuracy is required. Hence the simulation becomes slower as the research goes on. This section shows two cases in which fast simulations are required.

4.1.1 Simulations for testing control policy performance

Figure 4-1 shows a typical manufacturing system. A control point (CP1 or CP2) depicts a machine or a processing station, to which a control policy such as EDD or CPP can be applied.

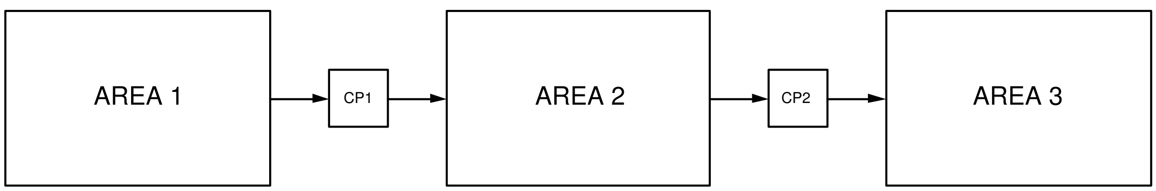

Figure 4-1: Typical Manufacturing System

If the purpose of the simulation is to test control policies, we do not need the internal simulation results of each area (area 1,2,3) other than specific locations related to the performance measures of interest. For example, if the performance measure of interest is the production rate, it can be measured by the production rate of the last machine in each area. What is required to the simulation model of each area in Figure 4-1 is its stochastic properties to be the same as the original manufacturing system, not high degree of details.

4.1.2 Simulation for a decision making tool

Suppose there is a real manufacturing system and we want to modify something in the system, then simulation will be a very good method to predict the effect of modifications in the system. In some cases, such modifications may involve many parameters to tune, and the number of simulation runs for tuning can be huge. If modifications are frequent, it is very important to be able to make a satisfactory decision in a short time. But if the simulation is slow, and it contains many parameters, making a fast decision is generally not

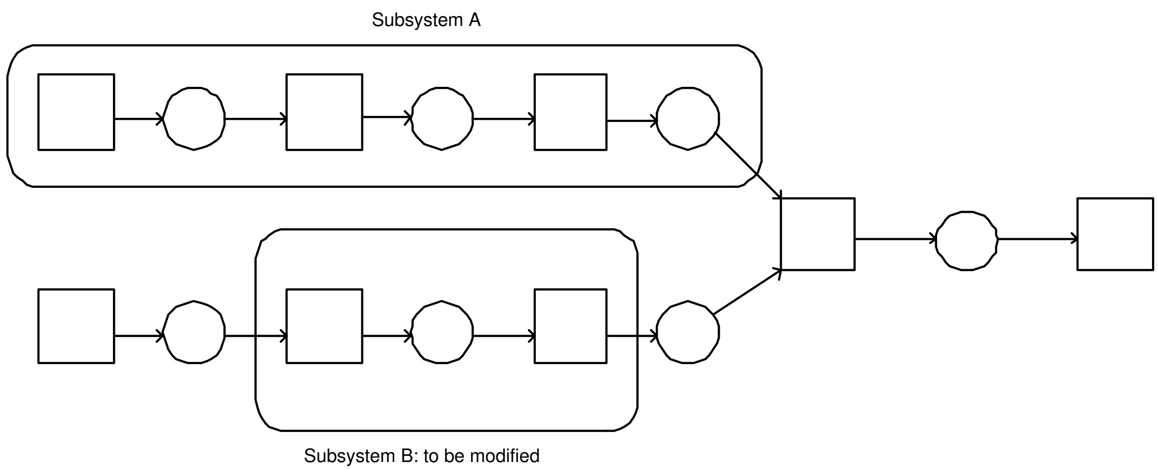

Figure 4-2: Manufacturing system to be modified

possible.

For example, Figure 4-2 shows a manufacturing system with subsystems A and B. Assume subsystem B is to be modified and involves a set of parameters, then optimizing parameters can be time consuming if the simulation is slow. Especially, if the subsystem A is slow, but if subsystem A does not influence so much on the performance of the whole system, then the slowness of subsystem A is not good for the current purpose which is making modifications on subsystem B.

4.2 General Methodology

4.2.1 Problems with the degree of details

There are two problems with regard to the degree of details in a simulation model. The first problem is that as the model involves more details, it gets bigger and slower, as stated above. For the second problem, assume that area 2 in Figure 4-1 is the limiting factor or the most complex and variable subsystem. If area 1 has more details in the simulation model than area 2, the details only make the simulation slower. For the best performance, area 2 should have more details than the other areas.

These days many large scale manufacturing systems are well balanced so that there is no specific limiting factors in the systems, or the limiting factors are moving around as the situations are changed. For this kind of systems without specific bottlenecks in them, the simulation models should be also well balanced in terms of degree of details.

4.2.2 Methodology overview

Our goal is to make the simulation fast with enough degree of accuracy, regardless of the degree of details. This section will present an overview of a methodology to achieve our goal.

The first step is to treat a portion of a manufacturing system as a black box and collect data on some important performance measures, which can be vary according to the management situation. Assuming a single part type subsystem for now, such performance measures can include the following.

- Average Production Rate
- Variance of Production Rate
- Average Cycle Time
- Variance of Cycle Time
- Average Work in Process
- Variance of Work in Process
- Probability of blockage of a specific buffer
- Frequency of blockage of a specific buffer
- Probability of starvation of a specific buffer
- Frequency of starvation of a specific buffer
- Service Level

The basic idea is that we may choose the most important n performance measures from the above, then build a very fast and analytic submodel which has the same values of performance measures as the black box. This submodel will be the substitute for the black box.

Little's Law Little's law states that, in G/G/1 queue,

$$L = \lambda \cdot W$$

with probability 1, where L is time average number of parts in the system, λ is arrival rate, and W is average waiting time in the system. Therefore, among the performance measures above, production rate (λ), cycle time, and total WIP level are related by little's law. See [6] for details.

4.2.3 Building a simplified simulation model directly from the manufacturing system data

Assume we don't have any simulation model. If we need to build a simulation model for the quick decision making and for looking rough behavior of the system, we can directly build a simplified simulation model from the data of the real factory. Building a simplified simulation model is relatively easy and fast. For rough decision making purpose, the reliability or accuracy are also satisfactory.

Assume that the system has many assembly lines and only small number of lines are major lines. If we need detailed simulation model, it is sufficient to concentrate on describing the details of major lines. Unimportant assembly lines or non-bottleneck subsystem can be simplified, and the simulation model can be satisfactory.

4.2.4 Building detailed simulation model then performing substitution

Assume that we already have a detailed simulation model for a manufacturing system. If we need to control it, or change some of the parameters, the simulation must be fast. Thus, we may replace some submodels of original simulation model with simplified and fast ones.

Data measured in the real manufacturing system often insufficient to accept as steady state data. If we have a detailed and accurate simulation model, we can get the more accurate steady state data easily, because getting steady state data requires only small number of runs or just a long run. Therefore, the simplified model also has higher reliability because it is based on more accurate steady state data.

There is one more important benefit. Suppose, by using the simplified model, we obtained the rough optimal set of parameters of the manufacturing system. Then we can validate the optimality and the performance by trying several runs using the original detailed simulation model.

4.3 Assembly line substitution

There are two kinds of substitutions. First is a substitution of a simplified subsystem for an assembly line. The other is a substitution of a simplified subsystem for a subsystem in a main line. This section presents the substitution method for an assembly line, and section 4.5.2 discusses the substitution method for a main line.

4.3.1 Overview

According to Li [14], if we want to get the production rate of the system shown in Figure 4-3, we only need to know the probability of starvation of buffers SB1 and SB2 in the secondary flows. Note that the starvation of a buffer means emptiness of itself, and the starvation of a machine means that at least one of its upstream buffers is empty.

