Worker flexibility in dual resource constrained (DRC) shops

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CHAPTER 3

RESULTS

This chapter examines the research questions raised in Chapter 2. Section 3.1 deals with research question 1, the impact of part type repetitions and the individual learning patterns on system performance. Section 3.2.1 focuses on research question 2, the relationship between the level of cross training and part type repetitions. Section 3.2.2 centres on the relationship between the degree of chaining and part type repetitions. In each section, results are reported; analysis, discussion and conclusions are provided.

3.1 The impact of part type repetitions and the individual learning patterns

Research question 1

> What are the impact of part type repetitions and the individual learning patterns on system performance? In other words, how will the differences in performance between fast and slow learners vary with part type repetitions?

The number of part type repetitions determines the extent to which workers learn and forget, and consequently, has a direct impact on the level of worker efficiency, which in turn influences system performance. Workers have different learning patterns. Some learn fast, while others learn slowly. This section is thus concerned with how part type repetitions and the individual learning patterns affect system performance in DRC parallel shops. Or in other words, it examines how the performance of fast or slow learners differs with part type repetitions.

To evaluate the impact of part type repetitions and individual learning patterns on system performance further in detail, we employ four performance measures: (1) mean flow times, (2) worker utilization, (3) maximum production capacity, and (4) the differences in mean flow times between fast and slow learners. The first two have introduced in the previous chapter. The latter two are specially used for this section. A conceptual framework is depicted in Figure 3.1, in which 4 hypotheses could be formulated.

Note that the hypotheses proposed in this section might be considered as rather straightforward. Still the results indicate the magnitude of the impact of part type repetitions and the individual learning patterns on system performance, and provide a performance range for the selected parameters, which serves as a reference for the research questions in the following sections.

The rest of this section is organized as follows. First, in Section 3.1.1, the relationships between the independent variables and dependent variables will be examined in greater detail, and the related hypotheses will be developed. Next, in Section 3.1.2 the experimental design for testing the proposed hypotheses will be explained. After that, in Section 3.1.3, the results will be presented. Finally, in Section 3.1.4, discussion and conclusions will be provided.

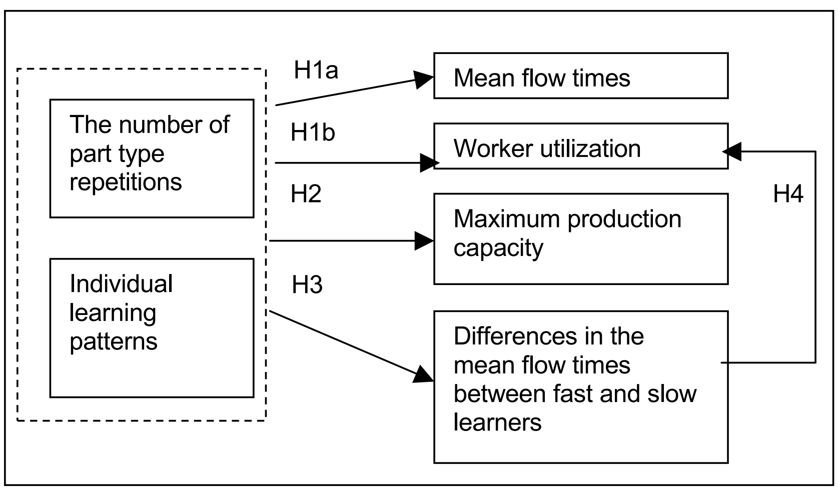


Figure 3.1
Conceptual framework:
the impact of part type repetitions and the individual learning patterns on system performance

3.1.1 Hypotheses

This section examines the relationships between part type repetitions and the individual learning pattern and system performance, as indicated in Figure 3.1.

3.1.1.1 The number of part type repetitions, mean flow times, and worker utilization

When there is learning and forgetting in the system, part type repetitions may have influence on mean flow times and the level of worker utilization. The number of part type repetitions might determine how much time workers have in the learning of the production procedure for a new part type, how far they can move down on their learning curves, and finally what efficiency levels they can finally achieve. When a part type will only be produced for few times, workers do not have the opportunity to reach the end of their learning curves, and may spend most of their time on the steep part of these curves. Their actual processing time may be higher than the standard processing time. When a part type can be produced for many times, workers may reach the bottom of their learning curve, and may operate at a higher efficiency level.

Therefore, the number of part type repetitions may be negatively related to mean flow times. A small number of part type repetitions may be related to a low level of worker efficiency, which in turn leads to long mean flow times. On the contrary, a large number of part type repetitions may result in a high level of worker efficiency, and thus, results in short mean flow times.

As for the level of worker utilization, given a fixed workload (i.e. a constant job arrival interval), a high efficiency level means that tasks can be done quicker, and consequently, workers may have more idle time. On the contrary, a low efficiency level means that tasks are processed more slowly, and workers have less idle time. Therefore, the number of part type repetitions may affect the level of worker utilization. A small number of part type repetitions will lead to a high level of worker utilization, whereas a large number of part type repetitions will result in a low level of worker utilization.

The above argument leads to the following hypotheses:
Hypothesis 1a: the number of part type repetitions is negatively related to mean flow times.
Hypothesis 1b: the number of part type repetitions is negatively related to the mean utilization level of the workers.

3.1.1.2 The number of part type repetitions and maximum production capacity

The term maximum production capacity refers to the maximum number of jobs that a shop can produce within a certain time period, while the shop will not become congested.

In a DRC parallel shop, workers are the most compelling resource constraint. Therefore, the amount of time they can spend on production activities determines the maximum rate of output. When there is learning and forgetting, and new part types come to the system, the actual processing time will be longer than the standard processing time. This extra time spent on learning is referred to as learning costs. Since the total working time for a worker is a constant, the more time spent on learning, the less time will be left for actual production, which in turn leads to the decrease of the maximum output rate.

When the learning and forgetting rates are fixed, the time needed for learning is only affected by the number of part type repetitions. A small number of part type repetitions implies that new part types come to the system at a high frequency, and overall, more time is needed for learning and less time is left for the real production activities. On the other hand, a large number of part type repetitions suggest that new part types come to the system at a low frequency, and on the whole, less time will be consumed for learning and more time will be dedicated to production.

Thus, we argue that a small number of part type repetitions will lead to a low maximum production capacity, whereas a large number of part type repetitions will result in a high maximum production capacity. Therefore,

Hypothesis 2: the number of part type repetitions is positively related to the maximum production capacity.

3.1.1.3. The number of part type repetitions and the individual learning patterns

Nembard and Uzumeri (2000) observed in an empirical study that fast learners learn fast but also tend to forget fast, and they are associated with a lower final efficiency level. On the contrary, slow learners learn slowly but also tend to forget slowly, and they can reach a higher final efficiency level. Based on the findings of Nembhard and Uzumeri (2000), and using Carslon's and Rowe's

(1976) learning and forgetting model, we made the illustrative learning and forgetting curves for fast learners and slow learners, shown in Figure 3.2 (for further detail, see Appendix).

Figure 3.2 Learning and forgetting curves for fast and slow learners

In Figure 3.2, at the early stage of the learning curve, fast learners (i.e. with learning and forgetting rate 80%) have a higher efficiency level, and slow learners (i.e. with learning and forgetting rate 85%) have a lower efficiency level. At the end of the learning curve, slow learners reach their final efficiency level, which is assumed to be 25% of the initial processing time, while fast learners are assigned with a final efficiency level as 37.5% of the initial processing time. Thus, slow learners are assumed to be 50% more efficient than fast learners at the end of the learning curve.

The number of part type repetitions determines which stage of the learning curve a worker is on for most of their working time. Thus,

Hypothesis 3: there will be an interaction effect of the number of part type repetitions and the individual learning patterns on mean flow times and worker utilization level: for a small number of part type repetitions, fast learners will realize a lower level of mean flow times and worker utilization; for a large number of part type repetitions, slow learners will realize a lower level of mean flow times and worker utilization.

3.1.1.4 the differences in the mean flow times between fast and slow learners and the level of worker utilization

In DRC research, worker utilization has been used in two different ways: for comparison, and for sensibility studies.

Worker utilization is an intermediate result, and it has been used mainly as a comparison base in most DRC research. The majority of DRC literature assumed a labor utilization of approximately 90% (Fry 1973-1976, Nelson 1968, Treleven and Elvers 1985, and Weeks and Fryer 1976).

Worker utilization can be used to determine a feasible workload for all the experimental cells, and then based on that, the performance of all the cells can be compared. It is determined as follows. From all the experimental cells, one is selected as a base case. For this particular cell, we first choose a job processing time, based upon industrial practice or previous literature. After that, we select a job arrival interval. The combination of these two parameters should yield a worker utilization level, somewhere between 85% and 90%. These two parameters are then fixed and used for the rest of the experimental cells. The resulting worker utilization level of these experiment cells will fluctuate around the base case level. The difference in worker utilization between two experimental cells shows which one is more effective. A good solution is indicated by a low worker utilization level, and short mean flow times.

Performance criteria are shown to be sensitive to the level of worker utilization (Hogg, Philips, Maggard, and Lesso, 1977, and Rochette and Sadowski 1976). Hogg et al. used two levels of worker utilization (75% and 90%), and found that the difference in the performance of alternative policies are relatively small at a low worker utilization level and large at a high worker utilization level.

Hypothesis 2 proposed that the number of part type repetitions is positively related to the maximum production capacity. With the maximum production capacity, the worker utilization level is set around 85%, which is considered as the highest level in this study. Hypothesis 3 proposed that there will be an interaction effect of the number of part type repetitions and the individual learning patterns. Based on these two hypotheses, we propose that the difference in mean flow times between fast and slow learners increases with the increase of worker utilization level. At the maximum production capacity, the differences will be the biggest. Therefore, we come up with:

Hypothesis 4:the difference in mean flow times between fast and slow learners is positively related to the level of worker utilization.

