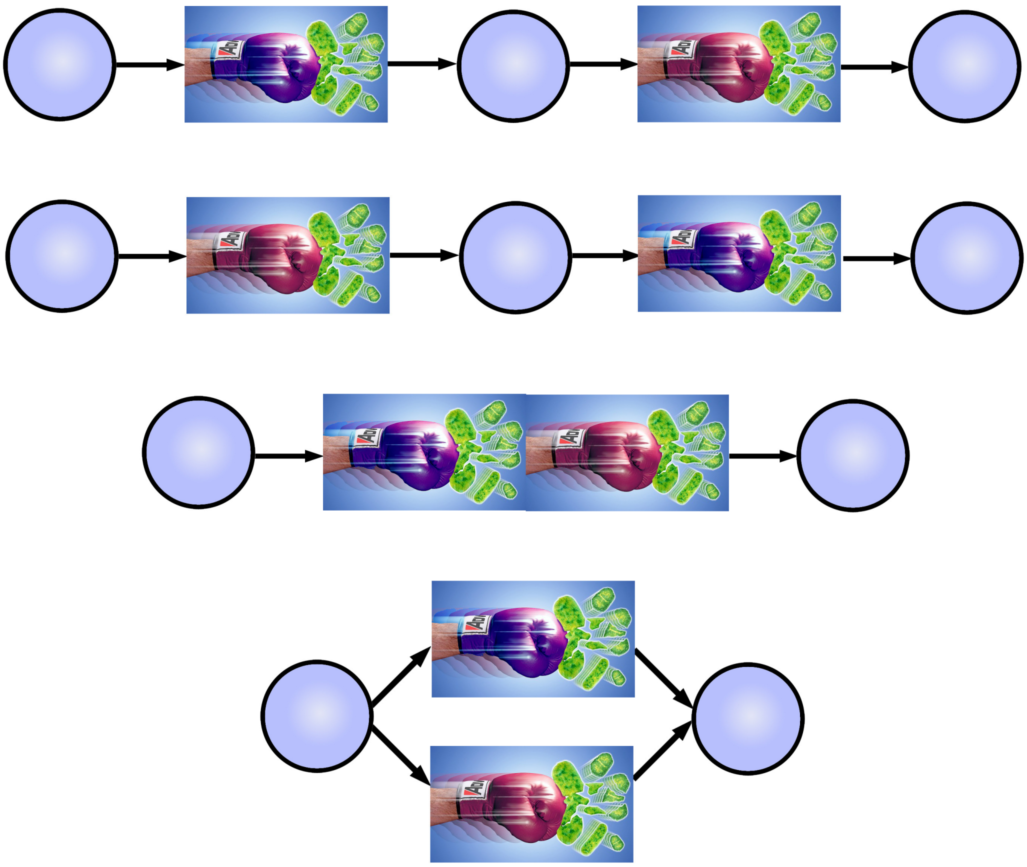
Knock-out heuristic : quantification of the implementation

Knock-out heuristic

Quantification of the implementation



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1. Introduction

This report has been written as a result of a simulation study in which the impact of the implementation of a particular redesign heuristic has been quantified. The heuristic investigated in this study is the knock-out heuristic (Reijers, 2003), (Van der Aalst, 2000). In order to be able to make a quantification of the impact of the implementation, a set of models has been created. These models have been simulated and the results have been analyzed and compared. Finally conclusions have been drawn, based on the results of the output analysis.

1.1 Business process simulation

According to van Hee and Reijers (2000), two quantitative techniques can be used:

- Analytical techniques
- Simulation techniques

Due to the highly variable activity times and interdependencies between the resources (Tumay, 1996), analytical techniques are not suitable in this project. The ability of simulation techniques to model stochastic, dynamic situations make this technique very suitable to comply with the goal of this project. Therefore it is chosen to use a simulation study to quantify the impact of a business process redesign effort.

Greasly (2003) defines business process simulation (BPS) as a technique that allows the current behaviour of a system to be analyzed and understood and helps to predict the performance of that system under different scenarios determined by the decision maker. In this study, the redesigned knock-out system is the scenario of which the performance is predicted. Cho et al. (1998) state that BPS can be used not only to analyze an “as-is” model of the existing process, but also assess the potential value and feasibility of “to-be” models. Here, the “to-be” models are again the redesigned knock-out models for a number of scenarios.

1.2 Project plan

Before the start of the simulation study a project plan has been made, based on the plan of Law and Kelton (2000) and Mehta (2000). The following steps have been taken in this simulation study:

1. Project definition
    - Establish objectives
    - Determine scope and level of detail
    - Choose performance measures that will be used
2. Define and build models
3. Make pilot runs for validation purposes
4. Validate the model
5. Design experiments
    - Determine length of warm-up period
    - Determine run length
    - Calculate number of replications
6. Make the actual production runs and record results
7. Analyze the output of the production runs
8. Document results and draw conclusions

Step 6 and 7 appeared to be an iterative process, because additional measurements have been executed after the simulation of the proposed setups in order to gather stronger evidence for the conclusions.

Table 1 shows where in this report the above mentioned steps are described.

Step	Section/Chapter
1. Project definition	Chapter 1
2. Define and build models	Chapter 2 and 3
3. Pilot runs	Section 2.3
4. Validation	Section 2.3
5. Design of experiment	Chapter 4 and 5
6. Production runs and results	Appendix D, E and F
7. output analysis	Chapter 6, 7 and 8
8. conclusions	Chapter 9

Table 1: Structure of the report

1.3 Project definition

The first step in this simulation study has been the project definition step. In this step the objectives are established, the scope and level of detail are determined and the performance measures are specified.

Project objective
The main objective of this simulation study is:
The quantification of the impact of the implementation of "the knock-out redesign heuristic".

The KO redesign heuristic consists of three separate redesign rules. A set of sub-objectives is drawn up for every KO redesign rule in order to comply with the main objective of this study, stated above.

Swapping tasks rule:

- Determine for every model variant what the impact of the swapping tasks rule is.
- Determine what the impact of the swapping tasks rule is with different resource setups.
- Determine what the impact of the swapping tasks rule is with different service times.

Combining tasks rule:

- Determine for every model variant what the impact of the combining tasks rule is.
- Determine what the impact of the combining tasks rule is with different arrival rates.
- Determine what the impact of the combining tasks rule is with different setup ratios.

Parallel tasks rule:

- Determine for every model variant what the impact of the parallel tasks rule is.
- Determine what the impact of the parallel tasks rule is with equal and different parallel service times.
- Determine what the impact of the parallel tasks rule is with high and low parallel reject probabilities.
- Determine what the impact of the parallel tasks rule is with different arrival rates.

Scope and level of detail
To achieve the objective of this project, a balance must be found in the trade-off between the degree to which the model represents the reality and the complexity of the model. The model, which will be described in Section 2.1, has been chosen for this study. More extensive models that incorporate the ability to model overtime, part-time work and workers, shifts etc. have also been created. For the purpose of this study it is not necessary to use models, which incorporate such high levels of detail. Since eventually two models will be compared, all unused extra details will become redundant and be called off in the comparison.

Used performance measures

Before modelling the alternatives it must be clear what measures are going to be used to measure and express the impact of the redesign effort. The result of the preceding literature review (Loosschilder, 2006) is a set of quantified performance measures that could be used for performance measurement in workflows. In this simulation study a subset of the set of performance measures that has been drawn up in the literature review has been used. The performance measures of the three dimensions of performance that have been used can be found in Table 2. A detailed description of the measures can be found in Loosschilder (2006).

Performance measures		
Time	**Cost**	**Flexibility**
Lead time	Total utilization	Labour flexibility WF
Queue time per task	Utilization per res.	Labour flexibility Res.
Total queue time	Work in progress	Mix flexibility per task
Setup time		Routing flexibility
Service time		Volume flexibility
Wait time		

Table 2: Used performance measures

None of the external quality performance measures of Loosschilder (2006) have been used in this simulation project. It appears to be impossible to monitor external quality in this simulation study with the use of a CPN Tools simulation model. It has therefore been decided to omit the measuring of the impact of the redesign heuristic on the external quality dimension.

It also appears that internal quality is too complex and too much depending on factors that cannot be simulated with CPN Tools simulation models. Internal quality is highly dependable on the character and the personality of specific resource. This is also the reason why it has been chosen also to omit this performance dimension from the simulation study.

A new cost measure has been introduced:

- Work in progress: This measure depicts the number of cases that is in the complete system. The work in progress is an indicator of the inventory costs, which has been defined as “the cost of keeping records and products” (Loosschilder, 2006).

Another new measure has been introduced:

- Queue length per task: This indicator measures per task the number of cases in the queue. This measure is only measured for analysis purposes.

The measures queue time per task, total queue time and Queue length per task will only be used for the analysis, in order to explain and clarify certain phenomena. These measures will not be used to determine the impact of the heuristic on a specific dimension. The queue time per task and the queue time total are part of the lead time. Both measures represent times that are not experienced by the external customer (the initiator of the process), since this customer is only interested in good lead time. When for example a certain redesign effort results in longer queue times, but a shorter lead time, it can be concluded that the redesign effort positively affect the time dimension. The same goes for the measure queue length per task. Again, this is a measure that is not experienced by the customer. Therefore, also this measure is only used for the analysis.

All measures of Table 2 will be measured in the simulation study and the results of the different alternatives will be compared and analyzed.

2 Original situation

This report is about the impact of the implementation of the "knock-out heuristic, as already mentioned in the introduction. This particular redesign heuristic is applied to a certain model. This model is an abstract representation of the original situation. This chapter describes the original situation and model.

2.1 Original model

The process of the original situation consists of six sequential knock-out tasks and can be seen in Figure 1. A knock-out task is a task that checks a case in order to decide whether the case should be accepted or rejected. A knock-out task has two possible results: OK and NOK (i.e., not OK). If for a specific case a task results in NOK, the case is rejected immediately. A case is only accepted when all knock-out tasks have a positive outcome (Van der Aalst, 2000).

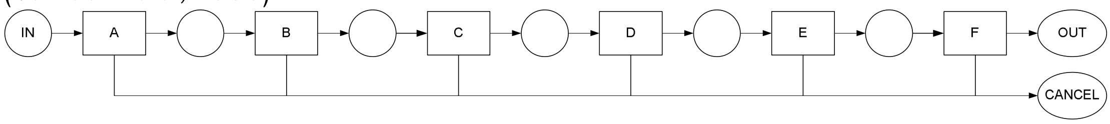

Figure 1: Model of the original situation

All tasks in the original situation are knock-out tasks, with their own reject probabilities, setup times and service times. All tasks have exponentially distributed setup and service times and it is assumed that all resources have equal setup and service times per task. It is assumed in this research that the KO tasks have no fail probability. Therefore a task is always completed successfully. This is in contrast to the research of Van der Aalst (2000). It is chosen to only model pure working time. This means that 1 week in the model consists of 40 hours (40*60=2400 minutes). Because of this it is assumed that overtime, part time work and shifts do not take place in the original situation and are therefore left out of consideration.

Various variants of the original model have been used as a starting point for the different redesign possibilities. This is described in Chapter 3. As a basis for the comparison with the redesigned situation, a coloured Petri net has been created in CPN Tools. Details and an explanation of the model can be found in the report "Explanation of the simulation model". The settings of the model, the results of the simulation and the comparison with the redesigned situation are discussed in Chapter 4 and Chapter 5.

2.2 Classification of the model

Law and Kelton (2000) state that in general simulation models can be classified along three different dimensions:

- Static vs. dynamic simulation models
- Deterministic vs. stochastic simulation models
- Continuous vs. discrete simulation models

The simulation model in this study can be classified as a "dynamic, stochastic, discrete simulation model".

- The model is a dynamic model, because the model represents a system that evolves over time and the flow of time is approximated by simulated time.
- The model is a stochastic model, because the model contains processes controlled by random variables.
- The model is a discrete event simulation model, because the state variables change instantaneous at separate points in time.

2.3 Validation of the original model

After completion of the basic simulation model, a validation of the model has been performed in order to check the validity of the model. A simplified version of the original model has been created, which can be used for this validation. From the different methods of validation described in Mehta (2000), it is chosen to compare the results of simulating the validation models with the analytical outcomes of mathematical queuing models.

The validation model is a network of queues. According to Kulkarni (1999) is a network of queues called a Jackson network when it satisfies the following assumptions:

- The network has N single-station queues
- The i-th station has s_i servers
- There is an unlimited waiting room at each station
- Customers arrive at station i from outside the network according to PP(λ_i). All arrival processes are independent of each other
- Service times of customers at station i are independent and identically, exponentially distributed random variables with parameter μ_i
- Customers finishing service at station i join the queue at station j with probability $p_{i,j}$, or leave the network altogether with probability r_i, independently of each other

The validation model complies with all these assumptions and is therefore a Jackson network, consisting of 6 M/M/s queues with the following parameters:

Parameters of the Jackson network						
	Task A	**Task B**	**Task C**	**Task D**	**Task E**	**Task F**
s	2	3	2	2	3	2
λ	1/15	0	0	0	0	0
μ	1/20	1/40	1/10	1/20	1/40	1/10
r	0	0	0	0	0	1

Table 3: Parameters of the Jackson network

With the formulas of Kulkarni (1999), the performance measures of Table 4 can be calculated.

Theoretical values validation model								
			Task A	**Task B**	**Task C**	**Task D**	**Task E**	**Task F**
ρ	Utilization of the resources	$\frac{\lambda}{s \cdot \mu}$	0.6667	0.8889	0.3333	0.6667	0.8889	0.3333
L_q	Expected number of cases in the queue	$p_s \cdot \frac{\rho}{(1-\rho)^2}$	1.0667	6.3801	0.0833	1.0667	6.3801	0.0833
W_q	Expected queuing time	$\frac{L_q}{\lambda}$	16.0000	95.7017	1.2500	16.0000	95.7017	1.2500
W	Expected time of a case in the system	$W_q + \frac{1}{\mu}$	36.0000	135.7017	11.2500	36.0000	135.7017	11.2500

Table 4: Theoretical values validation model

The theoretical value for the lead time is the sum of all system times in Table 4:

$$\sum W = W_A + W_B + \ldots + W_F = 365.9034$$

After the simulation the results have been collected and analyzed. The 95% confidence intervals are shown in Table 5.

Confidence intervals simulated values						
	Task A	**Task B**	**Task C**	**Task D**	**Task E**	**Task F**
ρ	(0,6583;0,6822)	(0,8812;0,911)	(0,3311;0,3426)	(0,656;0,677)	(0,877;0,9022)	(0,325;0,3340)
L_q	(1,0135;1,2043)	(5,8154;8,1645)	(0,0806;0,0931)	(0,9666;1,1693)	(5,3451;7,3813)	(0,0734;0,086)
W_q	(15,047;17,682)	(86,672;120,282)	(1,2048;1,3831)	(14,452;17,359)	(79,8183;110,378)	(1,1053;1,288)
W	(350,587983,396,555067)					

Table 5: Confidence interval of the simulated values of the validation model

In the last row of Table 5 only one confidence interval is shown. This is the 95% confidence interval of the lead time of a case.

From the values of Table 4 and the confidence intervals of Table 5 it can be concluded that all theoretical values fall within the 95% confidence intervals. Therefore the model can be considered as a valid simulation model.

More details on the validation of the simulation model can be found in the report "Validation of the simulation model.doc".

3 Redesigned situation

The redesigned situation is the result of applying the knock-out redesign heuristic to the model of the original situation. The paper of Van der Aalst (2000) has been used as a guide in the application of the knock-out heuristic.

3.1 The knock-out heuristic

The knock-out heuristic provides rules that can be used to redesign a knock-out process in order to increase a certain aspect of the performance of a business process. According to Van der Aalst (2000) there are three possibilities of redesigning a knock-out process:

- Swapping knock-out tasks
- Combining knock-out tasks
- Putting knock-out tasks in parallel

A combination of the above mentioned redesign possibilities can also be applied when redesigning a knock-out process. In a combination, the three possibilities can be executed in any order; however, Van der Aalst (2000) suggests applying them in the above stated order.

All three redesign possibilities have been investigated. The following three sections each describe one of the redesign possibilities. The used cases, the exact setup of the simulations and the chosen variations are described in Chapter 4.

3.2 Swapping KO tasks

The first redesign rule is the swapping KO tasks rule. As many knock-out processes are characterized by a high degree of freedom with respect to the order in which tasks can be executed, there is a possibility to change the order in which the tasks are executed (Van der Aalst, 2000). In this redesign it is assumed that there is no possibility for combining tasks or putting tasks in parallel and that are no precedence constraints.