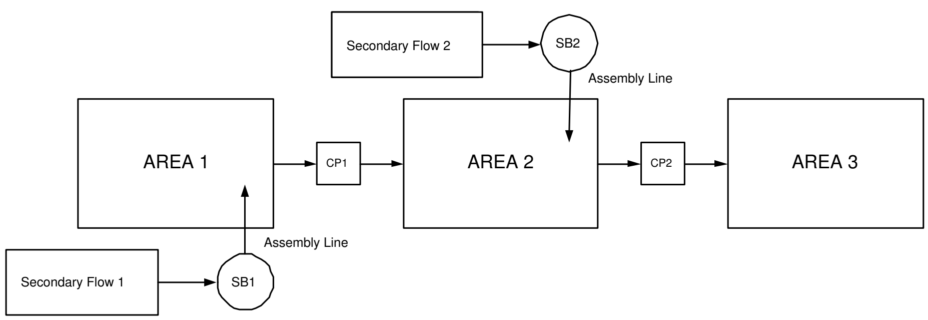

Figure 4-3: Manufacturing System with two assembly lines

Assembly line substitution method extends this idea, so that the other performance measures can be included also. For more accurate substitution, the frequency of starvation must be considered, as well as the probability of starvation. As in [7], even though the probability of starvation is the same, the duration of starvation affects the performance of the system. For example, given a probability of starvation, short and frequent starvation is better for the performance.

Once the probability of starvation and the frequency of starvation of each buffer SB are measured, we can change each of the secondary flow line to a single machine as in Figure

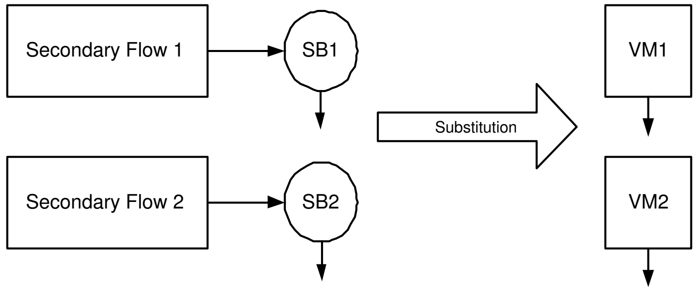

Figure 4-4: Substitution Scheme for Assembly Lines

4-4, provided that the probability of starvation and the frequency of starvation are kept. In the substitution process, the interaction between the assembly line and the main line should be considered. The probability of starvation and the frequency of starvation are also the result of the interaction between the assembly line and the main line. The substitution logic is as follows.

- The substitute machine represents the buffer SB.
- The substitute machine has two states: Up and Down.
- Downtime of the substitute machine represents starvation time of the original buffer. In other words, if the buffer SB is starved, the substitute machine is considered to be out of order.
- Uptime of the substitute machine represents the non-starvation time of the original buffer.
- The substitute machine speed is extremely fast. In discrete event simulation, the processing time should be set to zero. The actual production rate of the substitute machine is the same as the production rate of the main line.
- The substitute machine is never starved.
- When the main line machine is our of order, the current working part in that machine is reprocessed after the repair. The processing time follows the same random processing time distribution.

If the main line is perfectly reliable, the transition rate p, r completely determine the probability of starvation and the frequency of starvation. Note that this idea is only applicable to the assembly lines, not to the flow merging lines.

4.3.2 Timing behavior and Markov Process Modelling

Figure 4-5 shows the simplified assembly line. VM represents the virtual machine for the assembly line, and MM represents the main line machine which is an assembly machine. The assumptions are as follows.

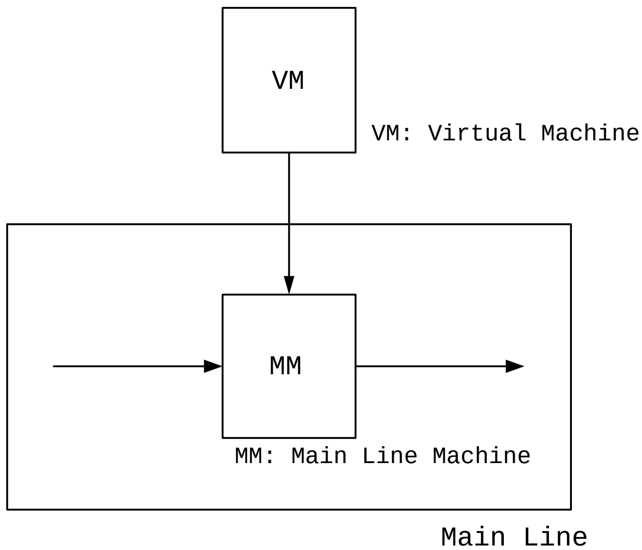

Figure 4-5: Substitute Machine for Assembly Line

- It is continuous time. Two events do not happen at the same time.
- Processing time, time between blockage, time between starvation, time to failure and time to repair are distributed exponentially.
- A failure happens only when the machine is on operation.
- Interaction between starvation from the upstream of MM and blockage from the downstream of MM is small, so that they can be assumed to be independent.

Figure 4-6 shows a sample path of random events in the system of Figure 4-5. The first line in Figure 4-6 represents a sample main line behavior when there is no assembly line. The second line is a sample behavior of the substitute machine (VM). Note that the

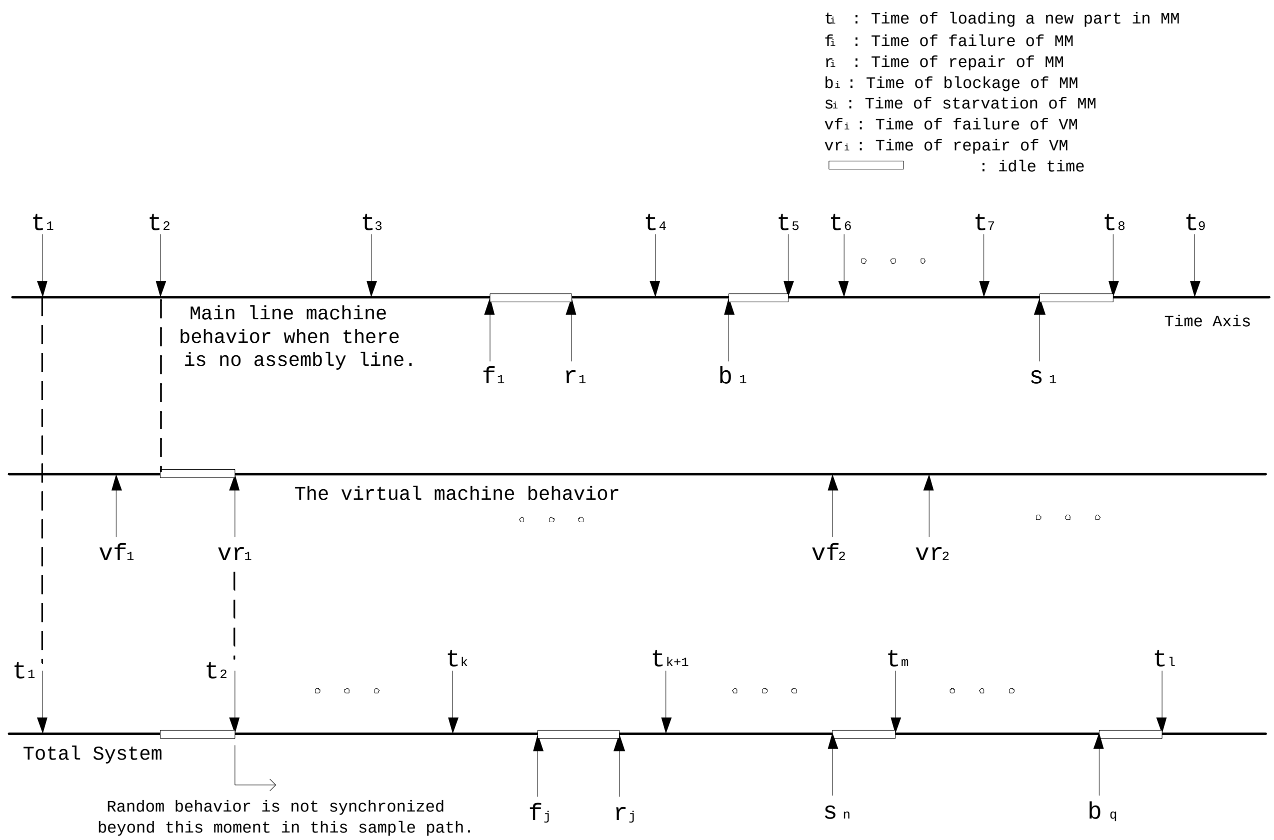

Figure 4-6: A sample path of random events in assembly line and main line

substitute machine behavior is not affected by the main line. The last line represents the sample behavior of combined system. Look at the legends in the figure for details.