3.1.2 Experimental design

The general model used in this study has already been described in Section 2.3. This section presents the experimental design specifically related to the hypotheses proposed above. The experimental design consists of three phases (see Table 3.1).

Table 3.1 Experimental phases

	Independent variables	Dependent variables	Hypotheses
Phase 1	1. Part type repetitions 2. Individual learning patterns	1. Mean flow times 2. Worker utilization level	1a, 1b, and 3
Phase 2	1. Part type repetitions 2. Individual learning patterns	Maximum Production capacity (A job arrival interval)	2
Phase 3	Worker utilization levels	Flow ratios	4

Note that the maximum production capacity is represented by a job arrival interval, which indicates within a certain time period the number of jobs that can be handled by a shop. The mean flow times directly measure the productivity of the shop. To bypass the trivial effects of worker utilization on the mean flow times, we will apply a dimensionless flow ratio to indicate relative differences in performance across various situations. This ratio is obtained by dividing the mean flow time of fast learners by that of slow learners, which reflects the differences in mean flow times between fast learners and slow learners.

The experiment will be carried out in three phases subsequently. The first phase tests Hypothesis 1a: the impact of the number of part type repetitions on mean flow times; Hypothesis 1b: the impact of the number of part type repetitions on worker utilization level; and Hypothesis 3: the interaction effect of the number of part type repetitions and the individual learning patterns. To illustrate the impact of the number of part type repetitions on system performance, we use a constant job arrival interval. The independent variables are the number of part type repetitions and the individual learning patterns. The dependent variables are the mean flow time and the worker utilization level.

The second phase is designed for testing Hypothesis 2, which states that the maximum production capacity will be affected by the number of part type repetitions and the individual learning patterns. For each level of part type repetitions, the effect of job arrival intervals on worker utilization level will be tested. The job arrival intervals are selected from high to low. The smallest job arrival interval represents the highest workload that the shop can handle. Furthermore, it is based on the less efficient workers, who constrain the maximum production capacity. The independent variables are still the number of part type repetitions and the individual learning patterns. The job arrival interval becomes a dependent variable for this particular phase.

The third phase tests Hypothesis 4, concerning the differences in mean flow times between fast and slow learners at various levels of worker utilization. The independent variable for this phase is the levels of worker utilization. The dependent variable is the flow ratio.

Table 3.2 shows the independent variable with different levels.

Concerning the first phase, six levels were selected for the number of part type repetitions. As indicated in Section 2.3, these levels disperse along the learning and forgetting curves, and capture a wide variety of dynamic production environments. For the individual learning patterns, two levels were used. The learning and forgetting rates are set for fast learners on 80%, and for slow learners on 85%. The dependent variables are mean flow times and worker utilization.

The second phase has the same independent variables and related experimental levels as the first phase. It has a different dependent variable, the maximum production capacity, which is the minimal job arrival interval that a shop can handle.

The outcomes regarding maximum production capacity should be reported later in the results reporting section. Because they will be used as the independent variable for the third phase, they are presented here.

For each level of part type repetitions, by running the model, we found the smallest job arrival interval, at which the worker utilization for the least efficient workers reaches about 85%. We started from the number of part type repetitions 1, and obtained the smallest job arrival interval 17.5. When the number of part type repetitions is 4, the smallest job arrival interval decreases to 17.15. Sequentially, for the number of part type repetitions 16, 64, 256, and 512, the smallest job arrival intervals are 13.85, 9.45, 6.9, and 6.7, respectively. These job arrival intervals are listed in row 2 of Table 3.2.

In the third phase, the sensibility study is carried out along the various levels of worker utilization. A group of lines are needed to represent worker utilization levels at various magnitudes. After that, we can examine how the difference in mean flow times between fast and slow learners varies with these lines.

There are actually many ways to draw a group of worker utilization lines. As mentioned above, we have already obtained the line of worker utilization 85%, which consists of a set of the number of part type repetitions, and their corresponding smallest job arrival intervals. In the same way, another line of worker utilization, i.e. 70%, can be found out. However, what we need is a group of lines, which represent worker utilization at different levels. We do not exactly need a line with equal worker utilization. From the first and second experimental phases, we have already obtained two groups of figures, the six levels of part type repetitions and the six levels of smallest job arrival intervals. The combinations of these two groups of data create a group of lines, which satisfy our need.

The coupling of the six levels of part type repetitions on the vertical dimension and the six levels of job arrival intervals on the horizontal dimension gives us six lines of worker utilization, which are demonstrated as Line 6 to Line 1 in Table 3.2.

These lines are further explained in Table 3.3. It can be seen that Line 1 consists of six levels of part type repetitions and their corresponding smallest job arrival intervals. This line has the highest worker utilization level. Line 2 comprises five levels of part type repetitions, i.e., from 4 to 512, with 1 (the most dynamic situation) excluded. Their corresponding job arrival intervals are one level higher that Line 1. Therefore, this line represents worker utilization at a level lower than Line 1. Following the same procedures, we acquire Line 3 to Line 6. As the line gets shorter, and the worker utilization level of the line decreases. We use Line 1 to Line 6 to capture the decreasing magnitude of worker utilization.

Table 3.2 Experimental settings

Experimental Variables		Job arrival interval					
		17,5	17,15	13,85	9,45	6,9	6,7
1. The number of part type repetitions	2. Learning and forgetting rate						
1	Fast learners, 80% Slow learners, 85%	85%					
4	Fast learners, 80% Slow learners, 85%		85%				
16	Fast learners, 80% Slow learners, 85%			85%			
64	Fast learners, 80% Slow learners, 85%				85%		
256	Fast learners, 80% Slow learners, 85%					85%	
512	Fast learners, 80% Slow learners, 85%						85%
3. The lines of worker utilization		Line6	Line5	Line 4	Line3	Line2	Line1

Table 3.3 Worker utilization lines

Line 1	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval	17,5	17,15	13,85	9,45	6,9	6,7
Line 2	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval		17,5	17,15	13,85	9,45	6,9
Line 3	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval			17,5	17,15	13,85	9,45
Line 4	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval				17,5	17,15	13,85
Line 5	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval					17,5	17,15
Line 6	Part Type Repetitions	1	4	16	64	256	512
	Job Arrival Interval						17,5

3.1.3 Results

An object-oriented programming language, EM-Plant 7.0, has been used to build the simulation model. The replication/deletion approach (Law and Kelton, 2000) was used to collect 30 independent samples of shop performance for each possible combination of experimental factors. Using the Welch method (Law and Kelton 2000), we set the warm-up period to 10,000 jobs. Observations were collected for 30,000 jobs. The results of this experiment consist of 30 replications of each of all 42 possible combinations of experimental levels.

Results from the experiments are summarized in Table 3.4 for each of the three performance measures, mean flow time, worker utilization, and flow ratio. In order to test the effects of the experimental variables on the performance measures, a MANOVA with main effects and a two-way interaction was conducted on the experimental data for each job arrival interval (see Table 3.5). The main effects of each experimental factor for all of the performance measures were significant at a .001 level. Therefore, the number of part type repetitions and the individual learning patterns have a significant impact on system performance.

Table 3.4 will be analyzed from three directions. Along the vertical direction, for each job arrival intervals, Hypotheses 1a, 1b, and 3 will be tested. Hypotheses 1 and 3 concern the impact of the number of part type repetitions on mean flow times and worker utilization, and the interaction of the number of part type repetitions and the individual learning patterns, respectively. Along the horizontal direction, for each level of part type repetitions, Hypothesis 2, the maximum production capacity (the smallest job arrival interval) will be tested. Along the direction from the left bottom up to the right top, the crossing lines in Table 3.2 will be examined to ascertain whether they represent worker utilization in an upward sequence. Finally, Hypothesis 4, the differences in mean flow times between fast and slow learners will be conducted along these lines. In the following sections, we report the results from testing these hypotheses.

3.1.3.1. H 1a: the part type repetitions and mean flow time

H 1b: the part type repetitions and worker utilization

Hypothesis 1a predicted that there would be a negative effect of the number of part type repetitions on the mean flow time of the jobs. Hypothesis 1b predicted a negative effect of the number of part type repetitions on the mean utilization level of the workers.

In Table 3.5, the MANOVA results indicate that, for each job arrival interval, the main effects of the number of part type repetitions on the mean flow time and the worker utilization level are significant at a .001 level. The number of part type repetitions has a significant effect on the mean flow time and the worker utilization level.

In Table 3.4, it can also be seen that, for each job arrival interval, as the number of part type repetitions increases, the mean flow time and the worker utilization level both decrease. For better understanding, the data for fast learners in Table 3.4 are plotted into graphs, and depicted in Figure 3.3. The reason that only the figures for fast learners are presented is because fast learners and slow learners differ only in the learning and forgetting rates, but follow the same learning and forgetting procedures. Therefore, it holds for both fast learners and slow learners that the increase in part type repetitions drives down the level of mean flow time and worker utilization level.

Figure 3.3 indicates that a low level of part type repetitions is related to a high level of mean flow time and worker utilization; while a high level of part type repetitions will lead to a low level of mean flow time and worker utilization. Thus, Hypotheses 1a and 1b are supported.

It can also be seen in Figure 3.3 that the decrease in mean flow time and worker utilization is fast, when the number of part type repetitions is relatively small, i.e. from 1 to 64, and the decrease becomes slow when the number of part type repetitions is relatively large, i.e. from 64 up. Overall, the decrease in mean flow time and worker utilization seems to follow the patterns of the learning curve.