The original model in this redesign possibility is the same as the earlier described original model and can be seen in Figure 2:

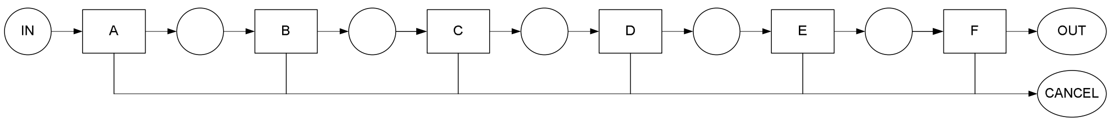

Figure 2: Original model swapping KO tasks rule

For every case and setup, the KO ratios (=reject probability/process time), described by heuristic 1 and 2 of Van der Aalst (2000), of every possible combination (e.g. AEDFBC) have been calculated. This resulted in 720 different ratios for every setup. A number of stable (none of the utilizations exceeds 100%) combinations is chosen from the sorted list of ratios and has been compared to the outcomes of the original situation. Which combinations have been chosen is described later in this report. An example of a swapping task redesign is shown in Figure 3.

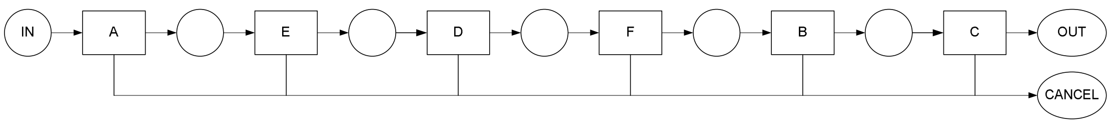

Figure 3: Example of a swapping task redesign

3.3 Combining KO tasks

The second redesign rule is the combining KO tasks rule. Two separate, subsequent KO tasks, which are executed by the same resource, can be combined into one composite knock-out task, which is executed by one resource without interruption. An advantage of this redesign is that no setup is needed for the second subtask. A drawback of this rule is that both subtasks are executed, even if the first subtask indicates that the case will be rejected (Van der Aalst, 2000).

In this redesign it is assumed that there is no possibility of putting tasks in parallel and that there are no constraints with respect to the order of execution of the tasks and the possibility of combining tasks.

The model of the original situation described earlier has also been used for this redesign as a starting point for the redesigning effort. After applying heuristic 2 (the swapping KO tasks rule) of Van der Aalst (2000), the combination of Figure 4 appeared to be the optimal combination. The application and the results of the swapping tasks rule are explained later in this report.

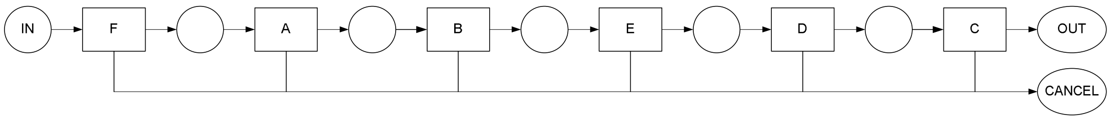

Figure 4: Original model after swapping tasks rule

The possibility of combining tasks has been investigated for different setups. The rules of heuristic 3 and 4 (Van der Aalst, 2000) have been used to determine what tasks to combine. Different redesigns have been simulated and compared to the original model. An example of a redesign is shown in Figure 5.

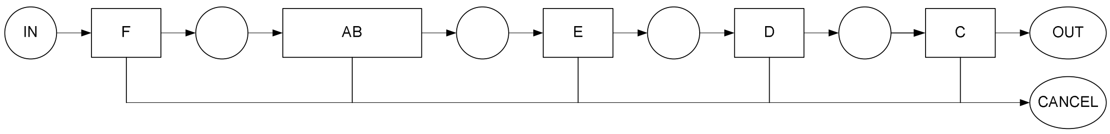

Figure 5: Example of a combining tasks redesign

3.4 Parallel KO tasks

When tasks can be executed at the same time, it can be considered to put tasks in parallel. This is the third KO redesign rule. Putting tasks in parallel can reduce the lead time of a case considerably. A drawback of putting multiple knock-out tasks in parallel is that all parallel tasks must be executed completely, even when one of the parallel tasks returns NOK. The case is only rejected after synchronization.

In this redesign it is assumed that there is no possibility for combining tasks into a composite task and that it is not possible to swap tasks.

Also for this redesign, the earlier described original model is the starting point for the simulation. The swapping tasks rule cannot be applied, due to the limitation regarding the order of execution of the tasks. The original model is depicted in Figure 6.

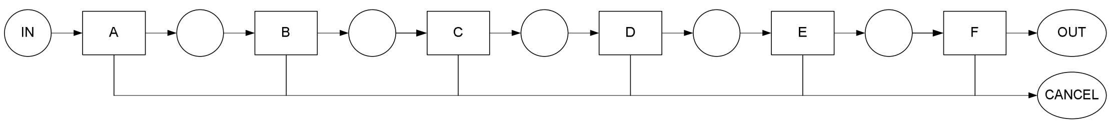

Figure 6: Original model parallel KO tasks rule

The redesigned model is a model in which tasks B and C are executed in parallel. It is shown in Figure 7.

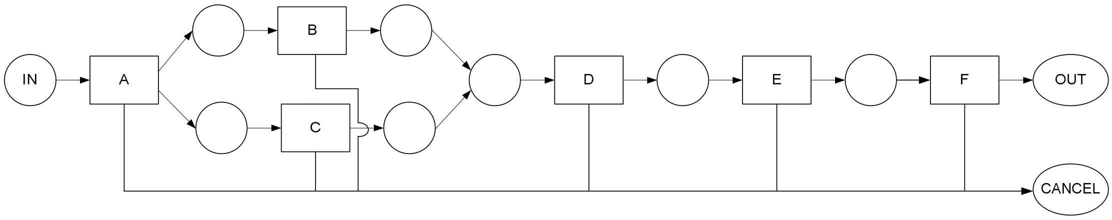

Figure 7: Parallel KO tasks redesign

Different variations and setups have been simulated for the parallel tasks rule. The exact setups, the used model variants and the setup of the simulations are described in the next chapter.

4 Experiments

This chapter describes step 5 of the project plan: the design of the experiments. First it has been decided what variation to use for every redesign possibility and model variants have been developed. Next, the warm-up period, the run length and finally the number of replications have been calculated.

4.1 Setup swapping tasks rule

This section describes the setup of the experiments concerning the swapping tasks rule. First the chosen variations are explained. Next the developed model variants are described.

4.1.1 Variations swapping tasks rule

In order to quantify the impact of the implementation of the swapping task rule, it has been chosen to introduce two types of variations: variations in service times and variations in resource classes and allocation.

Variations in service times

The first variation is a variation in service times. This variation is chosen in order to investigate what the impact of the swapping tasks rule is on systems with varying service times, since a variation in service time affects the KO ratio described in heuristic 1 and the KO ratio of heuristic 2 (Van der Aalst, 2000). Both heuristics can be used to determine the optimal redesign with the swapping tasks rule.

Three cases, with each differing service times, have been developed in order to introduce variation in service times. This variation results in three different sets of KO ratios. The following abbreviated terms are used in Table 6 and the following two tables:

- rp(t) = the reject probability of task t
- pt(t) = the processing time of task t

Case 1:

Task	rp(t)	pt(t) [min]	pt(t) [hours]	KO Ratio	Arrival rate [h^{-1}]
A	0.05	10	0.1667	0.30	19
B	0.15	25	0.4167	0.36	
C	0.20	40	0.6667	0.30	
D	0.12	20	0.3333	0.36	
E	0.10	15	0.2500	0.40	
F	0.17	30	0.5000	0.34	

Table 6: Parameters case 1 swapping tasks

The service times in case 1 have been chosen so that the KO ratios of the different tasks are in the same order of magnitude, with some ratios being identical.

Case 2:

Task	rp(t)	pt(t) [min]	pt(t) [hours]	KO Ratio	Arrival rate [h^{-1}]
A	0.05	7	0.1167	0.4286	17
B	0.15	25	0.4167	0.3600	
C	0.20	45	0.7500	0.2667	
D	0.12	10	0.1667	0.7200	
E	0.10	12	0.2000	0.5000	
F	0.17	35	0.5833	0.2914	

Table 7: Parameters case 2 swapping tasks

The service times of this second case are chosen in such a way that the KO ratios of the tasks are completely different, with none of the tasks having the same ratio.

Case 3:

Task	rp(t)	pt(t) [min]	pt(t) [hours]	KO Ratio	Arrival rate [h^{-1}]
A	0.05	40	0.6667	0.0750	12
B	0.15	40	0.6667	0.2250	
C	0.20	40	0.6667	0.3000	
D	0.12	40	0.6667	0.1800	
E	0.10	40	0.6667	0.1500	
F	0.17	40	0.6667	0.2550	

Table 8: Parameters case 3 swapping tasks

All tasks in case 3 have identical service times.

Constant arrival rates have been chosen for every separate case.

Variations in resource classes and allocation

The second type of variation is diversity in resource classes and the allocation of resources. This variation has been implemented in order to test what the impact of the swapping tasks rule is on models with varying resource setups. Therefore different resource classes have been defined and a varying number of resource classes have been introduced for every case. The categorization into the different resource classes and the executable tasks per resource class are shown in Table 9.

Alternative 1: 2 Tasks parallel						
# Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
6 Resource classes	A	B	C	D	E	F
3 Resource classes	AB	CD	EF			
2 Resource classes	ABC	DEF				
1 Resource classes	ABCDEF					

Table 9: Resource classes swapping tasks rule

4.1.2 Model variants swapping tasks rule

A Combination of the two variations of section 4.1.1 leads to 12 different model variants. The model variants are summed up in Table 10. The numbers behind the resource classes represent the number of resources per resource class.

Model variants swapping tasks								
	Case	Resources classes	1	2	3	4	5	6
Model variant SW1	Case 1	A-B-C-D-E-F	6	8	12	8	8	10
Model variant SW2	Case 1	AB-CD-EF	14	20	18			
Model variant SW3	Case 1	ABC-DEF	26	26				
Model variant SW4	Case 1	ABCDEF	52					
Model variant SW5	Case 2	A-B-C-D-E-F	6	8	12	8	8	10
Model variant SW6	Case 2	AB-CD-EF	14	20	18			
Model variant SW7	Case 2	ABC-DEF	26	26				
Model variant SW8	Case 2	ABCDEF	52					
Model variant SW9	Case 3	A-B-C-D-E-F	9	9	9	9	9	9
Model variant SW10	Case 3	AB-CD-EF	18	18	18			
Model variant SW11	Case 3	ABC-DEF	27	27				
Model variant SW12	Case 3	ABCDEF	54					

Table 10: Model variants swapping tasks

As modelling and simulating every possible swapping task redesign for all model variants (720 (=6!) possibilities per model variant) results in a massive simulation effort, it has been chosen only to simulate a number of combinations per model variant and to compare these to the original situation (ABCDEF). As both, heuristic 1 and 2 (Van der Aalst, 2000) can be used to redesign KO processes, the redesigns of both heuristic have been tested on correctness and applicability. The following combinations have been simulated for every model variant:

- The optimal combination according to heuristic 2
- The number 10 of the stable combinations according to heuristic 2
- The number 25 of the stable combinations according to heuristic 2
- An average, stable combination according to heuristic 2
- The least optimal, stable combination according to heuristic 2
- A combination with decreasing KO ratios according to heuristic 1

For some setups, the optimal combination according to heuristic 1 is identical to the optimal combination of heuristic 2 and for some setups, heuristic 1 leads to more then 1 optimal redesign.

A complete overview of all simulated combinations can be found in Appendix A.

4.2 Setup combining tasks rule

In contrast to the model variants of the swapping tasks rule where the processing times varied, one case has been developed for this rule, because the processing times are constant for all model variants. This case is the starting point for the simulation of all model variants. All variations that are described in the next subsection are inserted in this starting case. The parameters of the starting case are depicted in Table 11:

Task	Reject P	Proc T [h]	Proc T [min]	KO Ratio
A	0.07	0.1667	10	0.42
B	0.07	0.2000	12	0.35
C	0.12	0.6000	36	0.20
D	0.05	0.2000	12	0.25
E	0.1	0.3333	20	0.30
F	0.17	0.3333	20	0.51

Table 11: Starting case combining tasks rule

The processing time of a task is the sum of the setup time and the service time. A variation in the ratio setup time/service time is introduced and is specific for every model variant. The processing times of the tasks have been chosen so that:

- A and B have approximately equal processing times (10 vs. 12)
- E and D have differing processing times (12 vs. 20)
- D and C have completely different processing times (12 vs. 36)

These are the only tasks in the original model (FABEDC) that can be combined in the redesign, because two tasks can only be combined when they are executed subsequently and are sharing a resource class.

Also for this rule, a number of variations has been chosen and the resulting model variants have been developed. This is described in the next subsections.

4.2.1 Variations combining tasks rule

It has been chosen to introduce three types of variations, in order to quantify the impact of the combining tasks rule and to determine what the expected impact is on a certain type of model: variations in arrival rate, variations in resource classes and allocation and variations in setup ratios.

Variations in arrival rate
The first introduced variation is diversity in arrival rate. This variation has been chosen, because changing the arrival has a direct effect on the queue times of cases. Applying the combining tasks rule results in one task instead of two, so cases only have to wait in a queue once instead of twice. As arrival rate is also strongly related to the utilization, it has been decided to use three different arrival rates which result in a low, a medium and a high utilization for all resource classes in the original model. Table 12 gives an overview of different arrival rates and the related, approximate utilizations.

Arrival rate [h^{-1}]	Utilization	Arrival rate [h^{-1}]	Utilization
23	50 %	41	90 %
27	60 %	42	93 %
32	70 %	43	95 %
36	80 %	44	97 %
39	85 %	45	99 %

Table 12: Arrival rate - utilization combinations

When the arrival rate is 45 cases/h, the combination of the original model (FABEDC) is not stable any more, because one of the utilizations exceeds 100%.

The following arrival processes have been chosen:
- Poisson process with an arrival rate of 42 cases/h. This value has been chosen in order to investigate the system and the differences after redesign at a high utilization rate of the resources. With this arrival rate, the utilization of the resources is approximately 93% (high).
- Poisson process with an arrival rate of 36 cases/h. This arrival rate has been chosen in order to analyze the system with a utilization of approximately 80% (medium).
- Poisson process with an arrival rate of 23 cases/h. This process has been chosen in order to investigate the impact on a system with a utilization of approximately 50% (low)

Variations in resource classes and allocation
The second variation is a variation in resource classes and allocation. The variation of resource classes directly affects the possibility of combining tasks into one composite task, because combinable tasks must be executed by a resource from the same resource class. It has been decided to investigate models with two types of resource classes, to determine the impact of the combining tasks rule on the performance of systems with differing resource classes:
- A variant with three resource classes: AB-CD-EF. In this variation it is only possible to combine tasks A and B and to combine tasks D and C of the original model (FABEDC). E and F are not executed directly after each other and can therefore not be combined.
- A variant with only two resource classes: ABC-DEF. This resource class variation makes it possible to combine tasks A and B and to combine tasks E and D of the original model (FABEDC).

The number of resources per class has been adapted in such a way that the utilization of all resource classes is approximately equal in the original model. The number of resources per class is shown in Table 13:

<table>
<tr><th>Task</th><th>AB-CD-EF</th><th>ABC-DEF</th></tr>
<tr><td>A</td><td rowspan="2">14</td><td rowspan="3">30</td></tr>
<tr><td>B</td></tr>
<tr><td>C</td><td rowspan="2">22</td></tr>
<tr><td>D</td><td rowspan="3">32</td></tr>
<tr><td>E</td><td rowspan="2">26</td></tr>
<tr><td>F</td></tr>
</table>

Table 13: Number of resources per resource class

Variations in setup time ratios

The third introduced variation is a variation in setup time ratio. The setup time ratio is the part of the processing time of a task that is dedicated to the setup of that task. The setup time is strongly related to the decision whether two tasks should be combined. According to heuristic 3 and 4 of Van der Aalst (2000) it is profitable to combine two tasks if and only if $pt(t_2) \cdot sr(t_2) > pt(t_2) \cdot rp(t_1)$. So it is advisable to combine tasks when the advantage of not executing the setup of the second subtask outweighs the loss of executing the entire composite task when the first subtask returns NOK. For both setups four different setup ratios have been designed, which test this statement. Table 14 shows for every setup ratio whether the statement advices to combine tasks A and B, D and C or E and D.