At r_i, when the main line machine is repaired, the processing of the working part starts. Main line machine have two sources of starvation. One is from the upstream buffer in main line, and the other is from the buffer in the assembly line (SB). b_i is the time of the starvation from the upstream buffer in the main line. b_i or s_i is also the time of the completion of a working part. The actual random event that causes the blockage or the starvation should have happened earlier than b_i or s_i. But, it is appropriate to assume that the starvation or the blockage starts at the same time as the completion of a working part.

Now, Markov process model can be made for the system based on the observation in Figure 4-6. Appropriate state diagram for the Markov process model is shown in Figure 4-7. Notations for the transition rates are shown in the figure.

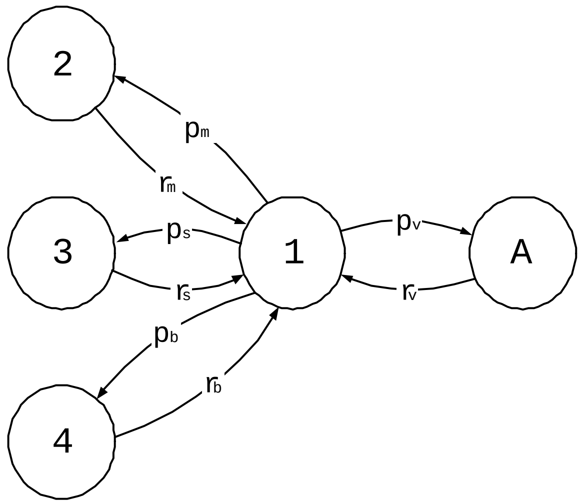

Figure 4-7: Markov process model for the simplified assembly system

- State A: Failure of the substitute machine
- State 1: Working of the main line machine
- State 2: Failure of the main line machine
- State 3: Starvation of the main line machine from the upstream buffer in the main line
- State 4: Blockage of the main line machine from the downstream buffer in the main line

Strategy The steady state probability of staying in state A, and the frequency of transition to state A should be the same as the original system. Once the desired data of original system are observed, the equivalent p_v and r_v can be calculated explicitly. p_v and r_v are the parameters of the substitute machine. Note that the fraction of time spent in state A is the probability of starvation of SB, and the fraction of the transition from state 1 to state A contains the information relevant to the frequency of starvation of SB.

4.3.3 Analytical Solution of the model

Figure 4-8 shows the embedded Markov chain model for the Markov process model. P_{ij} denotes the probability of state change from state i to state j. Let q_{ij} be the transition rate

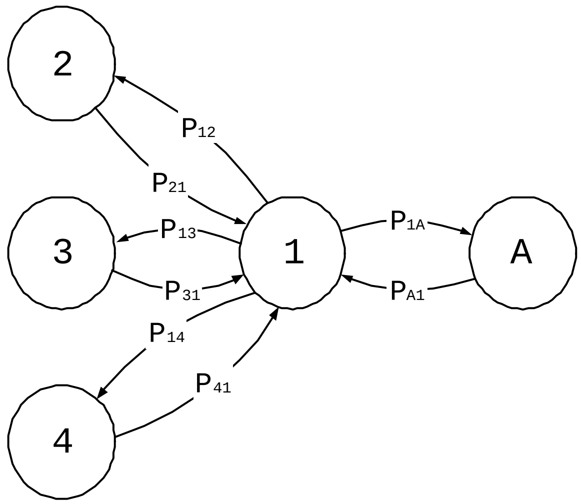

Figure 4-8: Embedded Markov chain model for the simplified assembly system

from state i to state j, and define $v_i = \sum_{j \neq i} q_{ij}$.

$$
\begin{aligned}
v_A &= r_v \\
v_1 &= p_v + p_m + p_b + p_s \\
v_2 &= r_m \\
v_3 &= r_s \\
v_4 &= r_b
\end{aligned}
$$

Then, the transition probability $P_{ij} = \frac{q_{ij}}{v_i}$. For example, $P_{1A} = \frac{q_{1A}}{v_1} = \frac{p_v}{p_v+p_m+p_b+p_s}$, and $P_{13} = \frac{q_{13}}{v_1} = \frac{p_s}{p_v+p_m+p_b+p_s}$. Let π_i be the steady state probability of the embedded Markov chain. Then π_i can be calculated from the following system of equations.

$$
\begin{aligned}
\pi_i &= \sum_i \pi_i P_{ij} \quad \text{for all } i \\
\sum_i \pi_i &= 1
\end{aligned}
$$

or,

$$\begin{aligned}
\pi_A &= \pi_1 P_{1A} \\
\pi_1 &= \pi_A + \pi_2 + \pi_3 + \pi_4 \\
\pi_2 &= \pi_1 P_{12} \\
\pi_3 &= \pi_1 P_{13} \\
\pi_4 &= \pi_1 P_{14} \\
\sum_i \pi_i &= 1
\end{aligned}$$

Therefore

$$\pi_A = \frac{p_v}{2v_1},\ \pi_1 = \frac{1}{2},\ \pi_2 = \frac{p_m}{2v_1},\ \pi_3 = \frac{p_s}{2v_1},\ \pi_4 = \frac{p_b}{2v_1}\ .$$

Let p_i be the fraction of time spent in state i. Then,

$$p_i = \frac{\pi_i / v_i}{\sum_k \pi_k / v_k}$$

or,

$$p_A = \frac{p_v}{r_v T},\ p_1 = \frac{1}{T},\ p_2 = \frac{p_m}{r_m T},\ p_3 = \frac{p_s}{r_s T},\ p_4 = \frac{p_b}{r_b T}$$

where, $T = 1 + \frac{p_m}{r_m} + \frac{p_v}{r_v} + \frac{p_s}{r_s} + \frac{p_b}{r_b}$. Note that p_1 is reduced to the production rate of zero buffer machine line with four machines with corresponding p's and r's.

Available data from observation or detailed simulation Instead of directly measuring the transition rates, it is easier to obtain the following data, because they are easier to measure in the real system and the methods to get these data are already available in many commercial simulation packages.

- The main line machine parameters p_m, r_m
- $\alpha = p_A =$ the probability of starvation of MM from the assembly line.
- $\beta = p_3 =$ the probability of starvation of MM from the upstream buffer in the main line.
- $\gamma = p_4 =$ the probability of blockage of MM from the downstream buffer in the main line.

- $f_{ij} = \pi_i P_{ij}$ = the fraction of transitions from state i to state j

Note that $f_{ij} = f_{ji}$ in the steady state.

Algorithm

- $T = 1 + \frac{p_m}{r_m} + p_A T + p_3 T + p_4 T$, thus $T = \frac{1+\frac{p_m}{r_m}}{1-p_A-p_3-p_4}$.