The level of part type repetitions also indicates the dynamics of the system. When the number of part type repetitions is relatively small, the system is highly dynamic in that the fluctuations in the number of part type repetitions may cause a relatively large change in the mean flow time and the worker utilization level. In the contrary, when the number of part type repetitions is relatively large, since the fluctuations in the number of part type repetitions will not cause much changes in the mean flow time and the worker utilization level, the system becomes more stable. The managers in a more dynamic situation may have more difficulties in making production schedule.

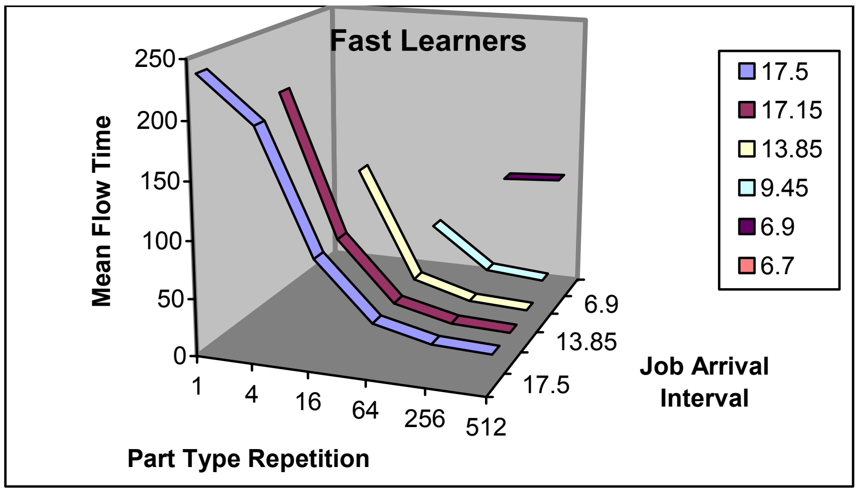
Table 3.4 Experimental results

		Job arrival intervals																	
		17.5			17.15			13.85			9.45			6.9			6.7		
PTR	LF	UT	MFT	Flow ratio	UT	MFT	Flow ratio	UT	MFT	Flow ratio	UT	MFT	Flow ratio	UT	MFT	Flow ratio	UT	MFT	Flow ratio
1	1	0,86	235,61																
1	2	0,86	236,56	1,00															
4	1	0,83	196,60		0,85	213,94													
4	2	0,83	204,96	1,04	0,85	222,63	1,04												
16	1	0,65	90,96		0,67	93,15		0,81	139,87										
16	2	0,69	102,75	1,13	0,70	105,80	1,14	0,85	184,04	1,32									
64	1	0,43	42,46		0,43	42,86		0,53	47,97		0,75	81,53							
64	2	0,48	51,40	1,21	0,49	52,04	1,21	0,60	60,80	1,27	0,85	151,93	1,86						
256	1	0,35	31,29		0,35	31,49		0,44	34,14		0,63	46,28		0,86	116,75				
256	2	0,33	29,79	0,95	0,34	29,91	0,95	0,41	32,11	0,94	0,59	41,84	0,90	0,80	91,21	0,78			
512	1	0,33	29,53		0,34	29,63		0,42	32,12		0,61	42,53		0,84	119,88		0,86	121,12	
512	2	0,28	23,61	0,80	0,28	23,66	0,80	0,35	25,01	0,78	0,50	30,06	0,71	0,68	43,84	0,37	0,70	47,15	0,39

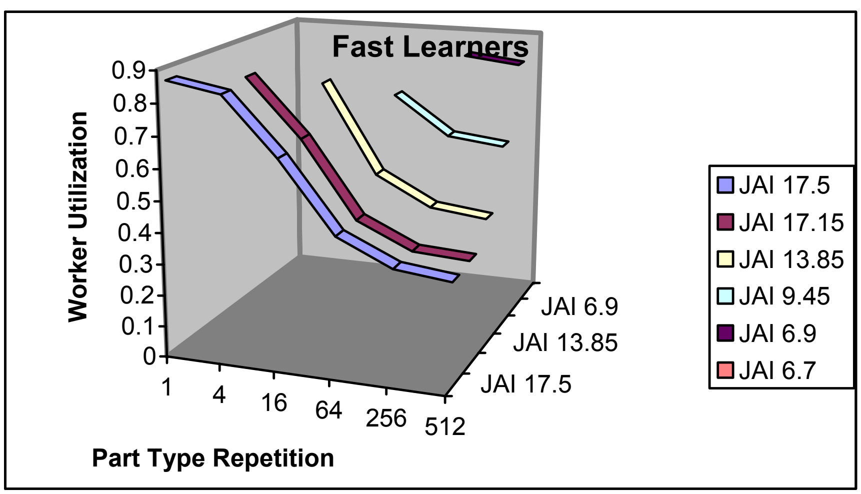
PTR, the number of part type repetitions
LF, the individual learning and forgetting patters
1, fast learners
2, slow learners
UT, worker utilization
MFT, mean flow times
Flow ratios, the mean flow times of slow learners over that of fast learners

Table 3 .5
MANOVA results with dependent variables: mean flow time (MFT), and worker utilization (UT); and independent variables: the number of part type repetitions (PTR), and the individual learning and forgetting patterns (LF).

Job Arrival interval		Multivariate			Univariate		
		F	df	p<	Variables	F	p<
17,5	PTR	24451,65	694	0,001	MFT	19711,06	0,001
					UT	272798,77	0,001
	LF	73,59	347	0,001	MFT	50,65	0,001
					UT	145,86	0,001
	PTR*LF	349,53	694	0,001			
17,15	PTR	31643,56	578	0,001	MFT	24958,79	0,001
					UT	280909,05	0,001
	LF	102,78	289	0,001	MFT	102,03	0,001
					UT	196,72	0,001
	PTR*LF	489,34	578	0,001			
13,85	PTR	18431,23	462	0,001	MFT	25908,26	0,001
					UT	214827,24	0,001
	LF	470,65	231	0,001	MFT	944,86	0,001
					UT	219,04	0,001
	PTR*LF	1918,65	462	0,001			
9,45	PTR	3338,07	346	0,001	MFT	6216,90	0,001
					UT	54332,20	0,001
	LF	1184,59	173	0,001	MFT	752,79	0,001
					UT	597,04	0,001
	PTR*LF	1372,10	346	0,001			
6,9	PTR	3137,75	115	0,001	MFT	2,10	1
					UT	6307,83	0,001
	LF	6763,45	115	0,001	MFT	11,09	0,001
					UT	13611,75	0,001
	PTR*LF	1369,16	115	0,001			
6,7	PTR		57,5		MFT		
					UT		
	LF	5763,69	57		MFT	25,98	0,001
					UT	11597,28	0,001
	PTR*LF		57,5				



(a). mean flow time



(b). worker utilization

Figure 3.3
The impact of part type repetitions on system performance, when learning and forgetting rate is 80% (fast learners), under various job arrival intervals.
JAI = job arrival interval

3.1.3.2. H 2: part type repetitions and maximum production capacity

Hypothesis 2 predicted that there would be a positive effect of the number of part type repetitions on the maximum production capacity.

Table 3.4 shows that for each level of part type repetitions, the decrease of job arrival interval drives up the worker utilization level, up to the ceiling 85%. This tendency is depicted in Figure 3.4, which (a) is for fast learners, and (b) is for slow learners. It can be seen that slow learners and fast learners form the boundary at the different stages of the learning curve. As indicated in Figure 3.2, slow learners have a lower efficiency level at the early stage of the learning curve, and form the boundary; while fast learners have a lower efficiency level at the later stage of the learning curve, and form the boundary.

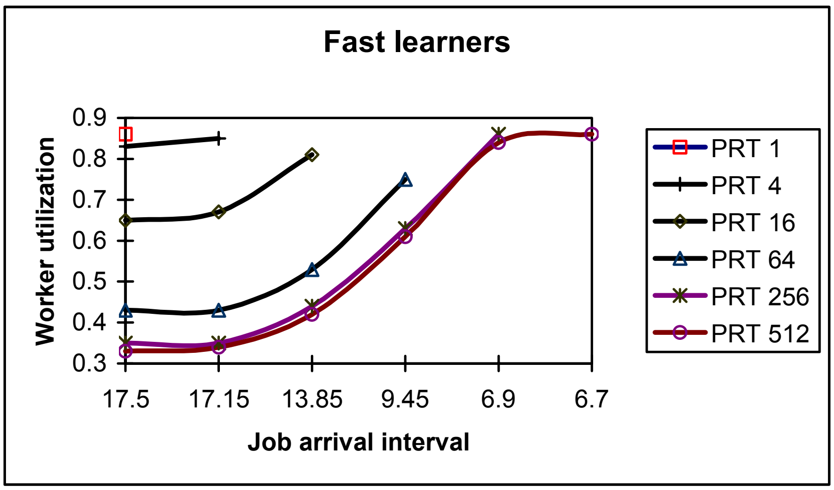
For a particular level of part type repetitions, when a job arrival interval realizes a worker utilization level about 85%, we say that this job arrival interval represents the maximum production capacity for this particular level of part type repetitions. It represents the highest workload that the job shop can possibly handle in this specific dynamic situation. Any job arrival intervals lower than that has the risk of causing the system to become unstable.

For a better understanding, the relationship between the number of part type repetitions and the maximum production capacity is depicted by Line 1 in Figure 3.5. The number of part type repetitions shows a significant positive relationship with the maximum production capacity, indicating that a high level of part type repetitions allows a job shop to have a high maximum production capacity. Thus, Hypothesis 2 is supported.