Combine?	Setup Ratio 1	Setup Ratio 2	Setup Ratio 3	Setup Ratio 4
AB	Yes	Yes	No	No
DC / ED	Yes	No	Yes	No

Table 14: Combine tasks, based on Van der Aalst (2000)?

Table 15 and Table 16 show the setup and service times [min] of the different setup ratios for the simulations, which are used in order to check the results of the statement, shown in Table 14.

	Setup ratio 1		Setup ratio 2		Setup ratio 3		Setup ratio 4	
Task	SetupT	ServT	SetupT	ServT	SetupT	ServT	SetupT	ServT
A	1	9	1	9	1	9	1	9
B	2	10	2	10	0.2	11.8	0.2	11.8
C	3	33	0.5	35.5	3	33	0.5	35.5
D	2	10	2	10	2	10	2	10
E	2	18	2	18	2	18	2	18
F	2	18	2	18	2	18	2	18

Table 15: Setup time ratios for AB-CD-EF

	Setup ratio 1		Setup ratio 2		Setup ratio 3		Setup ratio 4	
Task	SetupT	ServT	SetupT	ServT	SetupT	ServT	SetupT	ServT
A	1	9	1	9	1	9	1	9
B	2	10	2	10	0.2	11.8	0.2	11.8
C	3	33	3	33	3	33	3	33
D	2.5	9.5	0.5	11.5	2.5	9.5	0.5	11.5
E	2	18	2	18	2	18	2	18
F	2	18	2	18	2	18	2	18

Table 16: Setup time ratios for ABC-DEF

4.2.2 Model variants combining tasks rule

All the introduced variations, described in the previous subsection lead to 8 model variants for every arrival rate.

Model variant	Resource class setup	Setup ratio
Model variant C1	AB-CD-EF	Setup ratio 1
Model variant C2	AB-CD-EF	Setup ratio 2
Model variant C3	AB-CD-EF	Setup ratio 3
Model variant C4	AB-CD-EF	Setup ratio 4
Model variant C5	ABC-DEF	Setup ratio 1
Model variant C6	ABC-DEF	Setup ratio 2
Model variant C7	ABC-DEF	Setup ratio 3
Model variant C8	ABC-DEF	Setup ratio 4

Table 17: Model variants combining tasks rule

For every model variant, four models have been simulated. The simulated models are summed up in Table 18. Tasks between brackets are combined tasks.

Model variant C1 - C4	Model variant C5 – C8
F.A.B.E.D.C	F.A.B.E.D.C
F.(AB).E.D.C	F.(AB).E.D.C
F.A.B.E.(DC)	F.A.B.(ED).C
F.(AB).E.(DC)	F.(AB).(ED).C

Table 18: simulated models per model variant

In total 3 arrival rates × 2 resource classes × 4 setup ratios × 4 models = 96 simulations have been executed for this KO redesign rule.

A complete overview of all simulated model variants and models can be found in Appendix B.

4.3 Setup parallel tasks rule

The third KO redesign rule is the parallel tasks rule. As for the preceding two rules, variations have been selected and model variants have been developed for this KO redesign rule.

4.3.1 Variations parallel tasks rule

Also for the parallel tasks rule different variations have been introduced in order to quantify the impact of the implementation of the rule. Four types of variations have been introduced: Variations in arrival rate, variations in service times, variations in resource classes and allocation and variations in reject probabilities.

Variations in arrival rate

As for the combining tasks rule, the first introduced variation is a variation in arrival rate. This variation has been chosen, because changing the arrival rate has a direct effect on the queue times of cases. Applying the parallel tasks rule results in a parallel execution of two tasks, so cases can also wait in the queues at the same time. As arrival rate is also strongly related to the utilization, it has been decided to use three different arrival rates which result in a low, a medium and a high utilization for all resource classes in the original sequential situation. Table 19 gives an overview of different arrival rates and the related, approximate utilizations.

Arrival rate [h-1]	Utilization	Arrival rate [h-1]	Utilization
19	50 %	34	90 %
23	60 %	35	93 %
26	70 %	36	95 %
30	80 %	37	98 %
32	85 %	38	99 %

Table 19: Arrival rate - utilization combinations

When the arrival rate is 37 cases/h, the original model (ABCDEF) of one model variant is not stable any more, as one of the utilizations exceeds 100%. When the arrival rate exceeds 32 cases/h, the redesigned parallel model of one model variant is also not stable any more. Therefore 32 cases/h is the maximum possible arrival rate.

The following arrival processes have been chosen:

- Poisson process with an arrival rate of 32 cases/h. This value has been chosen in order to investigate the system and the differences after redesign at a high utilization rate of the resources. With this arrival rate, the utilization of the resources is approximately 85% (high).
- Poisson process with an arrival rate of 30 cases/h. This arrival rate has been chosen in order to analyze the system with a utilization of approximately 80% (medium).
- Poisson process with an arrival rate of 19 cases/h. This process has been chosen in order to investigate the impact on a system with a utilization of approximately 50% (low).

Variations in service times

The second type of variation is diversity in service times of the parallel tasks. This variation is inserted to test the difference in impact of the parallel tasks rule on models with parallel tasks that have equal service times and models with parallel tasks that have completely differing service times. A difference in impact can be expected according to heuristic 6 of Van der Aalst (2000). Two variations in service times have been developed and can be seen in Table 20.

Exponential Service times A-B-C-D-E-F						
Variants	A	B	C	D	E	F
1. Service times equal	20	30	30	20	20	20
2. Service times completely different	20	55	5	20	20	20

Table 20: Service time variants

Variations in resource classes and allocation

The third type of variation is variation in the resource classes and the allocation of resources. This diversity has been implemented in order to test whether there is a difference in impact on models with parallel tasks that share a resource class and models with parallel tasks that do not share a resource class. Also here, heuristic 6 states that a difference in impact can be expected. The categorization into the different resource classes and the executable tasks per resource class are shown in Table 21.

Alternative 1: 2 Tasks parallel				
# Classes	**Class 1**	**Class 2**	**Class 3**	
2 Resource classes	ABC	DEF		B and C in the same class
	ACE	BDF		B and C in a different class
3 Resource classes	AD	BC	EF	B and C in the same class
	AC	BD	EF	B and C in a different class

Table 21: Resource class variation parallel tasks rule

The categorization into the different resource classes is done in such a way that the results of a model in which the parallel tasks require resources from different resource classes can be compared with the results of a model in which the same tasks require resources from the same resource class. The number of resources per resource class has been selected so that the utilizations of the different resource classes are approximately equal and can be found in the tables with all the model variants in Appendix C.

Variations in reject probabilities
The fourth and last type of variation is diversity in reject probabilities of the parallel tasks. This variation is inserted to test the difference in impact of the parallel tasks rule on models with parallel tasks that have high reject probabilities and models with parallel tasks that have low reject probabilities. Again, heuristic 6 indicates that a difference in impact can be expected. Two variations in reject probabilities have been developed and can be seen in Table 22.

Reject probabilities A-B-C-D-E-F						
Variants	A	B	C	D	E	F
1. High reject probabilities	0.05	0.2	0.2	0.05	0.05	0.05
2. Low reject probabilities	0.15	0.05	0.05	0.15	0.15	0.15

Table 22: Service time variants

4.3.2 Model variants parallel tasks rule

A combination of all the variations of subsection 4.3.1 leads to four model variants for every arrival rate. Table 23 gives an overview of all model variants for the parallel tasks rule.

Model variants swapping tasks				
MV	**Service time variant**	**Reject probability variant**	**Arrival rate**	**Res classes**
MV P1	1) 20-30-30-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	19	All
MV P2	1) 20-30-30-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	30	All
MV P3	1) 20-30-30-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	32	All
MV P4	1) 20-30-30-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	19	All
MV P5	1) 20-30-30-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	30	All
MV P6	1) 20-30-30-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	32	All
MV P7	2) 20-55-5-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	19	All
MV P8	2) 20-55-5-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	30	All
MV P9	2) 20-55-5-20-20-20	1) 0.05-0.2-0.2-0.05-0.05-0.05 (high)	32	All
MV P10	2) 20-55-5-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	19	All
MV P11	2) 20-55-5-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	30	All
MV P12	2) 20-55-5-20-20-20	2) 0.15-0.05-0.05-0.15-0.15-0.15 (low)	32	All

Table 23: Model variants parallel tasks rule

In total, the variations result in 2 × 2 × 3 × 4 × 2 (original and redesign) = 96 simulations

4.4 Warm-up period

As the initial state of the model does not represent the normal working conditions (the model starts empty) of the actual system, a warm-up period must be considered (Mehta, 2000). This warm-up period is the amount of time a model needs to come to a steady state. Every replication starts with a warm-up period because CPN Tools resets the model after every replication. According to Mehta (2000) there are two ways of determining the length of the warm-up period:

- Estimation with time series
- Estimation with moving averages

In this case it is chosen to use the time series method to determine the length of the warm-up period. A pilot run of 20 replications has been made and the results have been analyzed. For every replication the WIP level (Work In Progress) has been plotted against the model time. One of these graphs can be seen in Figure 8. The point at which the model reaches steady-state has been determined for every graph. Based on these points, a warm-up length of 4800 minutes (=2 simulation weeks) has been chosen. When determining the warm-up length it has been considered that it is better to have a warm-up period that is too long rather than one that is too short (Mehta, 2000). The length of the warm-up period is the same for every experiment, in order to provide a basis when comparing "what if" scenarios (Mehta, 2000).

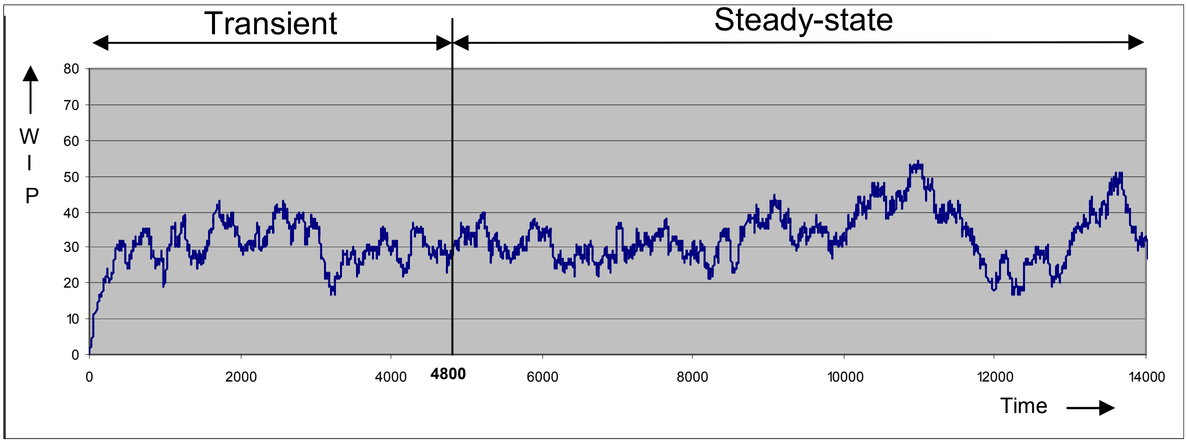

Figure 8: Example of the warm-up period for one of the replications

Starting conditions can be used as an alternative to the warm-up period. In this method, the model is already loaded with cases before the simulation starts. In this project it has been decided not to use this method, but to use a warm-up period instead, because two different systems are compared in this project (Mehta, 2000).

4.5 Run length

Once the warm-up period has been calculated, it is necessary to determine the length of one single run. The length of the simulation runs must be long enough for the resulting data to be independent. One way to determine the run length is to choose a "reasonable" run length and then check whether the data is independent or not. The von Neumann ratio, as proposed by Goossenaerts and Pels (2005), cannot be used in this study as CPN Tools resets the model after every replication. Therefore the model must warm-up before every single replication. Law and Kelton (2000) give two alternative graphical methods to test the data for independency. It is chosen to plot the data on a scatter diagram and investigate the dependency. The chosen run length of the total simulation is 10 working weeks (24000 minutes). As the warm-up length is 4800 minutes, there are 19200 minutes remaining for data collection. Next "lead time of the cases" is selected as the variable to test for dependency and the results of one replication are plotted on a scatter plot. The graph can be seen in Figure 9.

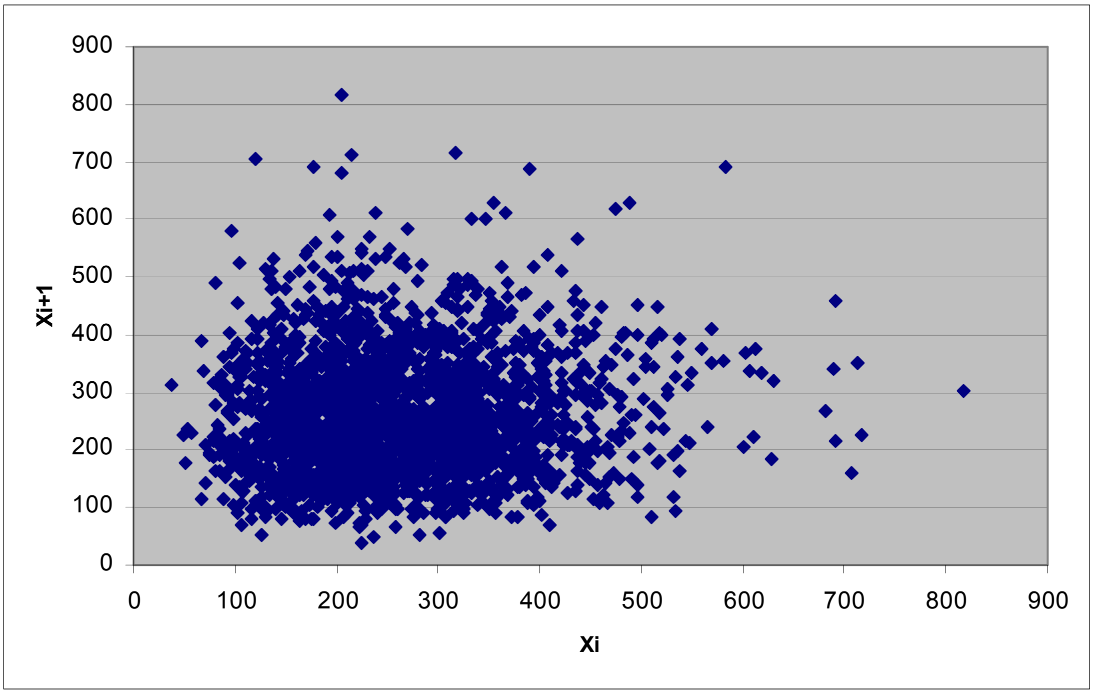

Figure 9: Scatter plot for lead time, run length = 10 weeks

From Figure 9 it can be concluded that the points are scattered randomly throughout the quadrant and are not forming a straight line. It can therefore be concluded that the data is independent. 10 weeks (24000 minutes) will be the run length of a replication in all simulations.

4.6 Number of replications

In the last step of the design of experiments phase, the number of replications should be determined. "Due to the very nature of random numbers, it is imprudent to draw conclusions from a model based on the results generated by a single model run" (Mehta, 2000). As a rule of thumb, Mehta (2000) proposes that the modeller should always perform at least three to five replications per simulation.

Law and Kelton (2000) provide a method with which the number of replications can be calculated based on a pre-specified precision of the collected data. The method consists of 3 steps:

- Step 1: perform a pilot run with the calculated run length and choose a variable to test
- Step 2: choose an absolute error
- Step 3: determine N by iteratively increasing i by 1 until the outcome of the formula ≤ the absolute error (β)

Step 1:
It has been decided to use 4 replications in the pilot run and to test the variable "lead time of the cases". The model of the original situation with only generalists as resources has been simulated. The following data resulted from the pilot run:

Results pilot run	
X_{av}	262.081025
S	8.782322

Table 24: Results pilot run

Step 2:
The error that will be used is 1,5% of the average value. This seemed to be a reasonable error margin. Other percentages can be chosen, depending on the process, the process owner and the cost and importance of an error.

262.081025 * 1.5% = 3,93 minutes ≈ 4 minutes.
The absolute error β in the next step is 4 minutes.

Step 3:
After iteratively increasing i in the next formula, N appeared to be 21

$$N(\beta) = \min\left\{ i \geq n : t_{i-1,\alpha/2} \cdot \sqrt{\frac{S^2(n)}{i}} \leq \beta \right\}$$

With:
$t_{i-1,\alpha/2} = t_{20;0,025} = 2.086$
n = 4
β = 4

So, 21 replications will be used in the simulations.