- p_A, p_1, p_2, p_3, and p_4 can be calculated.

- $f_{1j} = \pi_1 P_{1j} = \frac{\pi_1}{2}$, thus $P_{1j} = 2f_{1j}$ for $j \in \{A, 1, 2, 3, 4\}$

- $P_{j1} = 1$ for $j \in \{A, 1, 2, 3, 4\}$, thus $\pi_j = f_{j1}$

- $\pi_2 = f_{21} = \frac{p_m}{2v_1}$, thus $v_1 = \frac{p_m}{2f_{21}}$

- p_v, p_s, p_d, r_v, r_s, and r_d can be calculated. In particular, $p_v = 2v_1 f_{1A}$ and $r_v = \frac{p_v}{\alpha T}$. Therefore,

$$\begin{aligned} p_v &= \frac{p_m f_{1A}}{f_{21}} \\ r_v &= \frac{f_{1A}(1-\alpha-\beta-\gamma)p_m}{\alpha(1+p_m/r_m)f_{21}}. \end{aligned}$$

Now, we have explicit formulas for p_v and r_v. Therefore, once we have measured the original system data, the substitution process becomes very simple.

4.4 Simulation validations

The system in Figure 4-9 is used for the validation of the substitution method. The resultant simplified model is shown in Figure 4-10.

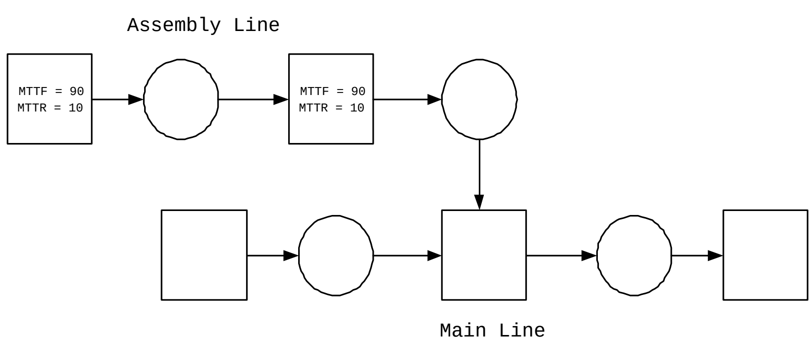

Figure 4-9: The original system to be simplified

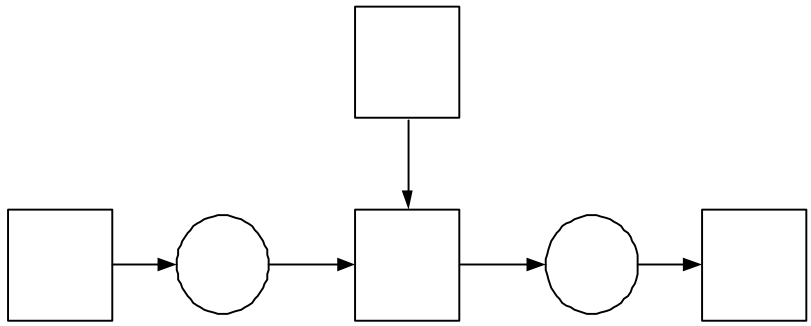

Figure 4-10: The simplified model

Table 4.1 shows parameters of the machines in the main line, and the buffers in the main line and the assembly line. The parameters of machines in the assembly line are fixed as shown in Figure 4-9. Each processing time is an exponential random variable with mean 1 minute. Table 4.2 shows comparison of some of the performance measures of interest. We can see that the accuracy is very high.

Table 4.1: Parameters for the simulation

	MTTF	MTTR	Capacity
Set 1	90	10	10
Set 2	60	20	10
Set 3	90	10	20
Set 4	60	20	20

Table 4.2: Simulation Results

	Set 1	Set 2	Set 3	Set 4
Error in Production Rate (%)	0.506	0.655	0.649	0.280
Error in Cycle Time (%)	-0.456	-0.649	-0.645	-0.249
Error in WIP (%)	-0.023	-0.010	-0.011	0.0284
MTTF of substitute machine	7.307	19.057	10.683	43.398
MTTR of substitute machine	1.709	2.250	1.510	2.048

The error is defined as $\frac{\text{simplifed data}-\text{original data}}{\text{original data}} \cdot 100(\%)$. The confidence interval ratios of the data shown in Table 4.2 are less than 3 %.

4.5 Main line substitution

4.5.1 Introduction

In contrast to the assembly line substitution, the substitution for a subsystem of the main line is more complicated, because the main line involves more performance measures of the whole manufacturing system such as WIP and cycle time. An assembly line is just a constraint for the main line, and our major interest lies in the main line. Suppose we want to find a model that will substitute for area 2 of the system in Figure 4-1.

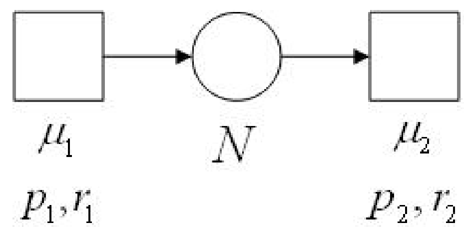

Figure 4-11: Exponential two machine one buffer model

One possible candidate of analytic submodel is the exponential two-machine, one-buffer model. Consider Figure 4-11. This model has 7 parameters including processing rates, failure rates, repair rates, and the buffer capacity, so this model can have up to 7 degrees of freedom. Furthermore, we already have the analytical equations and solutions of this model in [7].

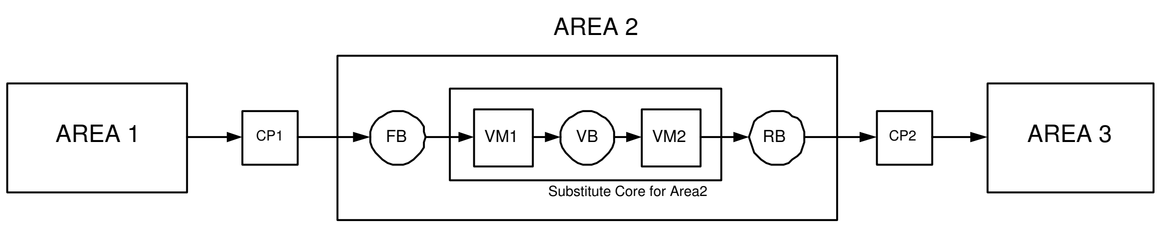

Figure 4-12: Substitution Scheme for Main Lines

Figure 4-12 shows one possible way of substitution for the subsystem of the main line. FB and RB represent buffers in the original system at the very first and the very last, respectively. In order for the acceptable performance of the substitution, we should consider the following.

- Probability of blockage, and frequency of blockage of buffer FB.

- Probability of starvation, and frequency of starvation of buffer RB.
- Total inventory level in area 2. Total inventory level can be calculated by summing the levels of FB, VB, RB, and the utilizations of VM1 and VM2, because a machine can hold up to one part in it.
- The cycle time that a working part is spending in area 2.
- The production rate of area 2.

4.5.2 Main line substitution methodology overview

The methodology is to find a solution of

$$F(x) = y$$

where $F : R^7 \rightarrow R^7$, $x \in R^7$, $y \in R^7$ and y is given. Note that the buffer sizes of FB and RB are fixed to the actual size of corresponding buffers in the real manufacturing system. Though y is in R^7, from Little's law, we can reduce one dimension of y. So, the problem is equivalent to the

$$\bar{F}(x) = \bar{y}, \quad x \in R^7, \ \bar{y} \in R^6$$

First, the original data with respect to the performance measures of interest should be collected from a detailed simulation or a real manufacturing system. Then, parameters of the model should be found. In order to find the solution, we can use general nonlinear optimization methods such as Newton's method or steepest descent method, by calculating numerical gradients of $\bar{F}(x)$. For details of nonlinear optimization methods, refer to [1]. More formally, the problem can be stated as follows.

$$\begin{aligned} &\text{minimize} \quad ||\bar{F}(x) - \bar{y}|| \\ &\text{subject to} \quad x \geq 0 \end{aligned}$$

4.6 Conclusion

This chapter presents a systematic method for speeding up the simulation model. In many situations, fast and accurate simulations are required for various purposes. The actual time saving by using the methods in this chapter can be huge if the original simulation is complex and slow. Furthermore, we can use these simplification methods in building a new simulation model as well as simplifying a existing simulation model.