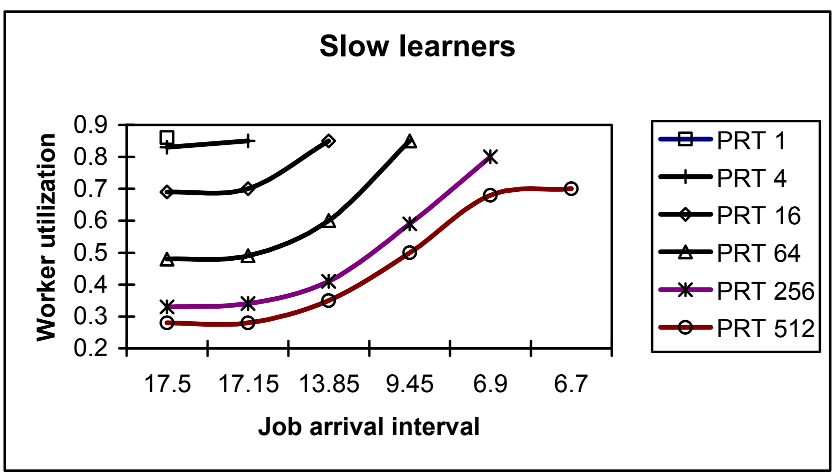
3.1.3.3. H 3: part type repetitions and individual learning patterns

Hypothesis 3 predicted an interaction effect of the number of part type repetitions and the individual learning patterns on mean flow time and worker utilization.

In Table 3.5, it can be seen that for each level of job arrival interval, the interaction of the number of part type repetitions and the individual learning patterns is significant at a .001 level. Figures 3.6 and 3.7 show that fast learners have a lower level of mean flow time and worker utilization for a low level of part type repetitions, and slow learners have a lower level of mean flow time and worker utilization for a high level of part type repetitions. This indicates that there is an interactive effect of the number of part type repetitions and the individual learning patterns. Therefore, hypothesis 3 is supported.



(a). fast learners (learning and forgetting rate is 80%)



(b). slow learners (learning and forgetting rate is 85%)

Figure 3.4
The relationship between job arrival intervals and worker utilization levels, for each level of part type repetitions
PRT, the number of part type repetitions.

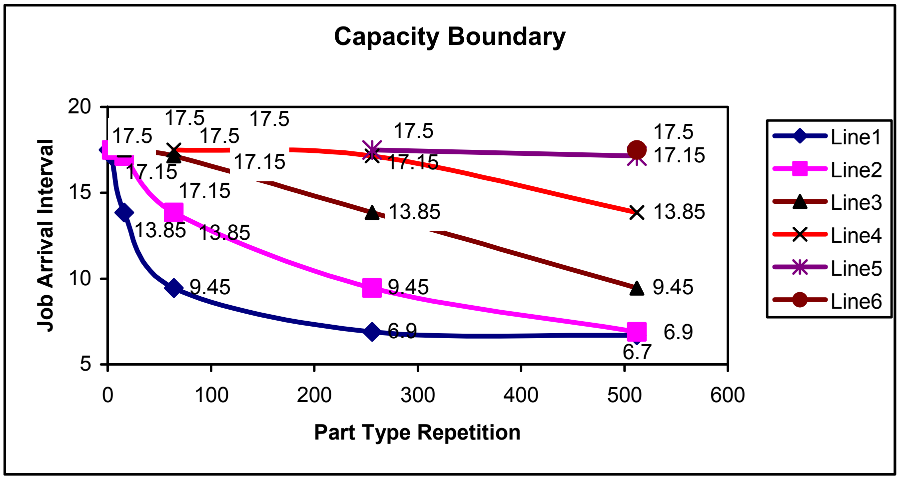
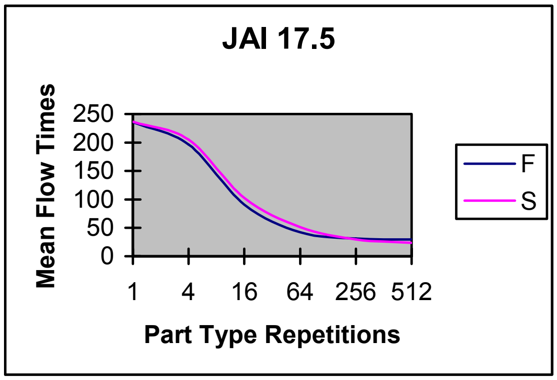
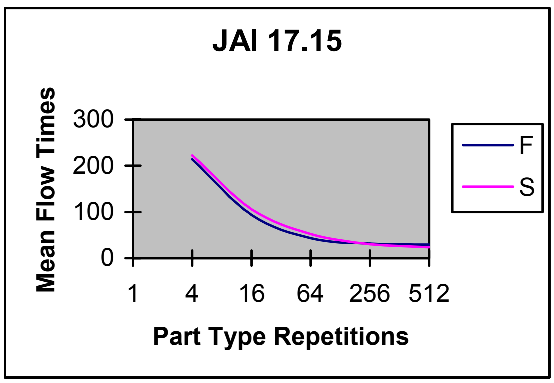
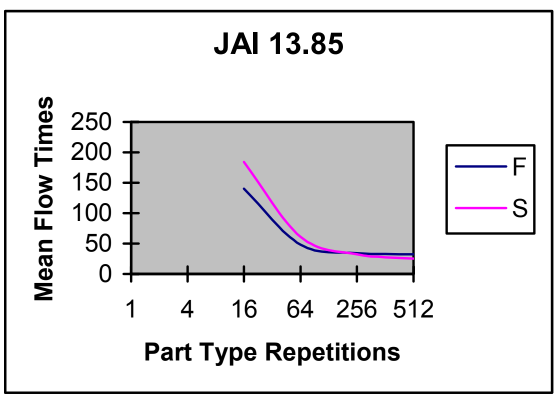


Figure 3.5
Capacity boundary and worker utilization lines
Line1 to Line6, represent worker utilization level in a descending sequence. For further explanation, see Table 3.3.

The results also indicate that there is a certain range of part type repetitions, in which the presence of fast or slow learners does not differ much in performance. For example, we assumed that fast and slow learners have the same initial processing time. When the part type repetition is 1, there are no learning and forgetting, and as a result, workers have the same efficiency levels. Furthermore, in the middle of the learning curve (i.e. part type repetitions 256 in Figure 3.6), slow learners may catch up with fast learners in the learning process, having the same efficiency level. Therefore, in the lower or higher range of part type repetitions, fast and slow learners really differ in efficiency, except part type repetition one or in the middle of learning process.


JAI 17.5
Mean Flow Times
250
200
150
100
50
0
1
4
16
64
256
512
Part Type Repetitions
F
S


JAI 17.15
Mean Flow Times
300
200
100
0
1
4
16
64
256
512
Part Type Repetitions
F
S


JAI 13.85
Mean Flow Times
250
200
150
100
50
0
1
4
16
64
256
512
Part Type Repetitions
F
S

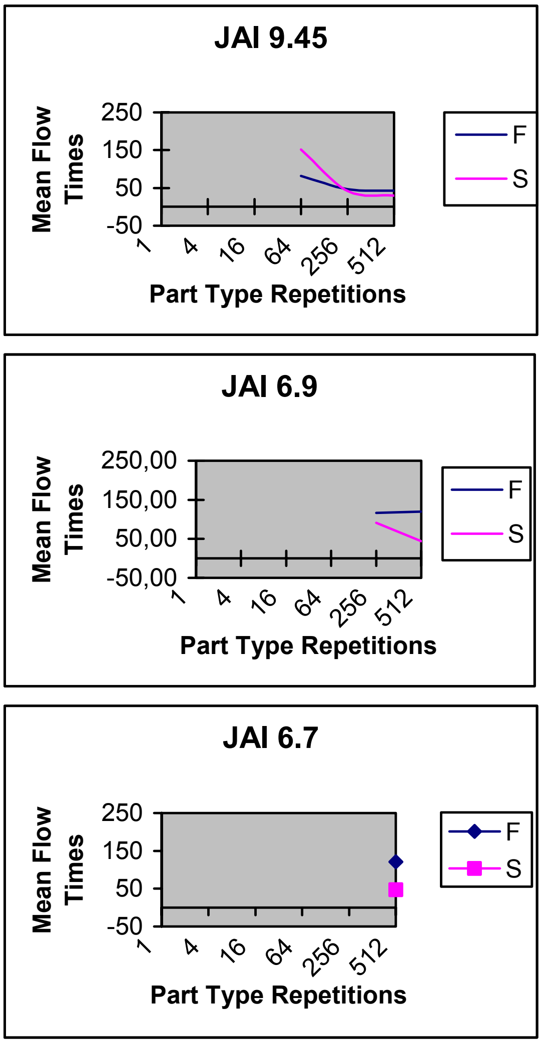
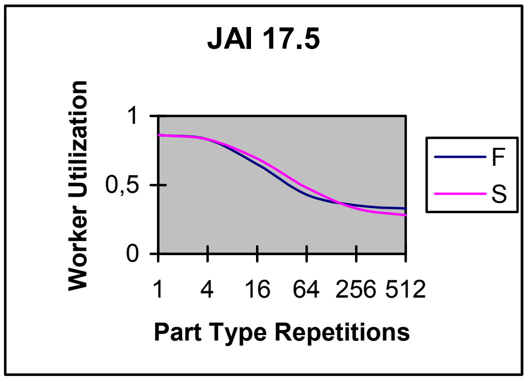
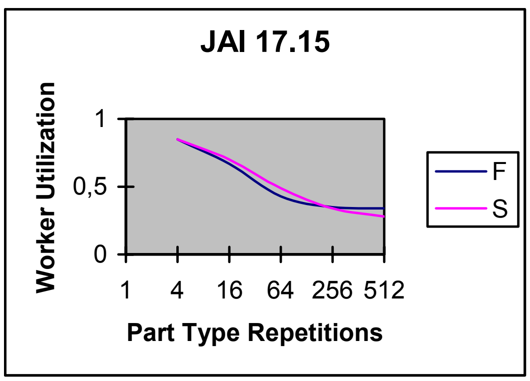
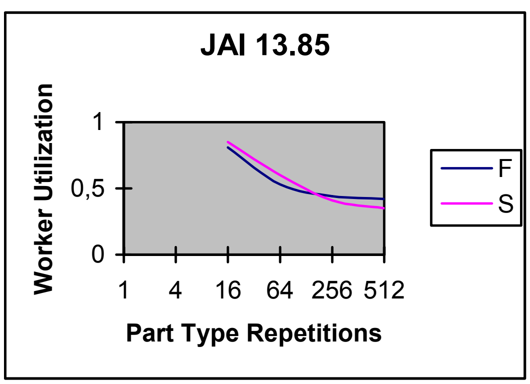


Figure 3.6
The interaction of the number of part type repetitions and the individual learning patterns on mean flow time
for various levels of job arrival interval.
JAI, job arrival intervals.
F, fast learners, with learning and forgetting rate 80%.
S, slow learners, with learning and forgetting rate 85%.