5 Setup of the output analysis

This chapter describes the setup of the analysis of the output data. The comparisons for every KO redesign rule and the procedure for the calculations are described in this chapter. The actual output analysis is explained in the next three chapters. These chapters also describe the setup and analysis of the additional measurements, when these have been performed. Finally Chapter 9 gives the conclusions.

5.1 Comparisons

Different models have been compared for all three redesign rules of the KO heuristic, in order to comply with the objectives of this simulation project, stated in Section 1.3. The next subsections describe for every rule what model variants and setups have been compared to quantify the impact of the KO heuristic.

5.1.1 Comparisons swapping tasks rule

For the swapping tasks rule two types of comparisons have been made in order to satisfy the objectives of Section 1.3.

Determine for every model variant what the impact of the swapping tasks rule is
The first sub-objective is to determine the impact of this rule on the model of every model variant. The combinations, summed up at the end of Section 4.1.2 have been simulated and compared to the original situation (ABCDEF), for every model variant. With these comparisons it is possible to test both heuristic 1 and 2 of Van der Aalst (2000) and to quantify the impact of this rule for every single model variant, so it can be decided in what case it is advisable to introduce the swapping tasks rule.

Determine what the impact of the swapping tasks rule is with different resource setups
The second sub-objective is to determine whether the KO rule has a different impact on models with other resource setups. The following model variants with the same service times, but differing resource setups have been compared:

- Model variant SW1 vs. SW2 vs. SW3 vs. SW4
- Model variant SW5 vs. SW6 vs. SW7 vs. SW8
- Model variant SW9 vs. SW10 vs. SW11 vs. SW12

The analyses of these comparisons are combined with the analysis of the separate model variants.

Determine what the impact of the swapping tasks rule is with different service times
The last sub-objective is to determine whether the KO rule has a different impact on models with other service times and KO ratios. The following model variants with the same resource setups, but differing service times have been compared:

- Model variant SW1 vs. SW5 vs. SW9
- Model variant SW2 vs. SW6 vs. SW10
- Model variant SW3 vs. SW7 vs. SW11
- Model variant SW4 vs. SW8 vs. SW12

The analyses of these comparisons are combined with the analysis of the separate model variants.

5.1.2 Comparisons combining tasks rule

Also for the combining tasks rule, three types of comparisons have been made to comply with the objectives of Section 1.3.

Determine for every model variant what the impact of the combining tasks rule is
The first sub-objective is to determine the impact of the combining tasks rule on the model of every model variant. The four models of Table 18 have been simulated under three arrival rates for every model variant. The performance of the three redesigns have been compared to that of the original situation in order to determine the impact of combining tasks under all three arrival rates in every model variant. The analysis is described per model variant separately.

Determine what the impact of the combining tasks rule is with different arrival rates
All models in every model variant have been simulated under three different arrival rates in order to test the difference in impact under a different arrival rate. The three models with the different arrival rates within a model variant are compared, to test the difference in impact. The analyses of these comparisons are merged with the analysis of the separate model variants.

Determine what the impact of the combining tasks rule is with different setup ratios
The third sub-objective is to determine whether the combining tasks rule has a different impact on models with other setup ratios. The following model variants with the same resource setups, but different setup ratios have been compared:

- Model variant C1 vs. C2 vs. C3 vs. C4
- Model variant C5 vs. C6 vs. C7 vs. C8

The analyses of these comparisons are also combined with the analysis of the separate model variants.

5.1.3 Comparisons parallel tasks rule

For the last KO redesign rule, four types of comparisons have been made. These comparisons have been setup in order to meet the objectives and sub-objectives stated earlier in Section 1.3.

Determine for every model variant what the impact of the parallel tasks rule is
Every single model variant has been simulated and analyzed separately in order to comply with the first sub-objective of this redesign rule. The four models with different resource setups, of the original situation have been compared to their redesigns for every model variant to determine the impact per situation.

Determine what the impact of the parallel tasks rule is with equal and different parallel service times
The second sub-objective is to determine whether there is a difference in impact of the parallel tasks redesign rule on the performance of a workflow between models with equal parallel service times and models with completely different parallel service times. The following comparison has been made:

- Model variant P1 – P6 vs. P7 – P12.

Determine what the impact of the parallel tasks rule is with high and low parallel reject probabilities
The third sub-objective is to asses the difference in impact between models with high parallel reject probabilities and models with low parallel reject probabilities. The following comparisons have been made in order to achieve the third objective:

- Model variant P1 – P3 vs. P4 – P6
- Model variant P7 – P9 vs. P10 – P12

Determine what the impact of the parallel tasks rule is with different arrival rates
The last sub-objective of this rule is to determine what the difference in impact is between models with varying arrival rates. Three different arrival rates have been chosen. The following comparisons have been made to determine the difference:

- Model variant P1 vs. P2 vs. P3
- Model variant P4 vs. P5 vs. P6
- Model variant P7 vs. P8 vs. P9
- Model variant P10 vs. P11 vs. P12

5.2 Calculations

The following procedure is followed in order to determine what the expected impact is on the performance of a workflow when implementing the knock out heuristic and to compare the differences of the different setups under which the heuristic has been implemented:

1. Determine for every measure whether the difference between the original situation and the redesigned situation for the first setup is significant.
2. Calculate the confidence intervals of the relative differences for all measures.
3. Repeat step 1 and 2 for all other setups.
4. Compare the different setups by comparing the confidence intervals.
5. Draw conclusions for all setups in the current model variant.
6. Repeat for all model variants
7. Compare the measures of the different model variants.
8. Draw conclusions for all model variants.

Step 1: Significance tests
First, for every measure it is determined whether the difference between the original situation and the redesigned situation is significant. The means of both situations are compared.

When comparing two means from two different populations, two types of tests can be used to test the significance of the difference and to construct the confidence interval:

- A two sample or pooled-variance t test
- A Welch or separate-variance t test

The difference between the two procedures is that, in contrast to the second procedure, the first procedure assumes equal variances. To make the correct choice, it is possible to use an F test to test the difference in variances, to see whether the assumption is reasonable for the used samples. "However, in circumstances in which they are needed most (small samples), the tests for homogeneity of variance are poorest" (Hays, 1994). Therefore testing the equality of variances is not an option. According to Bowerman and O'Connel (1997), both procedures give virtually the same results when both sample sizes are equal. Ott and Mendenhall (1994) confirm this by stating that the results of both procedures are equal or nearly equal when the sample sizes are also equal or nearly equal. Only when the sample sizes vary greatly (1,5 to 1) large differences appear between the results of the procedures. Furthermore they indicate that the separate-variance t test is somewhat more reliable and more conservative. Law and Kelton (2000) recommend against using the two sample t test when comparing results of simulating real systems, since equality of variances is probably not a safe assumption. Instead, they suggest the Welch t test.

In this project, equal sample sizes are used, so both procedures can be used to test the differences in means. In order to be flexible for future research projects (when maybe different sample sizes are needed) and to use the most reliable and conservative procedure (Ott and Mendelhall, 1993) it has been chosen to use the Welch t test.

The hypothesis H_0 is tested against H_1 for every performance measure using the Welch approach, in order to find out what performance measures change significantly in the redesigned model. The hypotheses are:

$$H_0 : \overline{X_1} = \overline{X_2}$$

$$H_1 : \overline{X_1} \neq \overline{X_2}$$

With $\overline{X_1}$ being the mean of the measure in the original model and $\overline{X_2}$ being the mean of the measure in the redesigned model.

The following test statistic is used:

$$t_0 = \frac{\overline{X_1} - \overline{X_2}}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}}$$

With:
$n_1 = 21$
$n_2 = 21$

H_0 is rejected (and the difference in means is significantly different from 0) when $|t_0| > t_{f,\alpha/2}$, with f degrees of freedom:

$$f = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(S_1^2 / n_1\right)^2}{n_1 - 1} + \frac{\left(S_2^2 / n_2\right)^2}{n_2 - 1}}$$

When comparing more than two alternatives and making several confidence interval statements simultaneously it is important to realize that the individual confidence levels of the separate comparisons have to be adjusted upwards, in order to reduce the number of Type 1 errors (rejecting the null hypothesis when it is true (Montgomery and Runger, 2003)). A method for controlling the error rate of the set of comparisons and to ensure that the overall significance level is high enough, is the Bonferroni inequality (Miller, 1981), (Kirk, 1982), (Hays, 1994), (Law and Kelton, 2000). The Bonferroni inequality implies that when making some number c of confidence interval statements it is needed to make each separate interval at level $(1 - \alpha/c)$, so that the overall confidence level associated with all intervals' covering their targets will be at least $(1 - \alpha)$ (Law and Kelton, 2000).

In order to be conservative it has been decided in this research to apply the Bonferroni inequality in the first step of the comparison.

For the swapping tasks rule, a maximum of 10 setups have been compared. Therefore, the α of the separate comparisons is 0.05 / 10 = 0.005.

For the composite tasks rule, the differences of 4 setups have been compared under three arrival rates. Therefore, the α of the separate comparisons is 0.05 / 12 = 0.00417.

For the parallel tasks rule, the differences of 8 setups have been compared. Therefore, the α of the separate comparisons is 0.05 / 8 = 0.00625.

Step 2: Confidence intervals
The second step is the calculation of the confidence intervals for all differences between the original model and the redesigned model. These "Welch confidence intervals" are calculated with the following formula:

$$\overline{X}_1 - \overline{X}_2 \pm t_{f,\alpha/2} \cdot \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \quad \text{with} \quad f = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(S_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(S_2^2/n_2\right)^2}{n_2 - 1}}$$

And
$n_1 = n_2 = 21$

Again, the Bonferroni corrected values for α are used to ensure a sufficiently high, overall confidence level.

Step 3: Repeat for all setups/combinations
Next, step 1 and 2 are repeated for all other setups. A significance test must be performed for all measures and all confidence intervals of the relative differences are calculated.

Measures that do not change significantly for all setups can be deleted from the analysis.

Step 4: Compare the measures of the different setups/combinations
Once all confidence intervals of a measure are calculated for all setups, they can be compared. When the confidence intervals of two or more setups overlap it can be concluded that the difference between these setups is not significant. A fictive example can be seen in Figure 10. From this picture it can be seen that the difference between setup AD-BC-EF and AC-BD-EF for this measure is not significant, as the confidence intervals overlap. The differences between all other setups are significant.

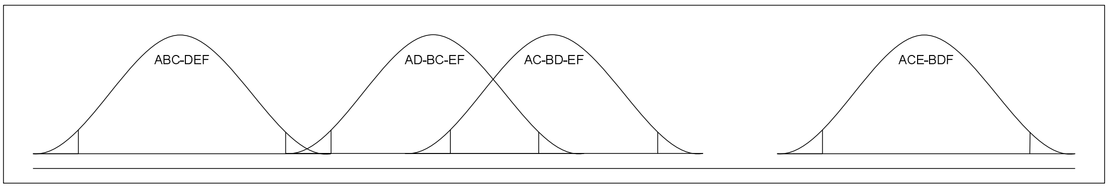

Figure 10: Example of s setup comparison

As confidence levels of 99.375% and higher have been used for the separate confidence intervals it is assumed that these intervals are wide enough to filter out any more inaccuracy caused by the application of multiple t tests.

Step 5: Draw conclusions for one model variant
In this step the conclusions are drawn for one model variant, based on the above described analysis.

Step 6: Repeat for all model variants
Now the same analysis is repeated for all other model variants. Again all differences are tested for significance and all confidence intervals of the relative differences are calculated for all measures.

Step 7: Compare the different model variants
In this step, the measures in the different model variants are compared in order to draw conclusions about the differences between model variants. The same technique as

described in step 4 is used here to compare the model variants. Figure 11 graphically depicts the comparisons of this step and those of step 4.

Step 8: Draw conclusions for all model variants

In this final step of this procedure, the conclusions are drawn for all model variants based on the comparisons in and between model variants.

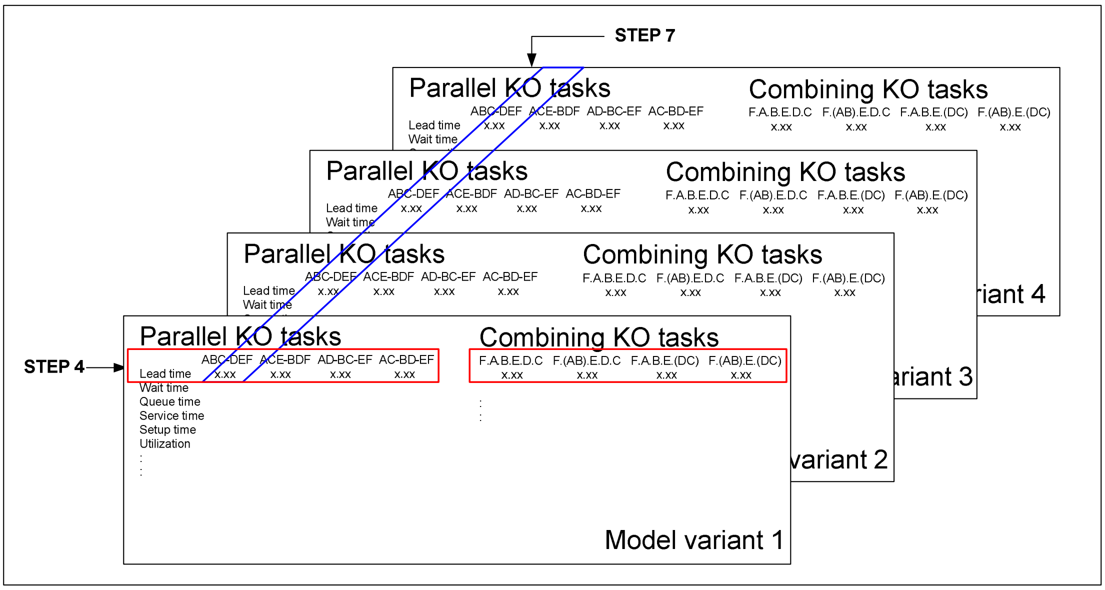

Figure 11: Comparisons in and between model variants

6 Output analysis swapping tasks rule

This chapter describes the output analysis of the swapping tasks rule, sums up the results, describes the analysis and results of the additional measurements and gives conclusions for the separate model variants and the comparisons between the model variants. The following chapters describe the analysis of the combining tasks rule and the parallel tasks rule. Finally Chapter 9, gives the final conclusions. Section 6.1 describes the analysis of the separate model variants. Next, Section 6.2 describes the analyses and results of the additional measurements. Then Section 6.3 gives an overview and a summary of the results. The chapter ends with the conclusions for the swapping tasks rule in Section 6.4 and a reflection on the results in Section 6.5.

6.1 Output analysis swapping tasks rule

Each of the following sub-sections describes the output analysis of one model variant. All percentages that are in the analysis of the following sections are the result of the comparisons between the original model and the optimal combination according to heuristic 2.

6.1.1 Analysis model variant SW1 (Case 1, A-B-C-D-E-F)

This model variant has the settings of case 1, described earlier in Section 4.1.1. This case has service times that result in KO ratios of the same order of magnitude. The model variant that is analyzed here has resource setup A-B-C-D-E-F, a setup with only specialists.

The output tables of this model variant that resulted from the comparison of the 10 proposed combinations can be found in Table 30 in Appendix D. The following observations can be made from Table 30.

Lead time: After the application of the swapping tasks rule it can be seen that the lead times of the cases that completed all 6 tasks are decreasing when the tested combinations are sorted according to heuristic 2. All redesigns have better lead times than the original except for DCEBAF (an average combination, which performs the same) and BCFDAE (the last combination, which has a lower lead time). This is according to the expectation since the original model was ranked around the average combination, and should therefore perform better than the last combination but worse than the others. The optimal combination has a 25.7% lower lead time than the original model. The decrease in lead time is caused by a decrease in queue time. It can also be seen that the variances of the lead times decrease when the ranking increases; the confidence intervals become wider. From the four combinations that resulted from heuristic 1, the two combinations that start with ED perform better than the combinations that start with EB. It appears that when two tasks have the same KO ratio, the task with the shortest service time of the two should be executed first. All confidence intervals of the lead times are shown in Figure 12.