In the assembly line substitution case, a Markov process modelling approach is presented and closed form solutions are derived for the substitute machine based on some assumptions. Simulation experiments show that the accuracy of the substitution is very high, so that we can believe they are equivalent. In main line substitution case, because of the complexity of the substitution process, an outline of the substitution method is presented.

Chapter 5

Automobile Manufacturing System Case Study

5.1 Introduction

These days, PSA Peugeot Citroën, an automobile company in France, is growing fast. The market share of PSA in Europe is currently in the second place, but they plan to move up to the first place in 5 years. These days, due to the increasing orders from customers, the manufacturing systems in PSA are highly utilized. High production rate means higher profit and more market share. Therefore, PSA wants more production rate by using already built manufacturing systems through more efficient controlling.

5.1.1 PSA Aulnay Factory Overview

PSA has a manufacturing system in Aulnay, France. Aulnay factory is also described in [16]. In Aulnay factory, two different models of cars are being produced: A6, A8[1]. The manufacturing of cars follows purely make-to-order discipline. Figure 5-1 shows the basic layout of Aulnay factory.

In the pressing shop, basic steel plates are pressed, and they move to the body shop. In the body shop, the pressed plates are assembled into a car body or a white car. The body shop is highly automated, so the simulation of the body shop is generally accurate than the others because there is relatively less human factors which incur most variability

[1] The product names of A6 and A8 are C2 and C3, respectively. A6 and A8 are aliases for production.

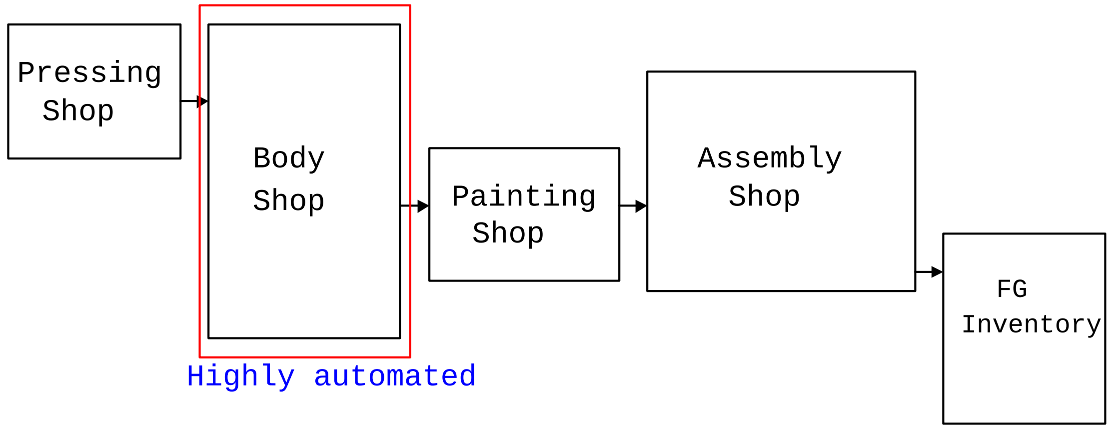

Figure 5-1: PSA Aulnay Factory Layout

in the simulation model. After the body shop, car bodies are painted in the paint shop. At the entrance of the paint shop, there is a large and expensive re-sequencing facility located. Because of the variety of colors and high set-up costs for the painting machines to change colors, the efficient re-sequencing ability is very important for more efficient painting processes.

After the painting shop, the painted car bodies are moved to the assembly shop and all the other parts are assembled in the assembly shop. For example, engines, seats, car audio systems, windows are assembled. Because all orders from customers are already scheduled beforehand in a specific sequence, a set of parts for each order is waiting to be assembled into the corresponding painted car body. The sets of parts are waiting in the original sequence. Thus, the entering sequence of painted car bodies into the assembly shop is very important for the efficiency of assembly processes.

5.1.2 The Body Shop

The layout of PSA Aulnay factory is shown in Figure 5-1. The body shop is the limiting factor in the systems. The production rate of the body shop is directly related to the production rate of the whole factory. Therefore, improving the performance of body shop is urgent. Figure 5-2 shows the layout of the body shop.

Each square in Figure 5-2 represents a set of working robots or machines, and each circle represents a buffer with a minimal transfer time from one end to the other end. The body

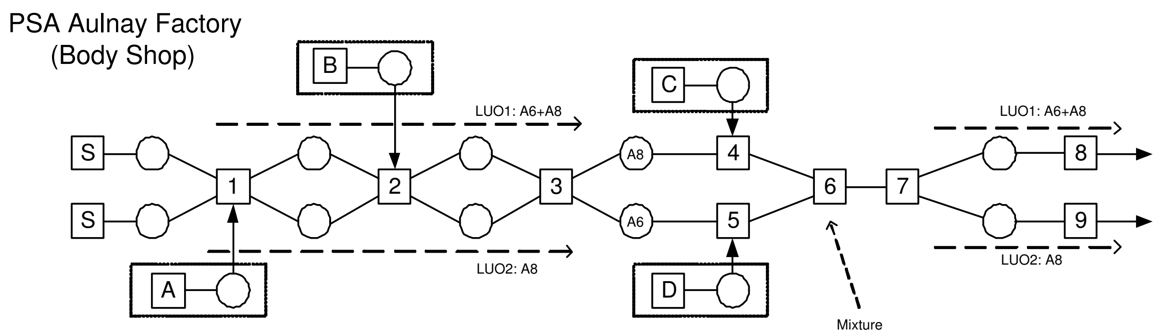

Figure 5-2: The Body Shop Layout

shop is producing two different car models, A6 and A8. There are two production sequences of cars named LUO1 and LUO2. LUO originally means a list of orders. An order listed in each LUO follows a specific route. Both A6 and A8 are listed in LUO1, while LUO2 only contains A8. Every 44 orders listed in LUO1 contains about 36 cars of A6 and about 8 cars of A8. Average production rate for the body shop is about 87 (cars/hour), and about 43.5 (cars/hour) for each LUO. The brief explanation of each processing station is listed below.

Main line

- Stations S: LUO servers – Production sequence generators
- Station 1: Platform process (PTF process) – assembling a front unit and a rear unit to form a under-structure (Though rear units of A6 and A8 are produced in the same set of machines, they are different for each model, but front units are common.)
- Station 2: Model specific platform process (STY process) – assembling the under-structure with a part different for A6 and A8
- Station 3: Finish of under-structure process (SOUB process)
- Station 4: Body Process for A8 – assembling body sides for A8
- Station 5: Body Process for A6 – assembling body sides for A6
- Station 6: Body Process for A6 and A8 – common process of A6 and A8 for assembling body sides
- Station 7: Drilling Process – common process of A6 and A8 for drilling holes

Metal finish lines (MEF processes)

- Station 8: Metal finish for LUO1 – attaching doors and inspecting car bodies by human workers: the only human factor in the body shop
- Station 9: Metal finish for LUO2 – attaching doors and inspecting car bodies by human workers: the only human factor in the body shop

Assembly lines

- Station A: Front units and rear units process – producing common front units for both of the models and different rear units for each model of car
- Station B: Bulkead-plenum assembly process – producing different bulkead-plenum assemblies for each model of car
- Station C: Body sides for A8 – producing left and right body sides for A8
- Station D: Body sides for A6 – producing left and right body sides for A6

5.1.3 Properties of The Body Shop

Mixtures If there is only one LUO, the original sequence in the LUO will not be changed. However, because there are two kinds of LUOs, and the processing station 4 and 5 are processed by model types not by LUO, the final sequence of LUO1 can be different from the original sequence in LUO1. Note that the sequence in LUO2 is not changed because LUO2 only contains A8.