JAI 17.5
Worker Utilization
1
0,5
0
1
4
16
64
256
512
Part Type Repetitions
F
S


JAI 17.15
Worker Utilization
1
0,5
0
1
4
16
64
256
512
Part Type Repetitions
F
S


JAI 13.85
Worker Utilization
1
0,5
0
1
4
16
64
256
512
Part Type Repetitions
F
S

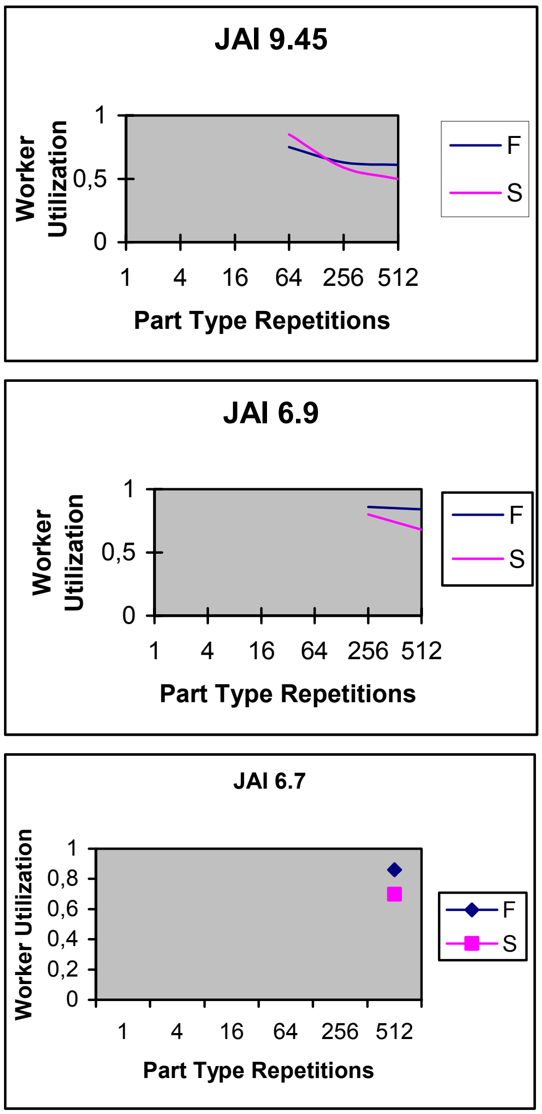


Figure 3.7
The interaction of the number of part type repetitions and the individual learning patterns on worker utilization
for various levels of job arrival interval.
JAI, job arrival intervals.
F, fast learners, with learning and forgetting rate 80%.
S, slow learners, with learning and forgetting rate 85%.

3.1.3.4. H 4: worker utilization level and difference in the mean flow times between fast and slow learners

Hypothesis 4 predicted that there would be a positive effect of the level of worker utilization on the difference in the mean flow times between fast and slow learners.

The results from Hypothesis 1 show that the decrease in part type repetitions drives up the worker utilization level. The results from Hypothesis 2 indicated that the decrease in job arrival intervals pushes up the worker utilization level In Table 3.4, it can be seen that from the left bottom to the crossing line in the middle, the worker utilization level increases.

As discussed in Section 3.1.2, a group of worker utilization lines was selected to represent the increase in worker utilization levels (see Table 3.2). To examine whether these lines meet our expectations, the resulting worker utilization levels along these lines are given in Figure 3.8.

Figure 3.8 shows that from Line 6 to Line 1, worker utilization level increases, with Line 1 having the highest worker utilization level about 85%. Therefore, it is confirmed that the selection of the worker utilization lines in Tables 3.2 and 3.3 in Section 3.1.2 was correct. Therefore, from Line 6 to Line 1, these lines represent the worker utilization at an upward sequence, and can be used for the comparisons of the differences in mean flow times between fast and slow learners at different worker utilization levels.

The difference in mean flow times between fast and slow learners is described by the flow ratio, the mean flow time of slow learners divided by that of fast learners. When the flow ratio is 1, it means that there is no difference between fast learners and slow learners in mean flow times. When the flow ratio is above 1, it suggests that fast learners outperform slow learners. If the flow ratio is below 1, the opposite is true.

Figure 3.9 shows that the flow ratio changes with the level of worker utilization. In general as the worker utilization level increases from Line 6 to Line 1, the flow ratios move away from 1. There is a certain range of part type repetitions, e.g. part type repetition one and around 256, in which the flow ratios are close to 1, or the performance of fast and slow learners does not differ much. Only in the case of moderate or high part type repetitions, the difference in the performance between fast and slow learners becomes bigger.

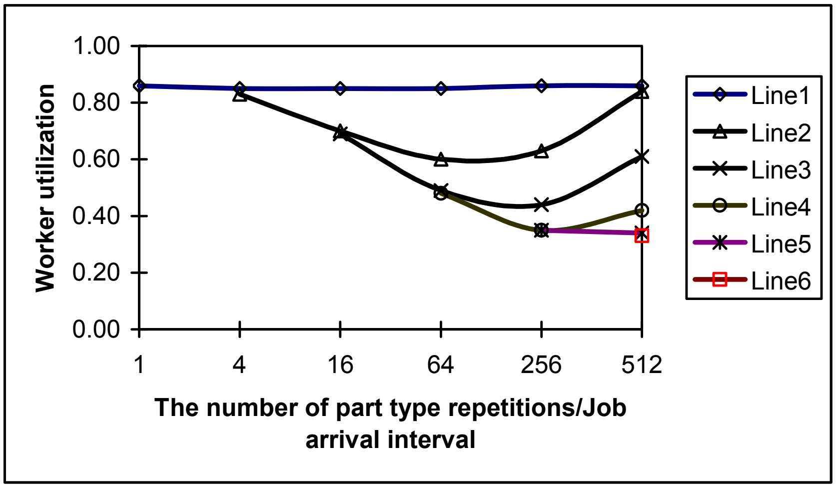


Figure 3.8
Worker utilization levels and worker utilization lines
Line1 to Line6, represent worker utilization levels in a descending sequence. For further explanation, see Table 3.3.

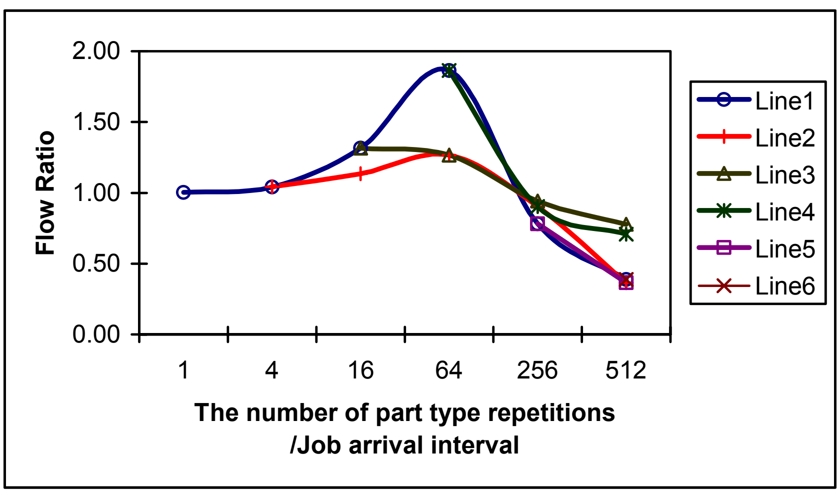


Figure 3.9
Flow ratio and worker utilization lines
Line1 to Line6, represent worker utilization levels in a descending sequence. For further explanation, see Table 3.3.

The flow ratio of Line 1 constitutes both the top and the bottom for this group of graphs. It indicates that when the worker utilization level increases, the magnitude of the difference in the mean flow times between fast and slow learners increases. Or in other words, when worker utilization level is about 85%, the job shop is operating on maximum production capacity, the magnitude of the difference in the mean flow times between fast and slow learners is the biggest. Furthermore, when the number of part type repetitions is low, the flow ratios are above 1, which indicates that fast learners outperform slow learners. When the number of part type repetitions is high, the flow ratios are below 1, which shows slow learners perform better than fast learners. Therefore, Hypothesis 4 is supported by the results.

3.1.4 Discussion and Conclusions

The results show that part type repetitions have a significant impact on mean flow times and worker utilization. A highly dynamic system is most likely to be related to a low level of productivity and a high level of worker utilization, while a more stable system tends to have the opposite. Managers should realize the possible impact of new part type introduction on productivity and worker utilization. When making a production schedule, these factors should be taken into consideration.

The results also show that a highly dynamic system has a low maximum production capacity, while a more stable system can actually handle more workload. When making capacity plans, the impact of learning and forgetting on the maximum production capacity should be an important managerial concern.