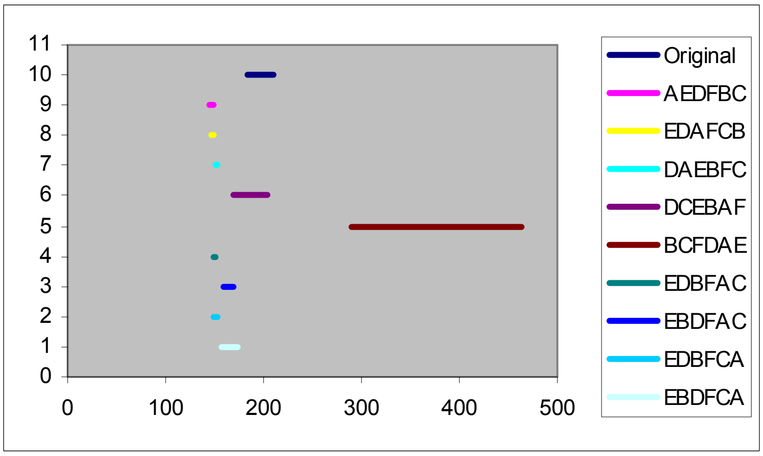

Figure 12: Confidence intervals of the lead times of model variant SW1

Utilization: When looking at the utilizations of all 6 resources it can be seen that the combinations that are ranked best according to heuristic 2 have more balanced utilization. The lower the ranking, the higher the difference in utilization between two or more resource classes. These more balanced utilizations lead to lower queue times. The utilizations of the higher ranked combinations are not significantly lower, except for the four optimal combinations of heuristic 1. These combinations have significant lower utilizations.

WIP: For this model variant, applying the swapping tasks rule results in lower WIP levels, which means lower inventory costs. The optimal combination has a decrease in WIP level of 31.7% compared to the original situation.

Flexibility: The measure labour flexibility increases when the ranking according to heuristic 2 increases. The optimal combination according to heuristic 2 has the highest labour flexibility, which is 9.9% higher than that of the original combination. Routing flexibility does not change since the number of routes remains constant. The 4 optimal combinations of heuristic 1 have the highest volume flexibility.

Conclusions model variant SW1 (Case 1, A-B-C-D-E-F):
The following can be concluded from the above described analysis:
In this original situation (with KO ratios of the same order of magnitude, a resource setup with only specialists and an arrival rate that results in a high utilization of at least one of the resource classes of the original model) using heuristic 2 of the swapping tasks rule results in lower lead times, more balanced utilizations, lower WIP levels and increased labour flexibility. All combinations that are ranked higher according to heuristic 2 perform better than the original model. Heuristic 1 can be used in this model variant to decrease the utilization of the resource classes and to increase the volume flexibility.

6.1.2 Analysis model variant SW2 (Case 1, AB-CD-EF)

Model variant SW2 also has the service times and reject probabilities of case 1, but this model variant has resource setup AB-CD-EF. The output data of model variant 2 can be found in Table 31 in Appendix D. The following observations can be made from Table 31.

Lead time: From the lead times of this model variant, shown in Figure 13, it can be seen that applying the swapping tasks rule to the process of the original situation leads to decreasing lead times and variances, but for this model variant the differences are smaller compared to model variant SW1. In this model variant, the optimal combination only has 2.3% lower lead times compared to the original model. The resources in this model variant are more generalists than the resources of model variant SW1 (A-B-C-D-E-F).

These generalists add more flexibility to the allocation, which results in lower queue times with the same arrival rate. With this arrival rate, the impact of the swapping tasks rule on the lead time is only limited as the queue times are also small. It is suggested to perform additional measurements with the same setup and settings but then with a higher arrival rate. It is expected that the impact of the swapping tasks rule will be higher with a higher arrival rate. This will be investigated later in Section 6.2.

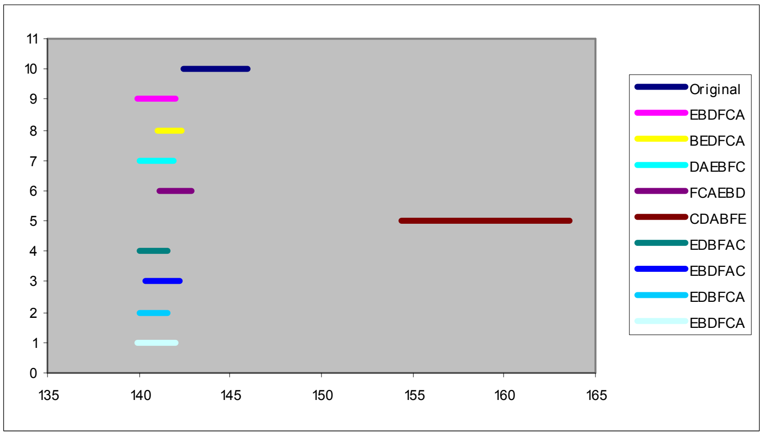

Figure 13: Confidence intervals of the lead times of model variant SW2

Utilization: Again, heuristic 2 leads to more balanced utilizations of all resource classes. The lower the ranking, the higher the difference in utilization between the resource classes. However, the arrival rates are not high enough in this model variant to result in high queue times. Heuristic 1 and 2 also lead to lower utilizations, since cases fail earlier in the process. The optimal combination has a 2.9% lower utilization.

WIP: For WIP, the same pattern as for lead time can be found, which means lower WIP levels. Also for this measure the differences are only small, compared to model variant SW1. It is expected that the differences will be bigger in the additional measurement with a higher arrival rate. Here the optimal combination has a 5.4% lower WIP level.

Flexibility: The labour flexibility (17.5%) and the volume flexibility (4.9%) both increase when the ranking of heuristic 2 increases.

Conclusions model variant SW2 (Case 1, AB-CD-EF):
From the analysis of model variant 2 it can be concluded that the pattern of the impact of the swapping tasks rule on the lead time and the WIP is as expected but that the magnitude is only limited. This is caused by the low queue times. What the impact is when the arrival rate and the queue times are higher will be assessed later in an additional measurement. The swapping tasks rule does also lead to more balanced, lower utilizations of the resource classes and to an increase in flexibility.

6.1.3 Analysis model variant SW3 (Case 1, ABC-DEF)

As the former two model variants, this model variant has the settings of case 1, but has resource setup ABC-DEF. The output data can be found in Table 32 in Appendix D. The following observations can be made from the output data.

Lead time: Again the same pattern can be seen in the decrease in lead time and its variance, when the ranking of the combination increases. However, in this model variant the differences between the different combinations are only small. The optimal combination only has a 2.1% decrease in lead time. This is because the resources in this model variant are again more generalists compared to the resources of the previous model variants. This results in lower queue times with the same arrival rate. Also for this model variant it is suggested to investigate, what the impact is when the arrival rate is higher. This will be analyzed later in Section 6.2. The confidence intervals of all lead times of this model variant are depicted in Figure 14:

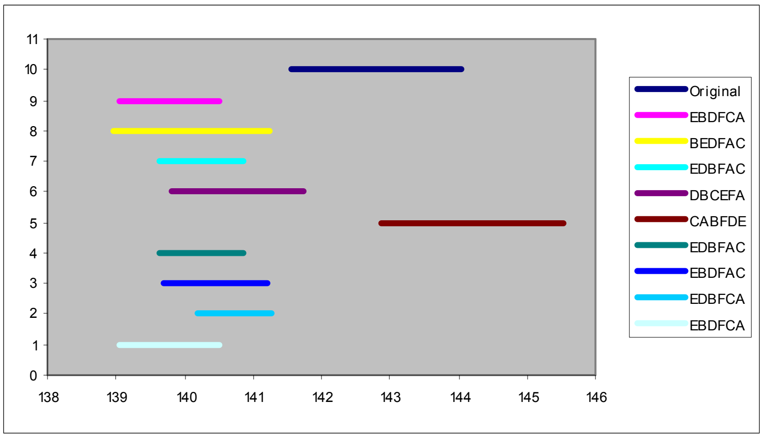

Figure 14: Confidence intervals of the lead times of model variant SW3

Utilization: Also for this setup, heuristic 2 leads to more balanced utilizations of the resource classes. The resource classes of the optimal combination have approximately equal utilizations. Again heuristic 1 and 2 both lead to lower utilizations. The original model has 3.4% higher utilizations compared to the optimal solution of heuristic 2.

WIP: The WIP levels of the combinations show the same pattern as for the lead time. Also here the differences are only small. The difference between the original model and the optimal model is 5.7%.

Flexibility: The same patterns as for model variant SW2 are found for the flexibility measures of model variant SW3. The better combinations of heuristic 2 have higher labour flexibility (18.7%) and volume flexibility (5.7%).

Conclusions model variant SW3 (Case 1, ABC-DEF):
Implementation of the swapping tasks rule leads to a positive result, regarding lead time, WIP, utilization and flexibility for this model variant. However, the reduction of lead time is only small. When swapping the tasks is costly it can be unadvisable to implement this redesign rule in this model variant with this arrival rate (low). Whether the impact is higher on this model with a higher arrival rate will be investigated later. The swapping tasks rule can be used to lower and balance the utilizations, lower the WIP level and increase the flexibility.

6.1.4 Analysis model variant SW4 (Case 1, ABCDEF)

This model variant has only one resource class that consists of only generalists. The service times and reject probabilities of this model variant are equal to those of case 1. The output is shown in Table 33 in Appendix D. From this data the following observations can be made.

Lead time: From the lead times of this model variant, shown in Figure 15, it can be seen that there is no significant difference between the lead times of the different combinations. As all resources in this model variant are generalists and can execute all tasks, the queue times are very low. Even in the worst combination there is no significant queue time, so cases never have to wait in a queue. The impact of the swapping tasks rule on this model variant with a higher arrival rate will be investigated and described later in this chapter. It is expected that the differences will be bigger with a higher arrival rate.

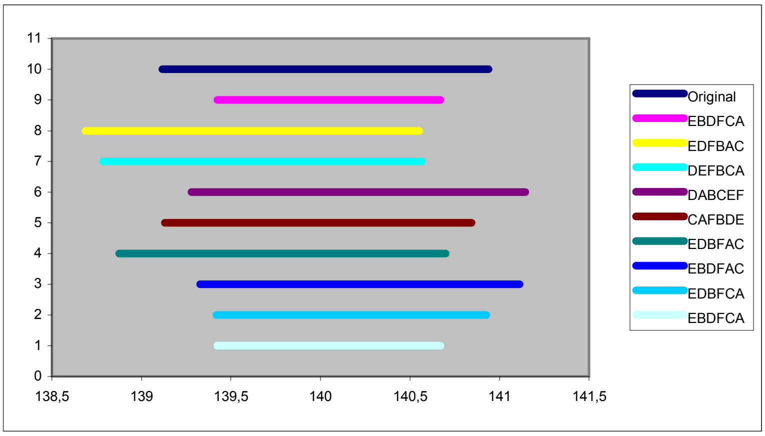

Figure 15: Confidence intervals of the lead times of model variant SW4

Utilization: The utilization is showing the same expected pattern as before. The utilizations of the higher ranked combinations are lower (3.5%) than those of the lower ranked ones.

WIP: The WIP level is also showing the same pattern. The WIP level of the higher ranked combinations is lower than those of the lower ranked combinations (3.4%). A lower WIP level results in lower inventory costs.

Flexibility: Labour flexibility (5.9%) and volume flexibility (6.0%) again have the same expected increase. The higher the ranking, the higher the values of the flexibility measures.

Conclusions model variant SW4 (Case 1, ABCDEF):
For this model variant, implementation of the swapping tasks rule does not lead to a decrease in lead time under this arrival rate. However, applying heuristic 2 to the model of the original situation still leads to a significant decrease in utilization and WIP level with both cost advantages and to an increase in flexibility. What the impact of the rule is on this model variant under a higher arrival rate will be investigated later. It is suggested not only to increase the arrival rate of model variant SW2, SW3 and SW4, but also to lower the arrival rate of model variant 1, in order to investigate whether the differences in lead time become smaller or even insignificant under a low arrival rate. This will also be tested with an additional measurement, which is described in Section 6.2.

6.1.5 Analysis model variant SW5 (Case 2, A-B-C-D-E-F)

This section describes the analysis of the model variant containing the first setup (A-B-C-D-E-F) of case 2. The difference between case 1 and case 2 is that the service times of case 2 have been chosen so that the KO ratios of the different tasks are completely different instead of in the same order of magnitude, like in case 1. As the KO ratios are different, heuristic 1 only produces one optimal combination. This optimal combination forms together with six others the set of compared combinations for this model variant. The output for this model variant can be found in Table 34 in Appendix D. The following observations can be made from this data.

Lead time: Applying the swapping tasks rule to this first model variant of case 2 has a positive effect on the lead time of the completed cases (13.6%). The lead times, shown in Figure 16, decrease when the ranking of a combination, according to heuristic 2, increases. The variances of the lead times also decrease. The original combination performs the same as the average combination and better than the last combination, as expected. The original combination is ranked around the average combination. The decrease in lead time is caused by a decrease in queue time. These lower queue times are the result of more balanced and lower resource utilizations for the higher ranked combinations.

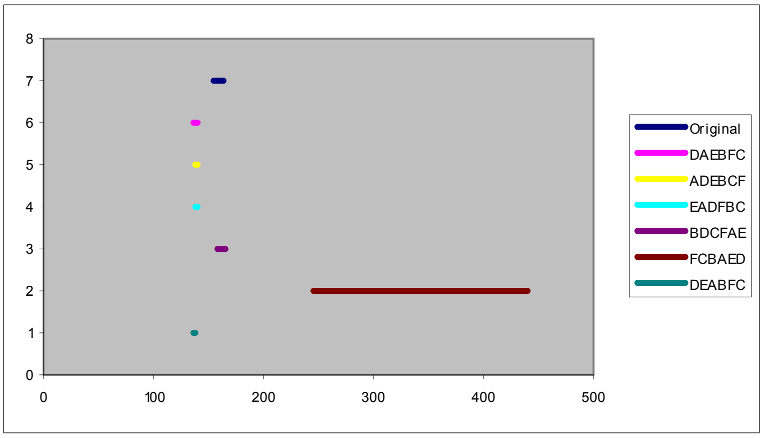

Figure 16: Confidence intervals of the lead times of model variant SW5

Utilization: As described above, the utilizations of the higher ranked combinations are more balanced and lower compared to the lower ranked ones (7.2%). This results in lower queue times, with obvious lead time advantages.

WIP: The pattern of the WIP level is the same as the pattern of the lead time graph. The WIP levels of the higher ranked combinations are lower than the WIP levels of the lower combinations. So, also for this model variant the swapping tasks rule leads to a decrease in WIP (22.3%), which means lower inventory costs.

Flexibility: The swapping tasks rule has a positive impact on both labour flexibility (19.0%) and volume flexibility (8.3%), since both flexibility measures increase after swapping the KO tasks. The routing flexibility remains the same.

Conclusions model variant SW5 (Case 2, A-B-C-D-E-F):
The conclusions, based on the analysis, are the same as for model variant SW1. Application of the swapping tasks rule results in a lower lead time, a more balanced resource utilizations, a lower WIP level and an increased flexibility. In a setting comparable to the setting of this model variant, heuristic 2 is perfectly useable to redesign the KO process.

6.1.6 Analysis model variant SW6 (Case 2, AB-CD-EF)

This model variant again uses the setting of case 2, but now with AB-CD-EF as resource setup. Again seven combinations are compared in this output analysis. The output data can be found in Table 35 in Appendix D. The data in this table results in the following analysis.

Lead time: Applying the swapping tasks rule to this model variant does not result in a decrease in lead time. Figure 17 does not show a significant difference between the lead times of the original situation and those of any of the higher ranked redesigns. The difference between the lead time of the last combination and that of the optimal redesign is only just significant. With this arrival rate, swapping the KO tasks according to heuristic 2 does not lead to a decrease in lead time. This is caused by the low queue times.

What the impact of the swapping tasks rule is on this model variant under a higher arrival rate will be assessed later with an additional measurement. The swapping tasks rule does decrease the variances of the lead time.