Schedules There are three kinds of schedule of operation as below. In a schedule, there are two kinds of stops. The technical stop is a long stop of 2 or 3 hours for maintenance once in a day. The short stops of 20 minutes are called as pauses.

- Main line schedule – Processing stations 1, 2, 3, 4, 5, 6 and 7: Main line schedule has only a technical stop of 3 hours, and no pauses. Therefore, the main line is operated for 21 hours a day.
- Metal finish line schedule – Processing stations 8 and 9: Metal finish lines have a technical stop of 2 hours, and three pauses of 20 minutes between shifts. Therefore, the metal finish lines are operated for 21 hours a day.

- Assembly line schedule – Processing stations A, B, C, and D: Assembly lines have a technical stop of 3 hours, and three pauses of 20 minutes between shifts. Therefore, the assembly lines are operated for 20 hours a day.

Performance Measures Because the PSA wants higher production rate, the production rate is the most important performance measure. In addition, keeping the original sequence in LUO1 is an important issue because of the complexities of re-sequencing before the paint shop and the assembly shop. PSA also wants the production to be balanced in the metal finish lines, because they involves human workers. If all above are satisfactory, then PSA will consider WIP and cycle time. Therefore, the performance measures of interest are listed below by its importance. (1: most important, 4: less important)

1. Production should be maximized for each line.
2. Variance of production should be small.
3. Each LUO should keep its sequence. (sequencing)
4. Production of each metal finish line should be balanced. (balancing)
5. WIP and Cycle time should be minimized.

Three kinds of line types

1. Transfer Line: All cars or working parts in a transfer line move a step to downstream at the same time. Therefore, the relative distances between cars are kept. If there is a vacancy in the transfer line, the vacancy is kept. Platform process, STY process and SOUB process are using transfer lines.
2. Free Line: Each car or working part in a free line moves freely upon the completion of its current process. The relative distances between cars can be changed. If there is a vacancy in the free line, the vacancy may be filled by the next part. Body process, and upstream processes are using free lines.
3. Transporter line: A line contains only transporters or pallets. Transporter lines are not shown in Figure 5-2.

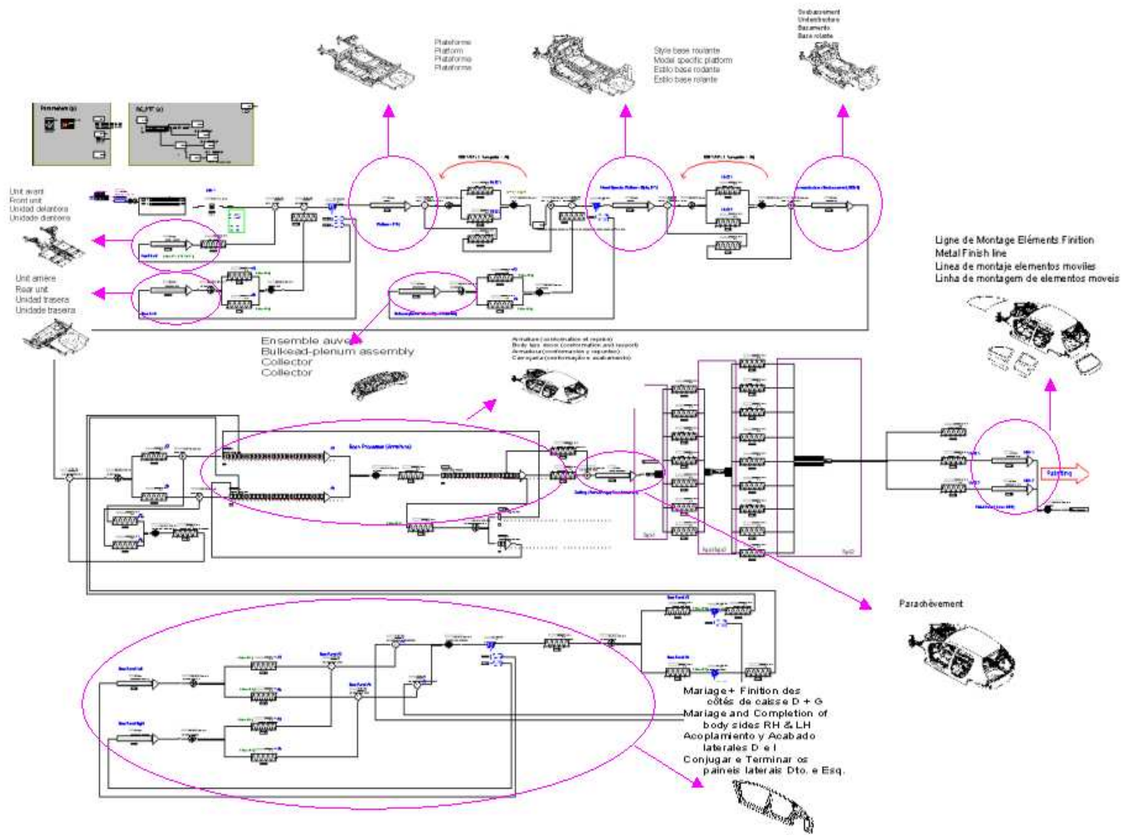

Figure 5-3: The Body Shop Simulation Model

5.2 Simulation Observations

5.2.1 Simulation Model

The simulation model for Aulnay factory is shown in Figure 5-3. All of the processing stations including transporter loops are described in the simulation model. The simulation is using ARENA version 5.0 with MUSE template version 4.3.4 especially designed for PSA manufacturing systems.

5.2.2 Some observations on the simulation model

Several problems are observed in the simulation model of the body shop. They are related to the metal finish line elements (MEF) in the simulation. See Figure 5-4.

Upper bound There is an upper bound on the production rate of the whole factory. This simulation model cannot make more than 1848 cars per day whatever happens in the

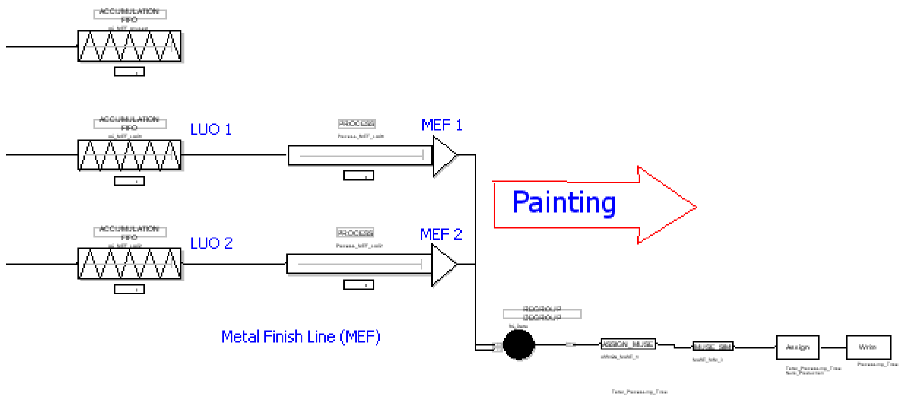

Figure 5-4: Metal finish line elements in the simulation model

factory, even if all events are favorable (i.e., no machine failures, etc.). It is observed that many daily productions are exactly this amount, which implies that the MEF is a bottleneck for many days in simulation. This is not the case in the real factory. This bound is due to the static and perfectly reliable behaviors of the MEF components in the simulation model. But in the real world, the MEF is very variable due to the heavy use of human resources.