With respect to the interactive effect of part type repetitions and individual learning patterns, the results show that fast learners perform better in a highly dynamic system, whereas slow learners perform better in a more stable situation. Therefore, the selection of workers in terms of the learning capability is of great importance in a dynamic situation. This issue becomes more critical when a shop is fully loaded, operating on the maximum production capacity, as the difference in the mean flow times between fast learners and slow learners is the biggest.

We conclude that when learning and forgetting incur considerable costs, the frequencies of new product introduction may have a significantly negative impact on mean flow times, worker utilization levels, and the maximum production capacity. The frequencies of new product introduction may interact with the individual learning patterns, in which fast learners perform better in a high dynamic environment, while slow learners have advantages in a more stable environment. This conclusion may be debatable but it is based upon the empirical findings of Nembard and Uzumeri (2000). Future research is needed for the generalization of their findings, and for the explorations of the reasons behind this phenomenon.

3.2 Cross training and chaining

Research question 2:

> In a learning and forgetting environment, what is the impact of cross training and part type repetitions on system performance? In other words, will the impact of the performance of cross training vary with part type repetitions?

Research question 3:

> What is the impact of chaining and part type repetitions on system performance when learning and forgetting are present? In other words, will the impact of the performance of chaining vary with part type repetitions?

The objective of this section is to investigate how cross training policies affect system performance in a variety of dynamic environments, in which learning and forgetting may incur considerable costs. In section 3.2.1, we first examine the impact of the level of cross training and part type repetitions on system performance, i.e. research question 1. After that, in Section 3.2.2, we explore how the effectiveness of chaining varies with the changes of part type repetitions, i.e. research question 2. In this section, we assumed that there are only slow learners in the job shop, with 85% learning and forgetting rates.

3.2.1 Level of cross training

In this section, we first explain the experimental design specifically related to the level of cross training, whereas the general model can be found in Section 2.3. After that, the results of the experiments will be presented. Finally, a discussion and conclusions will be provided.

3.2.1.1 Experimental design

As mentioned earlier in Section 2.3, we selected six levels of part type repetitions 1, 4, 16, 64, 256, and 512 to represent various dynamic situations. In Figure 3.10, three cross training configurations represent three levels of cross training. By comparing them, we can examine the benefits of cross training in various dynamic situations.

Configuration 1: The level of skills 2

	D1	D2	D3	D4
W1	S	S		
W2		S	S	
W3			S	S
W4	S			S

Configuration 2: The level of skills 3

	D1	D2	D3	D4
W1	S	S	S	
W2		S	S	S
W3	S		S	S
W4	S	S		S

Configuration 3: The level of skills 4

	D1	D2	D3	D4
W1	S	S	S	S
W2	S	S	S	S
W3	S	S	S	S
W4	S	S	S	S

Figure 3.10 Levels of cross training (with chaining incorporated)
D = department
S = slow learner
W = worker

The comparison of different levels of cross training will be carried out at two phases: a constant job arrival interval, and a constant worker utilization level. When the job arrival interval is constant, as part type repetitions increase, worker efficiency improves, and worker utilization goes down. Especially for the large number of part type repetitions, the comparison of cross training levels will be conducted under a relative low level of worker utilization, which is not really realistic in a real life situation. Furthermore, the difference in performance between alternative solutions will be hidden as well (Hogg et al. 1977). To avoid this shortcoming, we keep worker utilization level constant by adjusting job arrival intervals.

A constant worker utilization level is achieved as follows.

We first look for the particular cross training configuration that provides the worst performance in most of the cases. In this section, workers are trained for 2, 3, and 4 skills, and there are three cross training configurations. First, for a given level of part type repetitions, the configuration that has the highest mean flow times among the three configurations will be considered as the one with the worst performance. For each part type repetition, we find the one giving the worst performance. From six part type repetitions, six configurations are selected. Second, from these selected six configurations, the one that provides the worst performance most of the times will be regarded as the one, which forms the bottom of performance. To be more specific, in this section, configuration 3 (i.e., skill level 4) is selected.

The lowest job arrival intervals are then derived from this configuration. In particular, for each part type repetition, the lowest job arrival interval results in worker utilization around 85%. In this way, we obtained six lowest job arrival intervals, 17.5, 17.4, 16.9, 14.9, 10.5, and 8.5, which are shown in Table 3.6.

We then try to combine this group of job arrival intervals with the six levels of part type repetitions. Not all the combinations are possible. Some will cause the shop becoming overloaded, i.e. very long mean flow time, and they are not considered. For example, when part type repetition is 1, the shop can only handle the job arrival interval of 17.5. If jobs come faster than that, i.e. 17.4, the shop may become congested. In other words, the combinations of part type repetition 1 and the job arrival intervals faster than 17.5 are not possible. As for part type repetitions 4, the shop can handle job arrival interval 17.4. In other words, part type repetitions 4 can be combined with two job arrival intervals, 17.5 and 17.4. Overall, for one configuration, 21 combinations of part type repetitions and job arrival intervals are possible. For three configurations, we obtained 63 experimental cells.

Table 3.6 will be analysed along two directions. First, in the vertical direction, for each job arrival interval, it will demonstrate how performances of each configuration vary with part type repetitions. Second, along the line from the top left to the bottom right (i.e. the constant worker utilization line), it will illustrate how each configuration performs under a variety of dynamic situations (i.e. the number of part type repetitions) and a constant worker utilization level. In this way, the performance of each configuration can be 'fairly' compared.

The simulation runs and data collection procedure is similar to section 3.1.

3.2.1.2 Results

Results from the experiment are presented in Table 3.6 for each of the two performance measures, mean flow times, and worker utilization. In order to test the effects of the experimental variables on the performance measures, a MANOVA test was conducted for each level of job arrival interval (see Table 3.7). The main effects of each experimental factor for all of the performance measures were significant at a .001 level. Therefore, the number of part type repetitions and the level of cross training have a significant impact on system performance.

Table 3.6 Experimental results for the level of cross training

Cross training Policies		Job arrival intervals 17.5		17.4		16.9		14.9		10.5		8.5	
		UT	MFT	UT	MFT	UT	MFT	UT	MFT	UT	MFT	UT	MFT
Skill level 2	PTR												
	1	0.86	149.74										
	4	0.85	139.79	0.85	143.47								
	16	0.80	113.97	0.80	115.34	0.83	123.41						
	64	0.63	68.95	0.63	69.23	0.65	70.59	0.72	78.98				
	256	0.43	43.00	0.43	43.05	0.44	43.34	0.49	44.78	0.68	55.07		
	512	0.35	35.38	0.35	35.44	0.36	35.50	0.41	36.22	0.56	41.13	0.68	48.62
Skill level 3	PTR												
	1	0.86	141.04										
	4	0.85	133.73	0.86	137.29								
	16	0.82	118.79	0.83	120.31	0.85	129.58						
	64	0.71	82.91	0.71	83.27	0.73	85.97	0.82	103.59				
	256	0.50	51.70	0.51	51.78	0.52	52.14	0.58	54.27	0.79	75.02		
	512	0.41	42.20	0.41	42.24	0.42	42.41	0.48	43.35	0.65	50.23	0.78	65.80
Skill level 4	PTR												
	1	0.86	136.83										
	4	0.85	130.51	0.86	133.07								
	16	0.83	119.07	0.84	121.14	0.86	131.93						
	64	0.76	92.23	0.76	92.86	0.78	96.68	0.87	126.79				
	256	0.57	58.70	0.57	58.74	0.58	59.34	0.65	62.84	0.88	109.83		
	512	0.47	47.62	0.47	47.54	0.48	47.72	0.53	48.86	0.72	60.08	0.87	100.63

PTR, the number of part type repetitions.

UT, worker utilization.

MFT, mean flow times.

Table 3.7 Level of cross training
MONOVA results with dependent variables: mean flow times (MFT), and worker utilization (UT); and independent variables: the number of part type repetitions (PTR), and the level of skills (LS).

Job Arrival interval		Multivariate			Univariate		
		F	df	p<	Variables	F	p<
17.5	LS	1956.72	1042	0,001	MFT	298.01	0,001
					UT	12849.73	0,001
	PTR	24782.36	1042	0,001	MFT	33968.81	0,001
					UT	188081.3	0,001
	LS*PTR	440.46	1042	0,001			
17.4	LS	1886.31	868	0,001	MFT	1152.75	0,001
					UT	17217.92	0,001
	PTR	30763.63	868	0,001	MFT	54199.63	0,001
					UT	215999.8	0,001
	LS*PTR	510.6	868	0,001			
16.9	LS	1943.85	694	0,001	MFT	4542.74	0,001
					UT	25278.44	0,001
	PTR	37442.92	694	0,001	MFT	83090.14	0,001
					UT	237804	0,001
	LS*PTR	534.36	694	0,001			
14.9	LS	2424.26	520	0,001	MFT	12771.62	0,001
					UT	30415.74	0,001
	PTR	18481.61	520	0,001	MFT	76748.45	0,001
					UT	165899.3	0,001
	LS*PTR	745.08	520	0,001			
10.5	LS	1964.77	346	0,001	MFT	3880.03	0.001
					UT	18833.73	0,001
	PTR	16101.55	173	0,001	MFT	7346.97	0,001
					UT	32005.33	0,001
	LS*PTR	256.49	346	0,001			
8.5	LS	757.1	172		MFT	979.27	0,001
					UT	5602.88	0,001
	PTR		86.5		MFT		
					UT		
	LS*PTR		86.5				

As noted earlier, the analysis was carried out at two phases, at a constant job arrival interval, and at a constant worker utilization level. A flow ratio is calculated for the ease of comparison. As the level of cross training level 2, i.e. configuration 2, yields the lowest mean flow times most of the time, it is selected as the base for comparison. The flow ratio is the mean flow times of each configuration divided by that of configuration 2. A flow ratio less than 1 suggests a better performance than the base configuration, and the less the better. Conversely, a flow ratio larger than 1 implies a worse performance than the base case, and the bigger the worse.