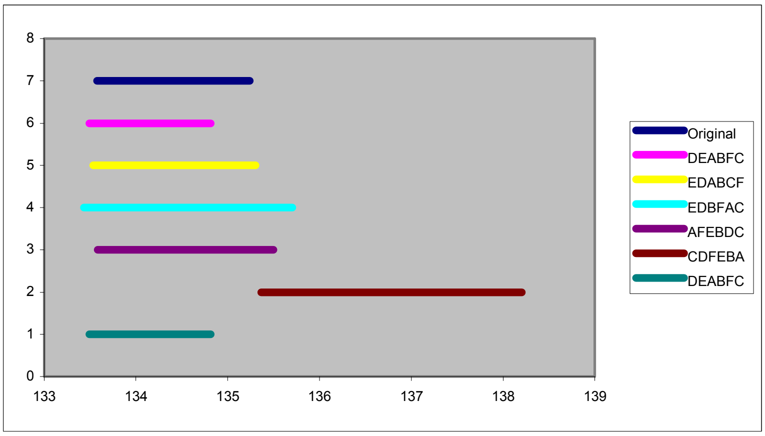

Figure 17: Confidence intervals of the lead times of model variant SW6

Utilization: Applying the swapping tasks rule to this model variant, leads to more balanced and decreased utilizations of the resource classes (6.4%). This decrease is caused the fact that the resources have to work fewer hours, since failing cases will be rejected earlier in the process. This has considerable cost advantages.

WIP: Although the swapping tasks rule does not have a significant effect on the lead time, it does have a considerable impact on the WIP level (7.1%). Again, the same pattern of decreasing WIP levels is found.

Flexibility: Also in this model variant, the volume flexibility (7.3%) and the labour flexibility (17.1%) of the workflows will increase when the swapping tasks rule is introduced.

Conclusions model variant SW6 (Case 2, AB-CD-EF):
The swapping tasks rule does not have a significant impact on the lead time. The arrival rate is too low to cause any queue times. Therefore the reduction of lead time is not significant. The implementation of the rule does lead to lower, more balanced resource utilizations and lower WIP levels, which both results in a less costly process execution. Swapping the tasks according to heuristic 2 also has a positive effect on the flexibility of the workflow. However routing flexibility remains the same.

6.1.7 Analysis model variant SW7 (Case 2, ABC-DEF)

This third model variant of case 2 has two resource classes: ABC-DEF. The settings of this model variant are the same as for model variant SW5 and SW6, those of case 2. The results of the simulations are reported in Table 36 in Appendix D. The following observation can be made.

Lead time: In this setup, resources are able to execute more tasks. This results in low queue times under the same arrival rate. Because of this, the impact of the swapping tasks rule on the lead time is only limited, as can be observed from Figure 18. In this graph it can be seen that the differences in lead time between the different combinations are only small or even insignificant, with this arrival rate. Introduction of the swapping tasks rule does not lead to a better lead time in this situation. Whether the impact on the lead time of the same model variant is higher under a higher arrival rate will be investigated later.

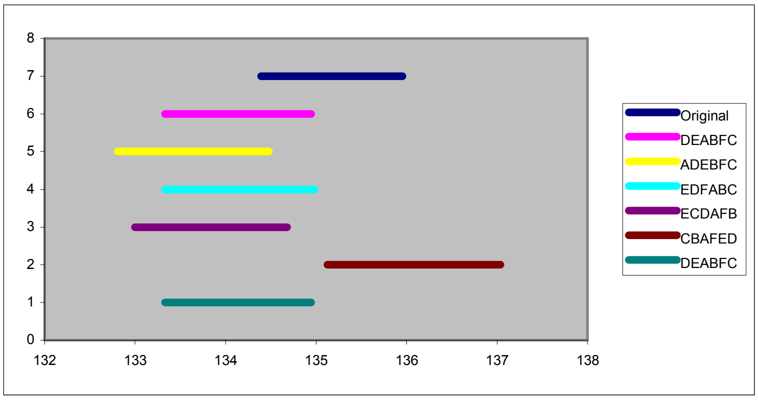

Figure 18: Confidence intervals of the lead times of model variant SW7

Utilization: As in earlier described model variants, the swapping tasks rule leads to more balanced, lower utilizations (7.2%).

WIP: As before, the swapping tasks rule results in a lower WIP level (7.9%).

Flexibility: Introducing the swapping tasks rule to this model variant also leads to increased labour flexibility (21.4%) and volume flexibility (8.3%).

Conclusions model variant SW7 (Case 2, ABC-DEF):
The swapping tasks rule does not have a significant positive impact on the lead times of this model variant. However it still has the same expected, positive impact on the utilization and the WIP level, which results in cost advantages. It also increases the flexibility of the workflow. Whether these impacts are different under a higher arrival rate will be cleared up with an additional measurement.

6.1.8 Analysis model variant SW8 (Case 2, ABCDEF)

The Last setup of case 2 is the setup with only one resource class that consists of generalists. The output of the simulation of all seven combinations can be seen in Table 37 in Appendix D. The following observations can be made form this data.

Lead time: From the confidence intervals of the lead times, shown in Figure 19, it can be seen that there is no significant difference in lead time between the different combinations. This is due to the very low queue times, which result from the flexibility of the generalists working in the process. In this model variant, the swapping tasks rule does not result in lower lead times. The impact of the swapping tasks rule is possibly bigger on this model variant under a higher arrival rate. This will be verified later with an additional measurement.

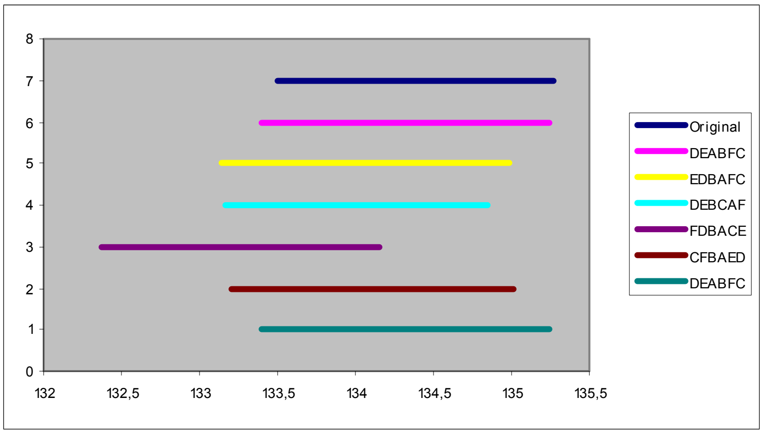

Figure 19: Confidence intervals of the lead times of model variant SW8

Utilization: The swapping tasks rule does lead to lower utilizations. In this model variant, the optimal combination has a 7.2% lower utilization than the original model. These lower, more balanced utilizations result in lower queue times and lower costs.

WIP: The WIP levels of all combinations of this model variant show the same pattern as all previous model variants. The WIP levels of the higher ranked combinations are lower (7.5%).

Flexibility: Labour flexibility and volume flexibility both increase with an increasing ranking of the combinations. The difference between the original model and the optimal redesign is 8.9% for labour flexibility and 8.2% for volume flexibility.

Conclusions model variant SW8 (Case 2, ABCDEF):
In this model variant with a low arrival rate and only generalists as resources, the swapping tasks rule cannot be used to lower the lead times of complete cases. It can be used to lower the utilizations and the WIP level, which both results in a less costly execution of the process. It can also be used to increase the flexibility of the workflow. The impact on this model variant with a higher arrival rate is tested later.

6.1.9 Analysis model variant SW9 (Case 3, A-B-C-D-E-F)

This ninth model variant is the first variant of case 3. This variant has a resource setup with only specialists. Case 3 has equal service times and an equal number of resources for all tasks. The results of the simulations are shown in Table 38 in Appendix D. The following observations can be made.

Lead time: When looking at the lead times of this model variant, shown in Figure 20, it can be seen that the averages of the lead times are decreasing when the ranking increases, but that the variances are so high that the difference are not significant any more. These high variances are caused by the unbalanced resource utilizations of all combinations. Even the optimal combination has very unbalanced resource utilizations. These unbalanced resource utilizations are the result of the equal number of resources per resource class (see Table 10). Because of this equal number of resources and equal service times, the utilization of the resource of the first task is very high, irrespective of what tasks is executed first. It is suggested to investigate the same model, but then with the number of resources per class chosen so that the utilizations are more balanced. This can be achieved by adding more resources to the task with the highest reject probability, which has the highest change of being executed first. It is expected that the variances will decrease. This will be tested with an additional measurement, and described later in Section 6.2.

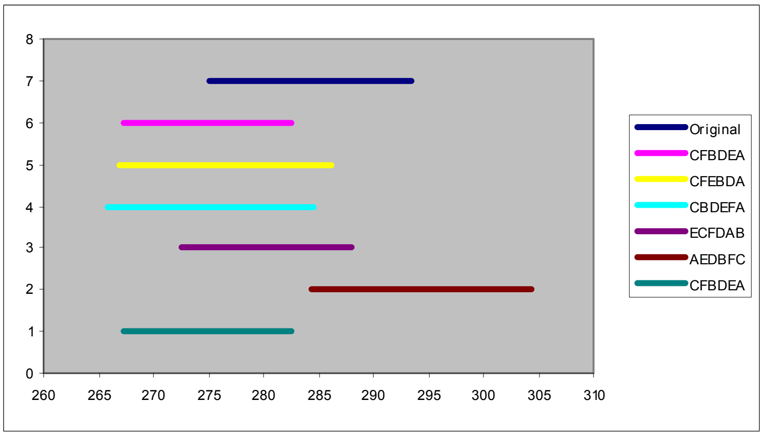

Figure 20: Confidence intervals of the lead times of model variant SW9

Utilization: In this model variant, heuristic 2 does not lead to more balanced utilizations. However the utilizations decrease with the implementation of the swapping tasks rule. The optimal combination even has an 11.6% lower average utilization compared to the original model.

WIP: The swapping tasks rule decreases the WIP level, despite the high variances in lead time. Though, the WIP levels also have higher variances compared to the other model variants. The optimal combination has a WIP level that is 13.3% lower than that of the original model.

Flexibility: Both labour flexibility (23.1%) and volume flexibility (22.4%) show the same increasing pattern with the increase of ranking. Both measures have low variances, despite the higher variances in the other measures.

Conclusions model variant SW9 (Case 3, A-B-C-D-E-F):
From the above described analysis it can be concluded that the swapping tasks rule decreases the utilizations of the resource classes and the WIP level for this model variant. The rule also increases the flexibility of the workflow. However, in a situation like case 3, with very unbalanced utilizations and high variances, the swapping tasks rule cannot balance the utilizations, with insignificant differences in lead time as a result. The rule cannot be used here to lower the lead times. This is different from the observation of case 1 and case 2. The difference with these earlier cases is that the number of resources and the service times are equal for all resource classes in case 3. The swapping tasks rule cannot balance the utilizations, because the utilization of the class that executes the first task is high, irrespective of what task is executed first. This causes the unbalanced utilizations and high variances.

6.1.10 Analysis model variant SW10 (Case 3, AB-CD-EF)

Model variant 10 consists of the second setup of case 3. The process in this model variant has again the settings of case 3, but now with three resource classes: AB-CD-EF. The results of the simulations of this model variant can be found in Table 39 in Appendix D. The following can be observed from the output data.

Lead time: From the lead times of this model variant, depicted in Figure 21, it can be seen that implementation of the swapping tasks rule decreases the lead time of the completed cases. The original model of this model variant is ranked low according to heuristic 2. This can also be seen in Figure 21, where the original model has approximately the same lead time as the last combination. The higher ranked combinations have considerable better lead times (6.2%). The differences between the averages of the combinations are smaller compared to those of model variant SW9. This is because the queue times are lower in this model variant, where the resources can execute more tasks. This was also the case in the model variants of case 1 and 2 with the same resource setups. It can also be seen that the higher ranked combinations have a smaller confidence interval, due to lower variances.

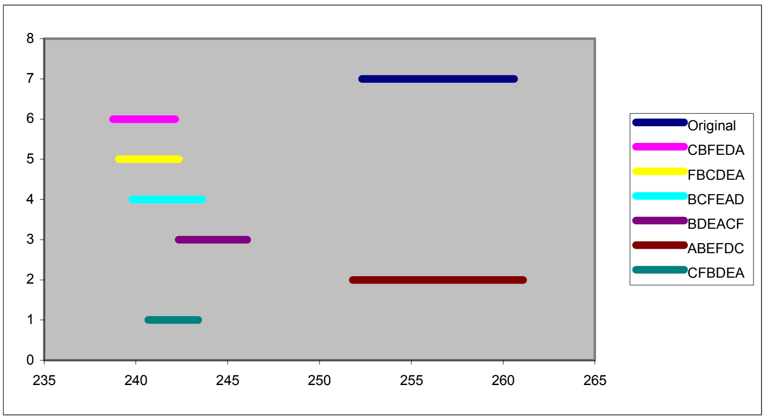

Figure 21: Confidence intervals of the lead times of model variant SW10

Utilization: Introduction of the swapping tasks rule decreases the utilization of the resource classes (10.8%) and realizes more balanced utilizations. The same decreasing pattern in utilizations is found.

WIP: The WIP level decreases after the swapping tasks rule has been applied (17.6%). A lower WIP level results in lower inventory costs.

Flexibility: Swapping the tasks according to heuristic 2 also leads to higher labour flexibility (35.9%) and volume flexibility (21.0%).

Conclusions model variant SW10 (Case 3, AB-CD-EF):
Implementation of the swapping tasks rule in a process with the same setting as this model variant will lead to a decrease in lead time, a decrease in variances of the lead time, more balanced, lower utilizations of the resources, a lower WIP level and increased flexibility.

6.1.11 Analysis model variant SW11 (Case 3, ABC-DEF)

The third model variant of case 3 is a model variant with a 2 resource class setup ABC-DEF. The results of the simulations can be found in Table 40 in Appendix D. The following observations can be made from the data in this table.

Lead time: Application of the swapping tasks rule results in lower lead times, as can be seen in Figure 22. However, the differences (3.1%) are only small compared to the previous model variant. This is also for this case caused by the low queue times. These are low, because the more flexible resources of this model variant can execute more tasks and be allocated more easily. Therefore, this model variant has lower queue times under the same arrival rate. It is expected that the differences increase when the arrival rate increases. This will be investigated with an additional measurement.

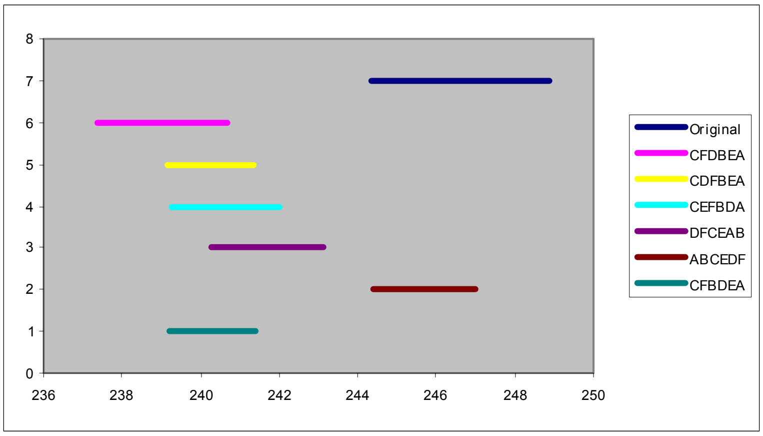

Figure 22: Confidence intervals of the lead times of model variant SW11

Utilization: The swapping tasks rule also has a positive effect on the utilizations of the resource classes. The utilizations of the higher ranked combinations are lower (11.5%) and more balanced compared to the lower ranked combinations.

WIP: The decrease in the number of cases in the system again shows the same pattern. The higher ranked models have a lower WIP level than the lower ranked systems (14.4%).

Flexibility: Both labour flexibility and volume flexibility increase with the implementation of the swapping tasks rule (39.2% and 22.6%).

Conclusions model variant SW11 (Case 3, ABC-DEF):
From the analysis of this model variant it can be concluded that the swapping tasks rule has a positive impact on the lead time, the utilization, the WIP level and the flexibility of a workflow. The decrease in lead time is smaller than that of model variant SW10. This is caused by the fact that the resource in this model variant can execute more tasks. These more flexible resources can more easily be allocated to busy tasks. Therefore, the same arrival rate as in model variant SW10 leads to lower queue times.

6.1.12 Analysis model variant SW12 (Case 3, ABCDEF)

This last model variant contains the fourth resource setup of case 3; ABCDEF, a setup with only generalists. The output data of this model variant is summed up in Table 41 in Appendix D. The following analysis can be made from the data.

Lead time: Implementation of the swapping tasks rule does not lead to better lead times in this model variant. As for the same setup in case 1 and 2, the resources in this model variant are generalists that can execute all tasks. The flexibility of these resources reduces the queue times of cases considerably in a model with this low arrival rate. As Figure 23 shows, there is no significant difference between the lead times of the combinations. Whether the lead times are significantly different under a higher arrival rate will be cleared up with additional measurements.