The deterministic behaviors of these MEF elements reduce the variability of the simulation as a whole. Besides giving misleading results, they reduce the opportunities for improvement of the factory's performance. As it will be shown below, these simplistic models of MEF elements accounts for nearly half of the production lead time.

Unbalanced modelling detail The details in the simulation model are unbalanced. For example, the process 4,5, and 6 are described in great detail, while the MEF elements are just described as static machines. This is unfortunate for two reasons:

- The great detail of the simulation models leads to very long simulation running times.
- The unrealistically simple simulation model of important processes leads to possibly great inaccuracy.

There should be some tradeoff between simplicity and accuracy. However, unbalancing the level of detail leads to the worst case: long running times and inaccurate results.

Lead time As far as observed by using the simulation model, the lead time is around 350 minutes. However, more than 150 minutes of that lead time are spent in the MEF models.

Since MEF process accounts for almost half the lead time, and it create a deterministic upper bound on the days' production, the inaccuracies in the simulation model of this portion of the factory accounts for most of the inaccuracies of the whole simulation. This implies that the effort expended in the detailed simulation is not well used.

Production rate The average production rate is not affected by the MEF elements. When we removed the MEF elements, we observed nearly the same production rates (but with higher variability). This is because that the processing rates of the MEF elements are slightly higher than the average production rate of the whole factory.

5.3 Control of a simulation model

In applying control policies to the simulation of the body shop factory, we need to tune several parameters for optimal performance. For example, CPP requires hedging times, due dates, etc. However, if running the simulation model is very slow, it is actually impossible to get the optimal parameters, although it is practical to predict performance. This is the motivation for speeding up the process of optimization and the simulation itself. We are seeking methodologies for speeding them up in the following ways.

- A statistical approach using *design of experiments* introduced below
- A substitution of simplified subsystem models for complex subsystems

5.3.1 Design of Experiments

In simulation, design of experiments gives us a way of decision making before the runs are made which set of configurations to simulate to obtain the information with the smallest number of simulation runs. Well designed experiments are more efficient than random simulations in which we simply try a number of alternative sets of configurations unsystematically to see what happens. Two representative methods are introduced here. Detailed explanation of the design of experiments can be found in [13].

2^k factorial design This design method is with k factors, each at two levels. Because each complete replicate of the design has 2^k runs, the arrangement is called a 2^k factorial design. These designs have a greatly simplified analysis, and they also form the basis of many other useful designs.

Response surfaces and metamodels A simulation model can be thought of as a mechanism that turns input parameters into output performance measures. In this sense, a simulation is just a function. If we plot outputs of this function corresponds to various values of the input parameters, we can obtain a *response surface*. Also, we would try to approximate the response surface with a simple explicit formula involving input parameters. Such a formula is called a *metamodel*. The purpose of a metamodel is to estimate or approximate response surface.

We could then use the metamodel to learn about how the response surface would behave over various regions of the input parameter space. In other words, a metamodel is a proposed model over a set of data to regress. Therefore, the accuracy of metamodel depends on the number of simulation runs because of the nature of regression. However, well designed experiments will minimize the number of runs for given degree of accuracy.

5.3.2 Assembly Line Substitutions

In the body shop, there is four assembly lines (A,B,C, and D) as in Figure 5-2. The assembly lines are also described as the same degree of details as the main line, and especially assembly lines C and D are bigger and slow. In addition, the body processes 4, 5, and 6 in the main line have great details, hence the major reason of slowness of the simulation. However, they deserve the details to some extent, because the body processes 4, 5, and 6 are the most delicate processes in the body shop. Though we admin that the body processes should have more details than the other processes, it would be better if the processes can be described more efficiently, which is another topic of research.

In Chapter 4, the substitution methodologies are presented. By the assembly line substitution methodology, the assembly lines in the simulation model can be replaced by much faster single machines, while keeping the stochastic properties of the main line.

5.4 Implementation of Control Policies

In this section, various kinds of control policies are applied to the simulation model of the body shop. First of all, the original control policy of the body shop will be introduced.

5.4.1 Original Policy

The body shop employs a simple control policy. No information distribution exists between the local systems in the original policy. The original control policy of the body shop is as follows.

- Push System with BBS assumption – Each machine works whenever there is any available space at the downstream.

- Local Balancing Between LUO1 and LUO2 at processing station 2 – The number of working parts from LUO1 between processing station 2 and 3, and the number of working parts from LUO2 between processing station 2 and 3 are compared. If the number from LUO1 is bigger than that from LUO2, LUO2 buffer has priority at the processing station 2, and vice verse. Though the ratio between the numbers counted from each LUO is 1 currently, this ratio can be changed as the managerial situation varies.

- First in first out – At the processing stations other than processing station 2, the loading rule is a simple first in first out policy between loading from LUO1 buffer and loading from LUO2 buffer.

Effect of schedules According to the different schedules in the body shop, each line type has different operation time in a day. In particular, the main line and the MEF lines have 21 hours of operation, but the assembly lines have only 20 hours of operation. Therefore, if we run the simulation without any pauses or technical stops, the production per day is larger than $\frac{21}{24}$ times the production per day with pauses and technical stops, because that the assembly lines have one more hour of operation.

Another effect of pause is that the cycle times of substantial number of the cars are calculated unduely higher than the actual cycle time that a car experiences during the factory is actually running. For example, if a car is in the system during a technical stop, the cycle time of that car will be 3 hours higher then the actual cycle time while the factory is running. This effect of pauses and technical stops can be even out among the produced cars statistically by running the simulation long enough.

Simulation results The simulation results of the original policy is shown in Table 5.1. Note that the confidence interval ratio is defined as the ratio of the length of confidence interval to the average magnitude of the data. WIP can be calculated easily from the Little's Law. Table 5.2 shows the simulation results when there are no MEF processing stations (8 or 9), and when there is no pauses and no technical stops in the system. The production in a day shown in Table 5.2 is scaled to 21 hours of operation a day by multiplying $\frac{21}{24}$. The cycle time is reduced because of the elimination of MEF elements, and the production per day increases because of slightly increased working hours of the assembly lines.

While the actual performance of the body shop is shown in Table 5.1, we can use the numbers in Table 5.2 for the policy performance comparison purpose in some cases. For example, time based CPP uses the current time as a parameter for making decisions. Therefore, the pauses and the technical stops incur complicated policy adjustment for CPP implementation. Rather than doing complicated policy adjustment, it is much more convenient and intuitive to compare the policy performances when there is no pauses or technical stops.

Table 5.1: The body shop performance when policy unchanged

	Average	99 % C.I. ratio
Production per day	1824.6	0.68
Cycle time(min)	342.1	0.53

Table 5.2: The body shop performance when policy unchanged without pauses and MEF processing stations in the system

	Average	99 % C.I. ratio
Production per day	1874.7	2.10
Cycle time(min)	158.9	2.83

5.4.2 CONWIP

The CONWIP policy is implemented into the body shop model. There are two kinds of lists (LUO1 and LUO2) and two kinds of cars (A6 and A8). LUO1 contains both A6 and A8, while LUO2 contains only A8, so there are essentially three kinds of cars of LUO1-A6, LUO1-A8, and LUO2-A8. The CONWIP loops can be applied to each of three kinds of cars. A CONWIP loop is connecting from a MEF element to a corresponding list generating machine S.

The invariants for the CONWIP loops are assigned by the number of cars that produced during N hours with the standard original production rate of each of three types of cars. The standard original production rates are about 36 cars/hour for LUO1-A6, 8 cars/hour for LUO1-A8, and 44 cars/hour for LUO2-A8. Therefore, the number of total working cars in the system plus the buffer levels of CONWIP buffers are $88 \cdot N$ all the time, by CONWIP control mechanism.