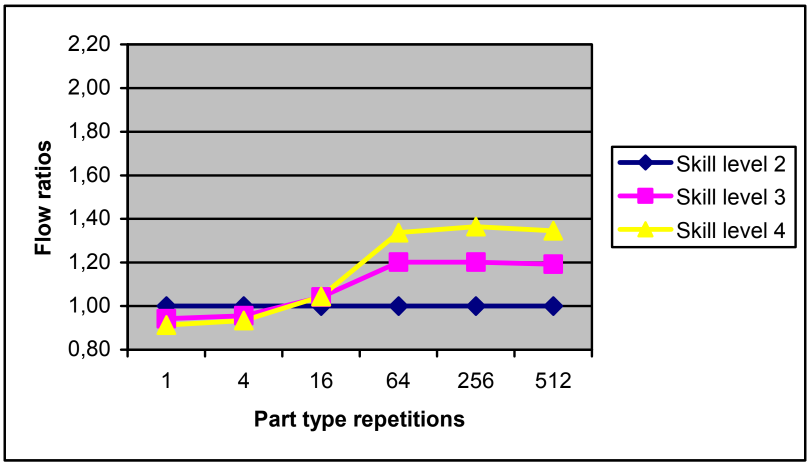
In Figure 3.11 (a), the job arrival interval is kept as a constant. It shows that with respect to the relative performance of the three cross training configurations, three situations may be distinguished.

The first situation is a highly dynamic environment, i.e. part type repetitions less than 16. In such an environment, skill level 4 performs better than skill level 3, which in turn better than skill level 2. In other words, a high level of cross training provides a better performance than a low level of cross training in a highly dynamic environment.

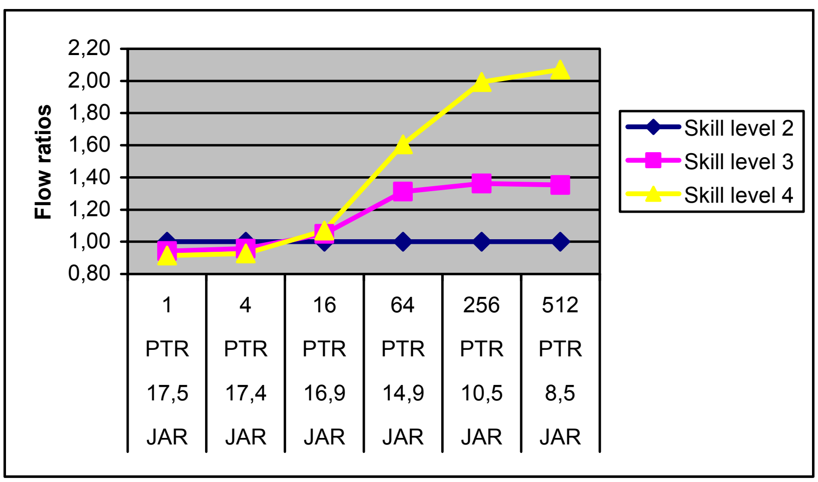
The second situation is a relatively stable environment, i.e. part type repetitions larger than 16 but smaller than 256. The results start flipping over. When part type repetitions become larger than 16, skill level 2 starts to have the best performance, and skill level 3 becomes the second best, while skill level 4 becomes the worst. Furthermore, the difference in performance between skill levels increases with the number of part type repetitions.

The third situation is a more stable environment, i.e. part type repetitions larger than 256. The differences between skill levels become more stabilized, or in other words, they do not change much with the increase of part type repetitions anymore.

In Figure 3.11 (b), the worker utilization is kept constant, i.e. around 85%. The three levels of cross training perform in a pattern similar to the case at the constant job arrival interval (see Figure 3.11 (a)). However, as expected, the differences in performance between skill levels become bigger, especially for the higher levels of part type repetitions.



(a). at a constant job arrival rate 17.5.



(b). at a nearly constant worker utilization level of 85%
PTR = the number of part type repetitions
JAR = Job arrival interval

Figure 3.11
Flow ratios as a function of part type repetitions (i.e. part type repetitions) and the level of cross training (i.e. skill levels, 2, 3, and 4).

3.2.1.3 Discussion and conclusions

In a highly dynamic environment, i.e. part type repetitions less than 16, it may be better to train workers for more skills. When part type repetitions are small, a part type will be produced a few times and then will be drawn out of the system. The fluctuations in workload will thus be rather strong. With a high level of cross training, workers may move more freely on the shop floor, and in this way, provide a quicker response to short-term shifts in workload patterns. Though there are costs related to learning and forgetting, it seems that they do not offset the benefits of additional worker flexibility. This explains why a higher level of cross training performs better in case of low part type repetitions.

In a more stable environment, i.e. part type repetitions larger than 256, it may be better to train workers for fewer skills. When part type repetitions are large, a part type will be produced many times before it is out of the system, and consequently, the fluctuations in workload will be smoother. On the other hand, according to our assumption, a part type will be assigned to one department, the workloads may not be evenly distributed among stations, and consequently, with large part type repetitions, the balance of workload among workers becomes an important issue. A low level of cross training, together with chaining, seems to be sufficient to shift work from a heavily loaded worker to a lightly loaded worker, and in this way, to redistribute workloads among workers, which in turn leads to a better performance. Conversely, a high level of cross training may be associated with a considerable amount of costs due to learning and forgetting, and as a result, its advantages have been compromised. This explains why a low level of cross training performs better in case of high part type repetitions.

The results suggest that the advantages of cross training may vary with part type repetitions. In a dynamic environment, a high level of cross training seems to be a better choice in terms of providing a quick response to the workload fluctuations. Conversely, in a stable environment, it may be better to train workers for fewer skills and to allocate their skills in a proper way (i.e. chaining), and in this way to reduce the costs related to learning and forgetting and to balance workloads.

Control rules are not studied in this study. Only several most commonly used control rules are used as the parameters in the model. We believe that control rules that aim at facilitating the learning processes and reducing the chances of interruptions may have the potential to improve system performance. Future research may pay attention to these rules.

3.2.2 Degree of chaining

In this section, we first specify the experimental settings, which are specially designed to examine the relationship between the effectiveness of chaining and part type repetitions. Next, we present the results from the experiments. At the end, we provide a discussion and conclusions.

3.2.2.1 Experimental design

As noted earlier in Section 2.3, six levels of part type repetitions 1, 4, 16, 64, 256, and 512 are selected to represent a variety of part type repetitions. The degree of chaining has been operationalized by two skill allocation configurations, shown in Figure 3.12 (see also Section 2.3, Table 2.2). In these configurations, workers are trained for two skills, but allocated in two different ways. One has one long chain, while the other has two short chains.

Configuration 1: a long chain

	D1	D2	D3	D4
W1	S	S		
W2		S	S	
W3			S	S
W4	S			S

Configuration 2: two short chains

	D1	D2	D3	D4
W1	S	S		
W2	S	S		
W3			S	S
W4			S	S

Figure 3.12 Degree of chaining
D = department
S = slow worker
W = worker

Similar to Section 3.2.1, the analysis of the results will be conducted along two directions (i.e. see Table 3.8). Along the vertical direction, it shows how the performance of worker skill allocation configurations varies with part type repetitions, for each job arrival interval. Along the line from the top left to the bottom right, it demonstrates how each worker skill allocation configuration performs with various part type repetitions, at a constant worker utilization level of around 85%.

To obtain the lowest job arrival intervals, similar to Section 3.2.1, we first look for the configuration that produces the worst performance in terms of the highest mean flow times in most of the cases. As shown in Table 3.8, configuration 2 with two short chains has the highest mean flow times most of the times, and therefore, it is considered as the bottom of the performance.

The lowest job arrival intervals are then calculated from configuration 2. For each part type repetition, we search for the job arrival interval, which results in a worker utilization level of 85%. We find 17.5, 17.4, 16.2, 12.3, 8.2, and 6.7, which correspond to part type repetitions 1, 4, 16, 64, 256, and 512, respectively.

We try to combine the six part type repetitions with the six lowest job arrival intervals. Not all the combinations are feasible. We obtain 21 combinations. For two skill allocation configurations, we get in total 42 experimental cells.

The simulation runs and data collection procedures are similar to previous sections.

3.2.2.2 Results

Results from the experiments are presented in Table 3.8 for each of the two performance measures, mean flow times, and worker utilization. In order to test the effects of the experimental variables on the performance measures, a MANOVA was conducted for each job arrival interval (see Table 3.9). The main effects of each experimental factor for all of the performance measures were significant at a .001 level. Therefore, part type repetitions and the degree of chaining have a significant impact on system performance.

Similar to Section 3.2.1, the analysis in this section was carried out in two phases, a constant job arrival interval, i.e. 17.5 seconds, and a constant worker utilization level around 85%.

Figure 3.13 (a) is based on a constant job arrival interval. It demonstrates that a long chain has advantages over short chains for all the levels of part type repetitions. It also shows that the difference in mean flow time between a long chain and short chains decreases with the increase of part type repetitions. This is mainly due to the decrease of worker utilization. It has been noted that the difference in performance between alternative options is smaller at a low worker utilization level (Hogg et al. 1977).

Figure 3.13 (b) is based on a constant worker utilization level around 85%. It shows that in general a long chain outperforms short chains in all the dynamic situations. However, the relative advantages may vary with part type repetitions. The relative performance of short chains presents a U-shape. In a highly dynamic environment, i.e. the number of part type repetitions less than 16, a long chain has more advantages. In a less dynamic environment, i.e. the number of part type repetitions is larger than 16 but less than 64, the advantages of a long chain reduce. In a more stable environment, it increases again.