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Figure 23: Confidence intervals of the lead times of model variant SW12

Utilization: As expected, the swapping tasks rule does decrease the utilization of the resource class (11.8%). This is due to the fact that cases are rejected earlier in the process. Therefore the resources have to work fewer hours on this process.

WIP: In this model variant, the WIP level is also decreased by the implementation of the rule (11.5%). The same pattern as before has been found.

Flexibility: The labour flexibility (23.2%) and the volume flexibility (23.2%) both increase according the same pattern, as the ranking of the combinations increases.

Conclusions model variant SW12 (Case 3, ABCDEF):
The observations of this model variant are as expected. Like for model variant SW4 and SW8, the swapping tasks rule does not lead to better lead times with this arrival rate. The rule does lead to lower utilizations, a lower WIP level and higher flexibility.

In the analysis of the 12 model variants for the swapping tasks rule, it has been suggested to execute some additional measurements to either confirm or reject a stated expectation. The next section describes the setup and the results of the additional measurements. Section 6.3 gives a summary of the results of the analysis and Section 6.4 states the final conclusions.

6.2 Additional measurements swapping tasks rule

Three additional measurements have been suggested during the analysis of the output of model variants SW1 – SW12. This section describes the setup and the results of the following additional measurements:

- **Additional measurement 1**: In Sections 6.1.2, 6.1.3 and 6.1.4 it is suggested to simulate model variants SW2, SW3 and SW4 under a higher arrival rate in order to see whether the differences in lead time would increase.
- **Additional measurement 2:** In Section 6.1.4 it is also suggested to simulate model variant SW1 with a lower arrival rate, in order to test whether the differences in lead time would become insignificant. This additional measurement checks the opposite of addition al measurement 1.
- **Additional measurement 3:** In Section 6.1.9, it has been suggested to simulate the combinations of model variant SW9 again, but now with the number of resources per resource class chosen so that the utilizations are more balanced. This additional measurement has been proposed in order to assess whether the variances of the lead time would decrease in these new measurements.

6.2.1 Output analysis additional measurement 1

The first set of additional measurements is the result of simulating model variants SW2, SW3 and SW4 under a higher arrival rate. The following higher, arrival rates have been used:

Model variant	Old arrival rate [h^{-1}]	New arrival rate [h^{-1}]
SW2	19	24
SW3	19	23
SW4	19	29

Note that the same combinations have been used except for model variant SW3. The last combination of model variant SW3 (CDABFE) was not stable any more under the new arrival rate. This combination has been replaced by the new, lowest ranked, stable combination, DBCAFE.

Results
The resulting data of the additional measurements can be found in Table 42, Table 43 and Table 44 in Appendix D. The following observations can be made based on the resulting data of simulating the models of the additional measurements.

The additional measurements indeed confirm the expectations. The lead times of the combinations, shown in Figure 24, Figure 25 and Figure 26, now show bigger, significant differences. The variances of the lead times are also lowered by the implementation of the swapping tasks rule.

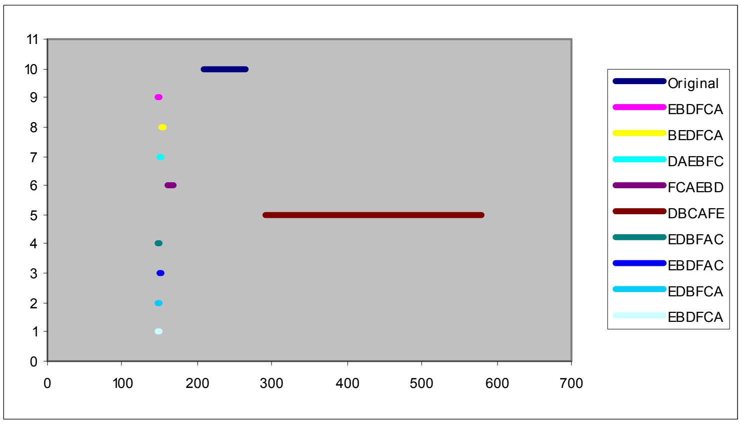


Figure 24: Confidence intervals of the lead times of additional measurement 1, AB-CD-EF

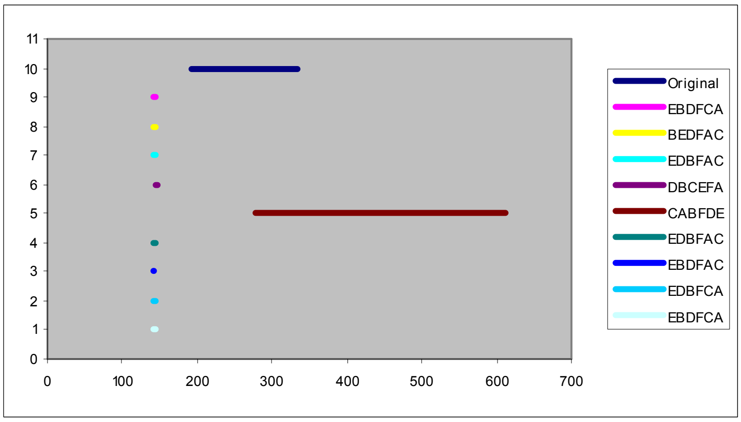


Figure 25: Confidence intervals of the lead times of additional measurement 1, ABC-DEF

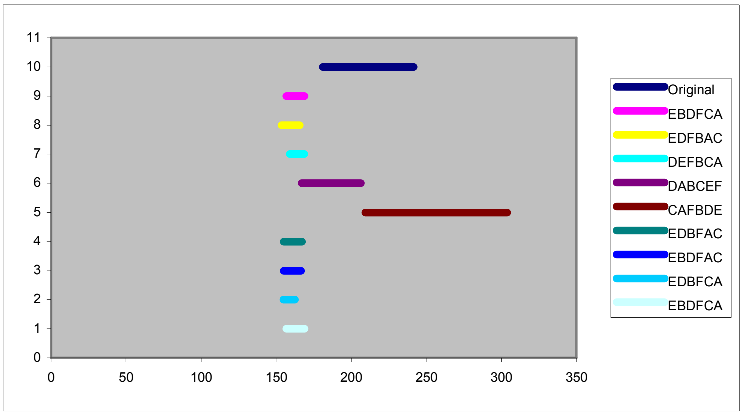


Figure 26: Confidence intervals of the lead times of additional measurement 1, ABCDEF

All other measures still show the same positive pattern; the swapping tasks rule decreases and balances the utilizations, lowers the WIP level and increases both flexibility measures. However the impact of the rule on all measures increases, except for utilization. The impact on the utilization is comparable for the models with high and low arrival rates. Table 25 shows all differences between the original model and the optimal redesign for low and high arrival rates. From this table it can be seen that the impact of the rule is higher on a model with a higher arrival rate.

	SW2		SW3		SW4	
	Low	**High**	**Low**	**High**	**Low**	**High**
Lead time	-2.3 %	-36.5 %	-2.1 %	-45.8 %	0	-23.0 %
Utilization	-2.9 %	-3.0 %	-3.4 %	-2.9 %	-3.5 %	-3.3 %
WIP	-3.4 %	-44.3 %	-5.7 %	-53.7 %	-3.4 %	-25.6 %
Lab. Flex	17.5 %	40.3 %	18.7 %	32.9 %	5.9 %	69.8 %
Vol. Flex	4.9 %	11.7 %	5.7 %	9.1 %	6.0 %	84.3 %

Table 25: Differences between high and low arrival rates

As the model variants for case 2 and case 3 had the same type of differences, concerning arrival rates as case 1, it is assumed that the above described results and observations can be generalized onto the model variants of case 2 and 3. No additional measurements have been conducted for these model variants, in order to reduce the simulation effort.

6.2.2 Output analysis additional measurement 2

The second additional measurement, suggested in Section 6.1.4, is the simulation of model variant SW1 under a lower arrival rate. This additional measurement has been proposed in order to verify whether the differences in measures between the combinations in this model variant become smaller or even insignificant under a lower arrival rate.

Two sets of simulations have been performed, both with a lower arrival rate. The following arrival rates have been used:

Model variant	Old arrival rate [h^{-1}]	New arrival rate 1 [h^{-1}]	New arrival rate 2 [h^{-1}]
SW1	19	15	12

The utilizations of the resource classes of the optimal combination are 40-55% for the model with an arrival of 15 cases per hour and 30-45% for the model with an arrival rate of 12 cases per hour.

Results

The results of the simulations of additional measurement 2 can be seen in Table 45 and Table 46 in Appendix D. From these results it can be seen that the differences between the combinations have become smaller in the models with the lower arrival rates. In Figure 27 and Figure 28, showing the confidence intervals of the lead times of models with arrival rate 15 and 12, it can be seen that in the model with the lowest arrival rate (12), the differences in lead time have become insignificant.

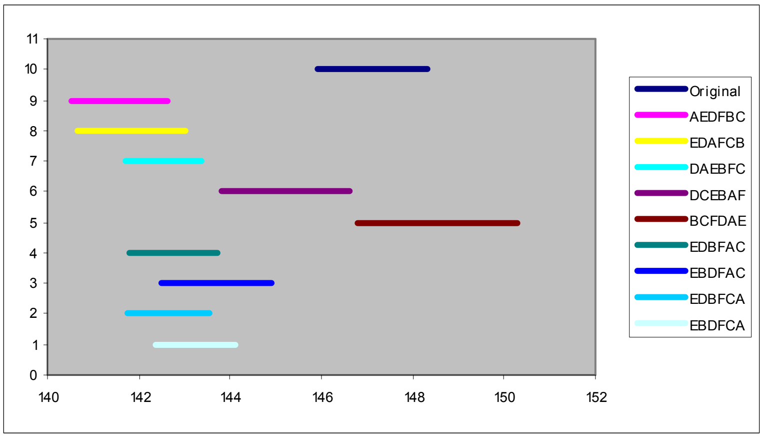


Figure 27: Confidence intervals of the lead times of additional measurement 2, A-B-C-D-E-F [15]

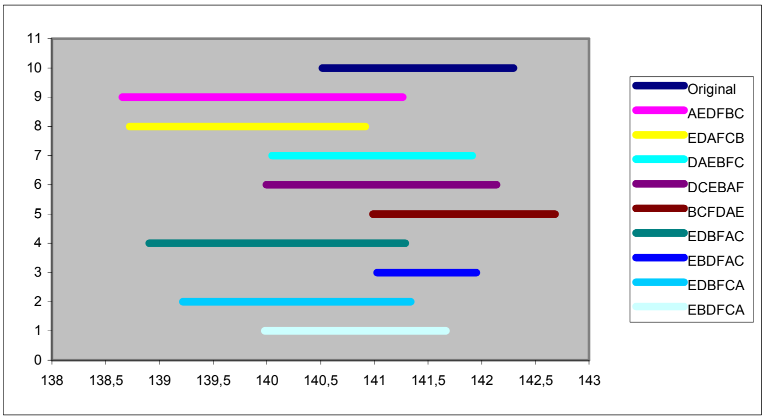


Figure 28: Confidence intervals of the lead times of additional measurement 2, A-B-C-D-E-F [12]

The swapping tasks rule results in more balanced, significantly lower utilizations and a lower WIP level in this additional measurement. It also increases both flexibility measures. It must be remarked though that the differences are smaller, under a lower arrival rate.

The resulting data fully complies with the expectation, and confirms earlier predictions.

6.2.3 Output analysis additional measurement 3

In this third additional measurement, suggested in Section 6.1.9, it has been investigated whether the variances of the lead times of model variant SW9 are lower and the differences between the combinations bigger, when the resources are chosen so that the utilizations are more balanced. The following setup of the resources has been chosen.

Tasks	Nr of resources old	Nr of resources new
A	9	8
B	9	8
C	9	12
D	9	8
E	9	8
F	9	10

Table 26: Resource setup additional measurement 3

Results
The resulting output data is shown in Table 47 in Appendix D. Figure 29, showing the lead times of all combinations, shows that the variances indeed have been lowered by the new resource setup. The differences between the combinations are significant in contrast to model variant SW9. With this setting, the swapping tasks rule decreases the variance of the lead time.

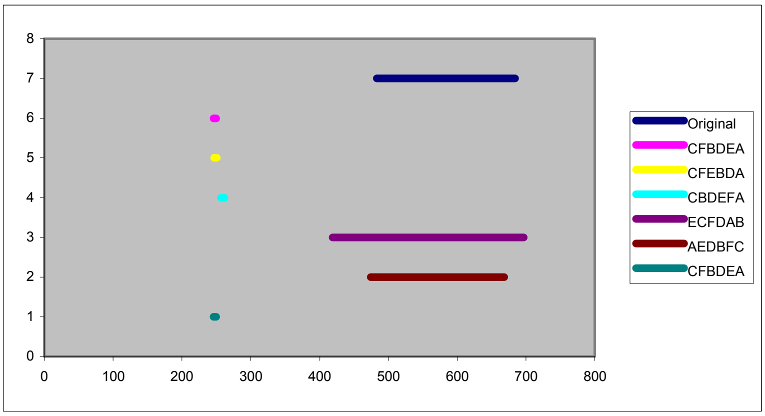


Figure 29: Confidence intervals of the lead times of additional measurement 3

The other measures are still positively affected by the swapping tasks rule. The utilizations are lower and more balanced, the WIP level is lower and the flexibility increases, just like in model variant SW9. The difference in lead time and WIP level, between the original model and the optimal combination are much bigger in this additional measurement compared to model variant SW9. The differences in utilization and flexibility measures are comparable.

6.3 Summary of the results of the analysis

This Section gives a summary of the results of the analysis that has been performed and described in Section 6.1 and 6.2. Table 27 shows an overview of the impact of the swapping tasks rule on the different model variants. A "-" means a decreasing impact, a "0" means no significant impact and a "+" means an increasing impact. The second column shows the impact on the average of the lead time of the model variants. The third column shows the impact on the average of the lead time in the additional measurements. The numbers represent the number of the additional measurement. Column four and five show what the impact of the rule is on the variance of the lead time in the simulations and the additional measurements. The "Balanced" column of the utilization shows whether the utilizations are more balanced in the optimal redesign. A "NA" means that more balanced resource utilization is not applicable for that model variant, as these model variants only have one resource class.

	Lt SW	Lt Add	Lt SW	Lt Add	Utilization		WIP	Lab flex	Vol flex
MV	Average		Variance		Balanced	Av	Av	Av	Av
SW1	-	o (2)	-	o (2)	Y	o	-	+	o
SW2	-	- (1)	-	- (1)	Y	-	-	+	+
SW3	-	- (1)	-	- (1)	Y	-	-	+	+
SW4	o	- (1)	o	- (1)	NA	-	-	+	+
SW5	-		-		Y	-	-	+	+
SW6	o	-	-	-	Y	-	-	+	+
SW7	o	-	-	-	Y	-	-	+	+
SW8	o	-	o	-	NA	-	-	+	+
SW9	o	- (3)	o	- (3)	N	-	-	+	+
SW10	-	-	-	-	Y	-	-	+	+
SW11	-	-	o	-	Y	-	-	+	+
SW12	o	-	o	-	NA	-	-	+	+

Table 27: Summary of the impact of the swapping tasks rule

The following, summarizing observations can be made from the data of Table 27.

Lead time: From the first five columns it can be seen that in some models the swapping tasks rule has a significant impact on the lead time and in some models it does not change the lead time significantly. There are two types of situations where the rule has no impact on the lead time:

- When the arrival rate is at such a low level that there are very low or even no significant queue times in the process
- When the utilizations of the resource are very unbalanced and the rule is unable to balance the utilizations

When the arrival rate and the queue times are low, the rule does not lead to a decrease in lead time, since cases never have to wait. It takes cases an equal amount of time to complete the process (six tasks) of the original situation compared to the optimal situation. This finding has been confirmed with two additional measurements. The impact on the lead time increased, when the arrival rates of model variants SW2, SW3 and SW4 were increased. The differences of model variant SW1 became insignificant when the arrival rate was lowered.

The second situation is the situation of model variant SW9. The utilizations are very unbalanced and swapping the tasks does not lead to more balanced utilizations. One of the resource classes (responsible for the execution of the first task in the redesign) always has a high utilization, since the service times and the number of resources are equal for all classes. Swapping tasks does not solve this problem. This results in high queue times and variances of the lead time. These high variances cause the insignificance in the differences. A better chosen division of resources over the resource classes (additional measurement 3) solves the problem. In this new situation, the lead time and the variance are both lowered by the implementation of the swapping tasks rule.