Simulation results The simulations are done for N = 3, 4, and 5. The brief results summary is shown in Table 5.3, and the lengths of 95 % confidence intervals are less then 3 %.

Table 5.3: CONWIP policy results for the body shop

N	3	4	5
Production per day	1360.5	1741.1	1780.2
Cycle time(min)	276.6	290.7	351.4

5.4.3 Control Point Policy: Token based policy with single part type assumption

The token based CPP is implemented into the simulation model of the body shop. In the implementation of token based CPP, the policy does not distinguish any differences in car types and LUOs. Therefore, this implementation assumes a single part type manufacturing system case for simplicity.

The token CPP logic is applied to the processing stations 1, 3, and 7. In other words, they are control points of token based CPP. A hedging buffer is connected to the downstream of the machine at each control point, and the downstream of the hedging buffer is connected to a synchronization machine with a backlog buffer in its upstream. A demand generator is shared by all the backlog buffers of control points. Therefore, if demand generator generates an order, it moves to each backlog buffer, and each control point is authorized to process a part or a car.

Simulation results The demand rate is set to 88 cars/hour. Because the production per hour of the original simulation model is around 87 cars/hour, many different demands around 87 are tested, and the most favorable demand is found to be 88 cars/hour in terms of production rate. The results of the token based CPP is summarized in Table 5.4

Table 5.4: Samples of token based CPP simulation results

Hedging buffer level	10	20	30
Production/day	1785.2	1783.7	1783.8
C.I. ratio (%)	0.19	0.62	0.61
Cycle time(min)	241.5	296.4	296.3
C.I. ratio (%)	1.77	2.77	2.71

5.4.4 Control Point Policy: Time based policy with multiple part type assumption

The time based CPP is implemented to the simulation model of the body shop. Processing stations 1, 2, 3, 6 are possible control points for the time based CPP. In applying CPP to the simulation model, there are two kinds of schemes that assigning due dates as in Chapter 2.

1. Due Date = Entry Time + Expected Cycle Time

2. Due Date = (Takt time)(Serial number + Offset)

From the simulation experiment results, the due date assignment scheme 2 has better performance in terms of the production rate, which is the most important performance measure of the body shop. Also, from the simulation results from Chapter 2, if we use due date assignment scheme 2, then hedging times mean nothing. This is also true for the simulation results of the body shop. Therefore, the number of parameters is reduced greatly.

Simulation results Table 5.5 shows some samples of time based CPP simulation results. Run 1 through 5 are results from the simulations without any pauses or technical stops in a day, but with the MEF elements. Run 6 to 8 are results from the simulations without any pauses or technical stops, and without the MEF elements in the model. Even though there is no pauses or technical stops in a day, the production is scaled to 21 hours. The results of time based CPP can be compared to results of the original control policy in Table 5.2 for fair comparison. Run 2 and run 3 have different sets of hedging times, and run 4 and run 5 also have different sets of hedging times. The effects of hedging times are so small that the differences are insides of the confidence intervals.

Table 5.5: Samples of time based CPP simulation results

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
Demand (v/day)	1828	1840	1840	1850	1850	1840	1850	1910
Production/day	1827.9	1838.5	1839.4	1844.0	1843.9	1840.2	1847.6	1851.2
C.I. ratio (%)	0.64	0.49	0.48	0.42	0.42	0.70	0.76	0.87
Cycle time(min)	306.8	331.4	341.3	395.1	399.6	149.8	146.0	144.9
C.I. ratio (%)	3.59	4.24	5.27	7.46	7.09	2.66	2.42	2.18

5.5 Conclusion

In this chapter, the simulation model of the body shop in the PSA Aulnay manufacturing system is presented. The fast growing situation of PSA makes them highly utilize their manufacturing systems. Because their market situation is very favorable, the most important performance measure in the body shop is the production rate.

Originally, the body shop employs *push* control policy, though the manufacturing of cars is totally order based, or make-to-order system. If the manufacturing system is producing only a single product type, then push control policy will be the best policy if the production rate is the only performance measure. This case study of PSA is to find a better control policy than the simple push policy, because the body shop is producing multiple product types. However, from the various simulation results time based CPP, token based CPP, and CONWIP are not able to increase production rate more than the original push policy.

PSA is considering production rate most seriously. Generally, there is a tradeoff between production rate and WIP or cycle time. However, because WIP and cycle time are ignored, the production rate is maximized when the working parts are pushed into the system. This is generally true for a single product type, but this is also true for the body shop case with two product types.

Regarding the balancing performance, as shown in Chapter 3, dynamic priority policies show better performance in balancing between multiple product types, though CPP also shows satisfactory balancing performance in some cases. There is nothing better than the dynamic priority policies in terms of the performance measures of PSA. The original priority policy of the body shop is assigning priority to the LUO type with lower downstream buffer level, or simply using FIFO. Therefore, the original priority policy is quite fair to both LUOs or car types. Hence the balancing performance is also satisfactory.

As a conclusion to this chapter, there is no reason to change the original control policy. However, if the managerial situation is changed, so the performance measures are changed, then the best control policy should be investigated and verified again.

Chapter 6

Conclusion

6.1 Summary

The motivation of the research in this thesis is based on the case study of the PSA. Since CPP is expected to have good performance in controlling the body shop with multiple vehicle types, it is determined to use CPP for the simulation model of the body shop. However, many practical problems should be solved in the process of implementation of CPP.

The first problem concerns the simulation model. Because of the presence of deterministic MEF elements at the end of the simulation model, the random behaviors of the simulation deviates from its actual random behaviors. Furthermore, the deterministic MEF elements in the simulation model do not reflect actual MEF processing stations. The second problem is that implementation of CPP required many parameters to be considered. Therefore, it needs a fundamental and systematic approach to find the best set of parameters and to see the behavior of CPP.

Simulations with sets of parameters imply that the hedging times are not effective in the situations in which machines are highly loaded and highly utilized. In addition, the due date assignment methods in the previous literatures of CPP should have been tested. These observations are motivations for the research in Chapter 2.

In order to extend the research in Chapter 2 to multiple product types, and in order to take the balancing performance into consideration, the fundamental research in Chapter 3 is done. Many control policies are experimented on in that chapter, and some possibilities of hybrid policies are shown.

The slowness of the simulation model was another important problem in the process of parameter optimization. Therefore, speeding up the simulation is required. Based on the observation that the simulation model of the body shop has too many details in the assembly lines, the substitution method for the assembly line is developed in Chapter 4.

Finally, PSA manufacturing system is introduced in Chapter 5. The original control policy is analyzed, and the performance measures of the body shop is presented. The simulation results of various control policies implemented into the body shop are presented.

6.2 Further research topics

In this section, some of the research ideas motivated by this thesis are presented.

- Find situations in which CPP can do better than the other control policies.
- In Chapter 4, the assembly line substitution methodology is presented. Do more extensive research to validate the assumptions and the results. Also, find situations in which the assembly line substitution method can be practically used in the design of manufacturing system purpose.
- In Chapter 4, the main line substitution methodology is introduced. Investigate to find the algorithm of the minimization problem presented in Section 4.5.2 by using the knowledge of the manufacturing systems, rather then using just general nonlinear programming algorithms.
- Develop a performance measure which represents the sequencing performance. For example, the initial sequence of releases of vehicles into the body shop in Chapter 5 is not the same as the final sequence out of the system. Therefore, some precise measures are needed to know how well the sequence is kept.
- Generalize the balancing performance. If we want to keep the production ratio other than 1 between different product types, discover which control policies will do the best, or at least will possibly keep such ratio.

- Find a algorithm of generating sets of parameters for evaluating control policy performances by using design of experiment introduced in [13].

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