Table 3.8 Experimental results for chaining

Cross		Job arrival intervals											
training		17.5		17.4		16.2		12.3		8.2		6.7	
policies		UT	MFT	UT	MFT	UT	MFT	UT	MFT	UT	MFT	UT	MFT
A long	PTR												
chain	1	0.86	149.74										
	4	0.85	139.79	0.85	143.47								
	16	0.80	113.97	0.80	115.34	0.86	139.70						
	64	0.63	68.95	0.63	69.23	0.67	72.76	0.85	116.26				
	256	0.43	43.00	0.43	43.05	0.46	43.72	0.59	48.67	0.85	94.56		
	512	0.35	35.38	0.35	35.44	0.38	35.72	0.48	38.04	0.70	51.05	0.85	89.73
Two short	PTR												
chains	1	0.86	177.58										
	4	0.85	165.53	0.85	167.22								
	16	0.80	127.27	0.80	127.88	0.85	158.44						
	64	0.63	73.64	0.63	74.02	0.67	78.75	0.85	134.09				
	256	0.43	44.58	0.43	44.67	0.46	45.46	0.59	51.86	0.85	114.88		
	512	0.35	36.30	0.35	36.32	0.38	36.81	0.49	40.10	0.70	56.78	0.85	114.32

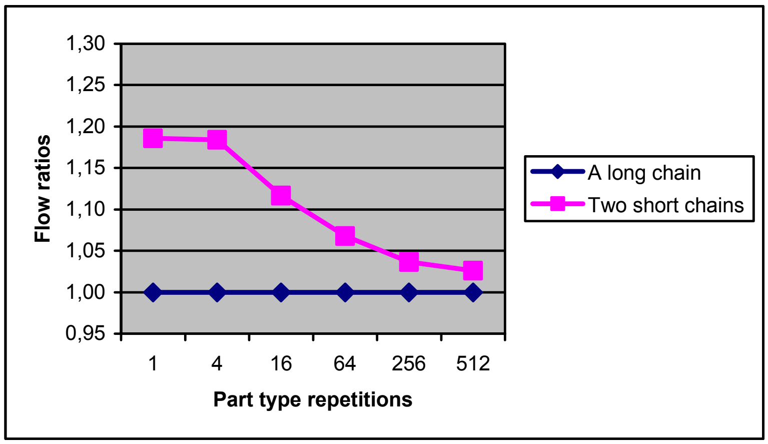
PTR, the number of part type repetitions.

UT, worker utilization.

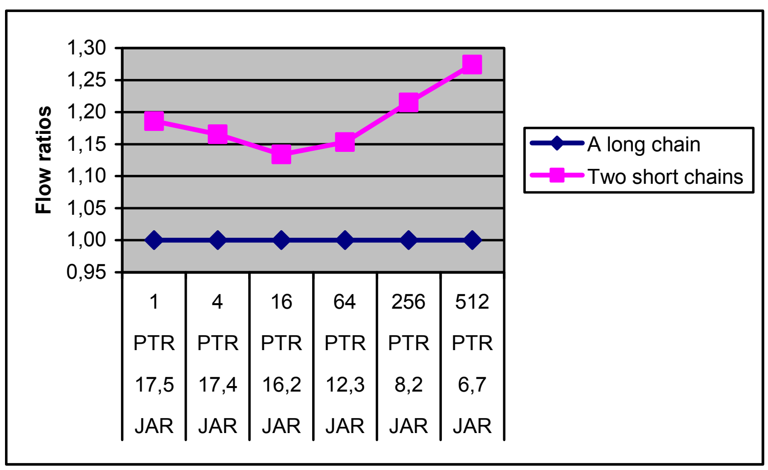
MFT, mean flow times.

Table 3.9
MANOVA results with dependent variables: mean flow times (MFT), and worker utilization (UT); and independent variables: the number of part type repetitions (PTR), and Chaining (CN).

Job Arrival		Multivariate			Univariate		
Intervals		F	df	p<	Variables	F	p<
17.5	CN	1242.95	347	0,001	MFT	1495.45	0,001
					UT	0	1
	PTR	19917.55	694	0,001	MFT	20055.4	0,001
					UT	176824.9	0,001
	CN*PTR	109.25	694	0,001			
17.4	CN	904.23	289	0,001	MFT	1189.97	0,001
					UT	3.72	0,1
	PTR	25579.42	578	0,001	MFT	33107.68	0,001
					UT	209781.63	0,001
	CN*PTR	121.1	578	0,001			
16.2	CN	798.21	231	0,001	MFT	1125.63	0,001
					UT	6.57	0,1
	PTR	36759.16	462	0,001	MFT	62463.71	0,001
					UT	222811.03	0,001
	CN*PTR	153.04	462	0,001			
12.3	CN	314.48	173	0,001	MFT	501.65	0,001
					UT	0	1
	PTR	10198.57	346	0,001	MFT	24779.83	0,001
					UT	129181.4	0,001
	CN*PTR	102.31	346	0,001			
10.5	CN	52.64	115	0,001	MFT	95.46	0.001
					UT	0.42	1
	PTR	9681.73	115	0,001	MFT	1453.43	0,001
					UT	19526.86	0,001
	CN*PTR	21.28	115	0,001			
8.5	CN	34.52	57		MFT	44.31	0,001
					UT	3.97	0,1
	PTR		57.5		MFT		
					UT		
	CN*PTR		57.5				



(a). at a constant job arrival rate 17.5.



(b). at a nearly constant worker utilization level of 85%

Figure 3.13 Flow ratios as a function of part type repetitions (i.e. the number of part type repetitions) and the degree of chaining (i.e. a long chain, and two short chains).
PTR = the number of part type repetitions
JAR = Job arrival interval

3.2.2.3 Discussion and conclusion

A long chain is always better than two short chains. However, the relative advantages of a long chain seem to be strongly related to part type repetitions.

When part type repetitions are small, a part type will only be produced a few times and then it is withdrawn from the system, and as a result, the shifts in workload patterns will be very frequently. By creating links between workers and their skills, a long chain can shift work from a heavily loaded worker to a lightly loaded worker, and in this way, it improves the utilization of worker capacity and accelerates the responsiveness to changes in workload. Furthermore, when part type repetitions are small, workers have just started learning, and the effect of learning and forgetting is not very strong. This explains the bigger advantages of a long chain in the case of small part type repetitions.

When part type repetitions are large, a part type will be produced many times before it goes out of the system. According to our assumption, a part type will be assigned to only one department, and consequently, the workloads may not be evenly distributed among departments. In such a case, the need for workload balance is higher. Furthermore, when part type repetitions are large, as workers have already learned, the effect of learning and forgetting is not very strong either. In such a case, a long chain has more advantages than short chains.

It seems that when the number of part type repetitions is at a moderate level, i.e. around 16, workload fluctuations are reduced to some extent in comparison to small part type repetitions, and workload unbalances are not as worse as in the case of large part type repetitions, and therefore, the need for chaining is reduced. Furthermore, the effect of learning and forgetting is stronger at this stage. In short chains, workers are less involved in the response to workload fluctuations, which results in less interference with the learning process, and workers may move fast along the learning curve. In the contrary, in a long chain, workers are more involved in the response to workload fluctuations, which in turn leads to more interference in the learning process, and workers may move slowly along the learning curve. As a result, the relative advantages of a long chain are smaller.

The results suggest that chaining performs well even in a learning and forgetting situation, though the relative advantages of chaining may vary with part type repetitions. In general, chaining is more important in situations with either high workload fluctuations, i.e. the consequences of small part type repetitions, or highly unbalanced workloads, i.e. the outcomes of large part type repetitions.

3.3 Summary of Chapter 3

With respect to research question 1, the impact of part type repetitions and the individual learning patterns, 4 hypotheses have been tested, and supported by the results. Table 3.10 provides an overall summary.

Table 3.10 Summary of results Hypotheses 1 to 4

Name	Hypothesis	Predicted Effect
H1a	the number of part type repetitions and mean flow times.	Negatively related*
H1b	the number of part type repetitions and mean worker utilization level	Negatively related*
H2	the number of part type repetitions and the maximum production capacity	Positively related*
H3	interaction of the number of part type repetitions and the individual learning patterns	Interaction*
H4	the difference in mean flow times between fast and slow learners and the level of worker utilization.	Positively related*

* supported

Hypotheses 1a and 1b proposed that part type repetitions are negatively related to mean flow time and worker utilization.

Hypothesis 2 stated that part type repetitions will have a positive effect on the maximum production capacity.

Hypothesis 3 showed that there is an interactive effect of part type repetitions and the individual learning patterns, and in particular, for small part type repetitions, fast learners will realize a lower level of mean flow time and worker utilization; for large part type repetitions, slow learners will realize a lower level of mean flow time and worker utilization.

Hypothesis 4 predicted that the difference in mean flow time between fast and slow learners increases with the level of worker utilization, and the differences are the biggest at the highest level of worker utilization.

As for research question 2, the relationship between the level of cross training and part type repetitions, the results show that the optimal level of cross training may depend on part type repetitions. In a highly dynamic environment, i.e. small part type repetitions, a high level of cross training outperforms. Conversely, in a more stable environment, i.e. large part type repetitions, a low level of cross training provides a better performance.

Concerning research question 3, the effectiveness of chaining in a variety of dynamic environments, the results suggest that a long chain is always better than short chains, however, the relative advantages of a long chain seems to vary with part type repetitions. A long chain seems to have more advantages in either a highly dynamic situation, i.e. small part type repetitions, or a highly stable situation, i.e. large part type repetitions. In a situation between these two extremes, i.e. moderate part type repetitions, the relative advantages of a long chain are compromised.