The above listed situations are also the situations in which the rule does not lower the variances of the lead times. In additional measurement 1 and 3, introduction of the rule resulted in lower variances.

Utilization: In all model variants, except model variant SW1, application of heuristic 2 results in lower utilizations. Model variant SW9 is the only model variant in which the application of the rule does not lead to more balanced utilization. As described earlier, the utilizations of this model variant are too unbalanced for heuristic 2 to balance them.

However, in additional measurement 3, where the same model variant is simulated, but with a better chosen number of resources per resource class, introduction of the rule did lead to more balanced utilizations.

WIP: Implementation of the swapping tasks rule leads to a lower WIP level, for all model variants.

Flexibility: Using heuristic 2, to redesign a knock-out process leads to an increase in labour flexibility for all model variants. As for utilization, model variant 1 is the only variant in which volume flexibility is not significantly increasing after the redesign. All other model variants show an increase in volume flexibility.

The following section gives the conclusions based on the analysis of the model variants and the additional measurements and the above stated summary of the results.

6.4 Conclusions swapping tasks rule

This section gives the final conclusions, based on the analysis of the output data.

Lead time:

- In models with an arrival rate at such a low level that the queue times are also low, implementation of the swapping tasks rule does neither lead to a decrease in lead time nor to a decrease in the variance of the lead time.
- In processes with very unbalanced utilizations that cannot be solved by the swapping tasks rule, implementation of the swapping tasks rule also does not lead to a reduction of lead time or a decrease in the variance of the lead time.
- In all other processes, swapping the tasks according to heuristic 2 results in a decrease in lead time and a decrease in variance.

Other measures:
Redesigning a workflow, by swapping KO tasks according to heuristic 2 results in:

- Lower and more balanced resource utilizations. This results in a less costly execution of the process, since resources spend less time working on the process.
- A lower WIP level. A lower WIP level means fewer cases in the system during execution. This leads to lower inventory costs and a more orderly process.
- Increased labour flexibility. This means that more resources are available to be allocated to a certain task or case.
- Increased volume flexibility. Since resources work fewer hours on the process, they have more available time. When the arrival rate increases or there is a peak in the arrival process, the redesigned process has more available capacity to handle these extra cases.

- Heuristic 1 (Van der Aalst, 2000) often leads to a good scoring redesign. It sometimes even results in the optimal combination. Heuristic 2 (Van der Aalst, 2000) has led to the optimal combination in all model variants and additional measurements. It is therefore recommended to use heuristic 2 for swapping tasks in order to redesign KO processes.

Final conclusion:
Using heuristic 2 to redesign a KO process leads to lower, more balanced utilizations, a lower WIP level and increased labour and volume flexibility. When the arrival rate is too low to cause queue times or the utilizations of the resource classes are too unbalanced for the heuristic to balance them, implementation of heuristic 2 does not results in a reduction of lead time. In all other processes, heuristic 2 results in lower lead times.

6.5 Reflection on the results of the swapping tasks rule

This last section of this chapter gives a reflection on the results of the swapping tasks rule. A comparison with the results of the KO research project of Van der Aalst (2000) is made. The differences between the research and research methods of Van der Aalst and those of this simulation project can be found at the end of this report, in the reflection in Section 9.2.

A comparison between the results of Van der Aalst (2000) and the results of this simulation project results in two differences:

- The results of the research of Van der Aalst (2000) indicate that heuristic 2 should be applied to processes in which tasks use different resource classes and can only be used to lower the lead time. In these processes, heuristic 1 can be used to minimize the overall utilization. In processes where tasks share a resource class, heuristic 1 should be used to obtain an optimal redesign with respect to lead time. From the results of this simulation study, it can be seen that application of heuristic 2 to several types of processes leads to a decrease in lead time and utilization, irrespective of tasks sharing a resource class or not.
- According to Van der Aalst (2000), swapping tasks using the ratio of heuristic 2 results in a reduction of lead time. However, the analysis of this study identified two situation in which implementation of heuristic 2 does not lead to a decrease in lead time: models with low arrival rates and models with unbalanced utilizations, which cannot be solved. The results of this study comply with the statement of heuristic 2 for all other situations.

7 Output analysis combining tasks rule

This chapter describes the output analyses and the results of the second KO redesign rule, the combining tasks rule. First, every model variant is analyzed separately. The results are described in Section 7.1. Next an overview of the results is given in Section 7.2. Finally Section 7.3 gives the final conclusions for the combining tasks rule and Section 7.4 gives a reflection on the results.

7.1 *Output analysis swapping tasks rule*

Each of the following sub-sections describes the output analysis of one model variant. Every model variant is simulated under three different arrival rates, as explained in Section 4.2.1. The analyses are based on the comparisons of Section 5.1.2.

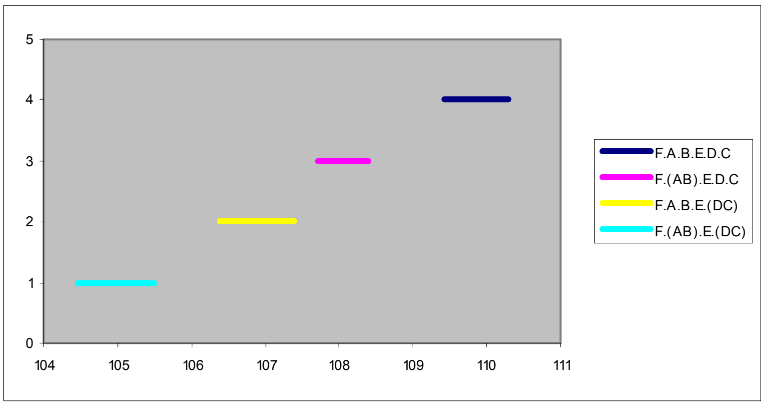
7.1.1 Analysis model variant C1 (AB-CD-EF, Setup ratio 1)

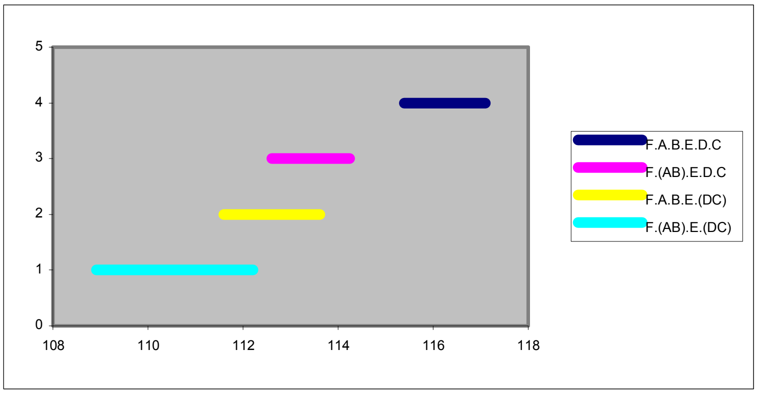
The resources of the first model variant are distributed over three resource classes (AB-CD-EF). The setup ratio of model variant C1 is setup ratio 1, a variant in which, according to heuristic 3 and 4 (Van der Aalst, 2000), it is advisable to combine tasks A and B as well as D and C. The results of simulating the four models of Table 18 can be found in Table 48 in Appendix E. The following observations can be made from the data of Table 48.

Lead time: It is expected that the implementation of the combining tasks rule will have a positive effect on the lead times of completed cases in this model variant. This is due to the setup ratio of this model variant, in which it is advisable to combine A – B and C – D. From the graphs of Figure 30, depicting the confidence intervals of the lead times of model variant C1 for arrival rate 23, 36 and 42, it can be seen that implementation of the rule indeed leads to lower lead times. This is obvious since the setup of the second task can be skipped in the redesign and the additional time of executing the entire composite task when the first subtask returns NOK is only low.

It can also be seen that the decrease in lead time of combining tasks D and C is bigger than the decrease of combining tasks A and B. This is because the queue times of tasks C and D are much higher in the original model than those of tasks A and B. Combining the tasks leads to elimination of one of the queue times. Therefore the reduction of lead time is bigger for the models in which tasks C and D are combined.

Another observation is that the impact of the rule is bigger on models with a higher arrival rate. This is also caused by the higher queue times that occur in models with higher arrival rates. A side effect of the higher arrival rate is that the variances of the lead times are higher. This causes an insignificant difference between the lead time of the original model and that of the model with only A and B combined. So, under a higher arrival rate, combining tasks A and B does not lead to a better lead time.





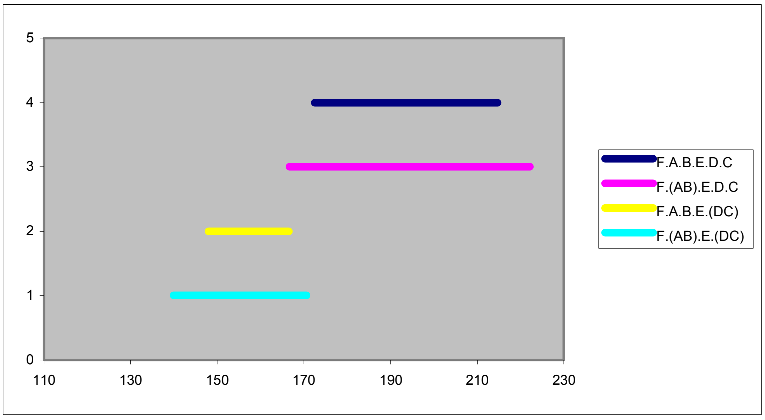


Figure 30: Confidence intervals of the lead times of model variant C1 for arrival rate 23, 36, 42

Utilization: Implementation of the combining tasks rule also results in lower utilizations. This is because the reduction of eliminating one setup outweighs the loss in time of executing the second subtask when the first subtask returns NOK. This means that the resources have to work fewer hours.

WIP: Considering WIP level it can be seen that the difference for this measure between the redesigns is only small or even insignificant for all three arrival rates.

Flexibility: Introduction of the combining tasks rule mainly has a positive impact on the labour flexibility. Especially combining tasks A and B results in a higher labour flexibility. This due to the fact that tasks A and B are executed in the beginning of the process. The rule also leads to an increase in volume flexibility. This is because the resources have more available time, since the utilizations are lower in the redesign.

Conclusions model variant C1 (AB-CD-EF, Setup ratio 1):
From the analysis stated above it can be concluded that implementation of the combining tasks rule results in lower lead times, especially when the arrival rates and the queue times are high. The rule also leads to lower utilizations, because the resources have to work fewer hours. It has a positive impact on the flexibility of a workflow. However, the WIP level remains the same. In a process with the same settings as this model variant, it is advisable to implement the combining tasks rule.

7.1.2 Analysis model variant C2 (AB-CD-EF, Setup ratio 2)

This second model variant also has a resource setup with three resource classes (AB-CD-EF), but has setup ratio 2. This setup ratio contains setup times that are chosen so that in this model variant it is not advisable to combine tasks D and C. However, tasks A and B should still be combined. Again all four models of Table 18 have been simulated. The results of the simulations are reported in Table 49 in Appendix E. The following observations can be made.

Lead time: In Figure 31, showing the confidence intervals of the lead times under the three arrival rates, it can be seen that combining tasks A and B results in a lower lead time for the models with arrival rates of 23 and 36. In the model with the highest arrival rate, combining tasks A and B does not result in a significant decrease. The high arrival rate causes higher queue times and variances in the lead times. Combining tasks A and B does lead to a small decrease in lead time and to small decrease in queue time, since cases only have to wait once instead of twice. However, these two small differences are not big enough to create a significant difference with these high variances. Combining D and C (which is not recommended in this setting) even leads to a significant increase in lead time in the model with the highest arrival rate. This is due to the dramatically increased queue time of the composed task.

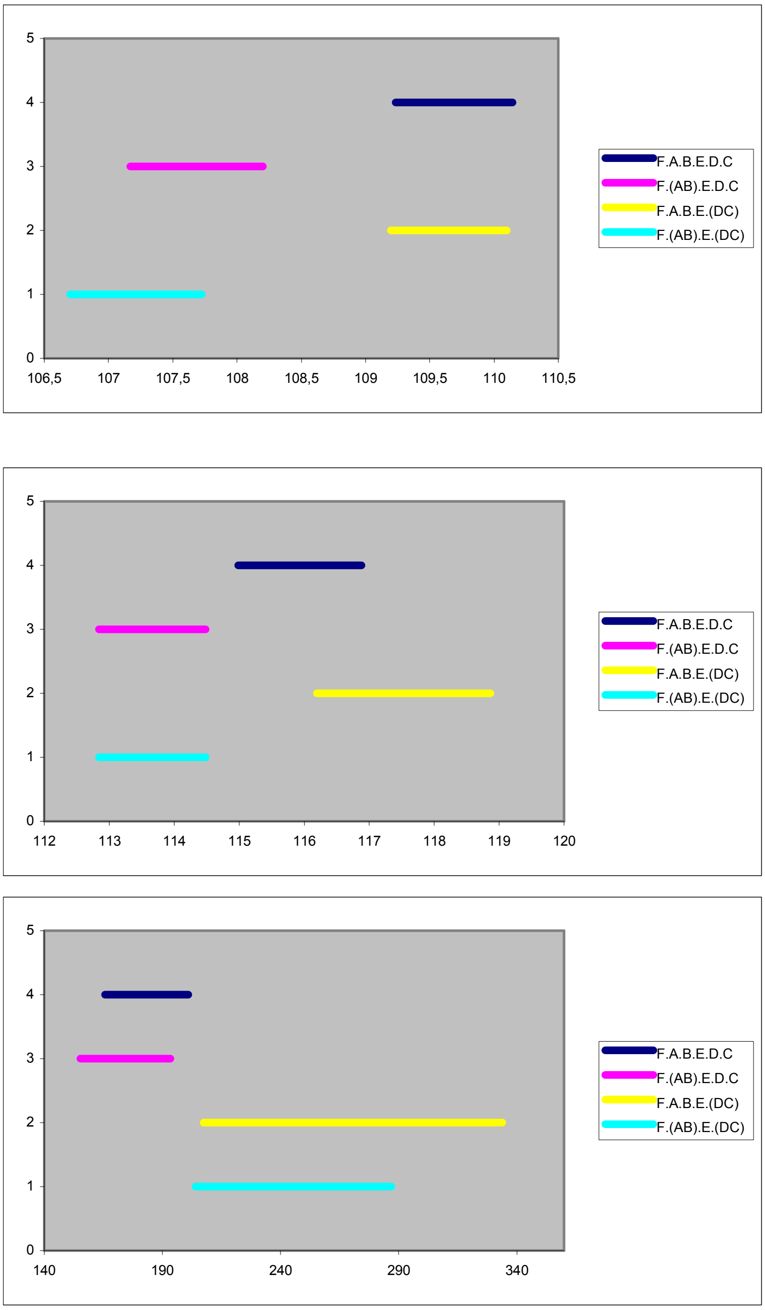


Figure 31: Confidence intervals of the lead times of model variant C2 for arrival rate 23, 36, 42

Utilization: The decreases of all three arrival rates show the same pattern, but only the difference between the model with A and B combined and the original model, with an arrival rate of 23 is significant. The differences of the other two arrival rates are insignificant.

WIP: None of the three models shows a difference in WIP level. Composing tasks does not have a significant impact on the WIP level in this model variant.

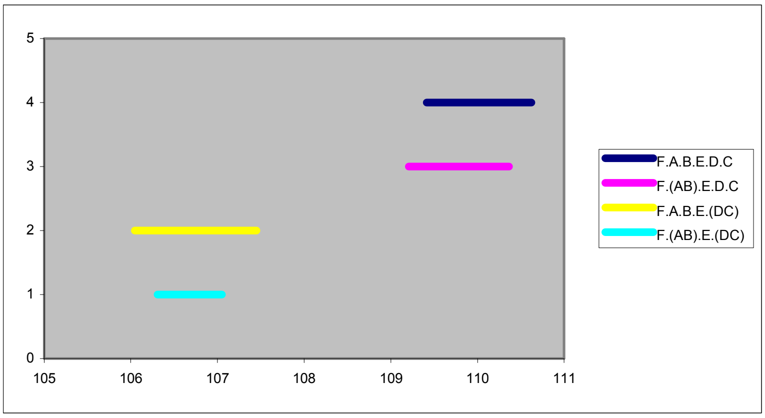
Flexibility: Only the model with the lowest arrival rate has a significant difference; an increase in labour flexibility when only combining tasks A and B. The models with the higher arrival rates do not show a significant difference. The same is true for volume flexibility. The model with an arrival rate of 23 is the only model with a significant increase, when A and B are combined.

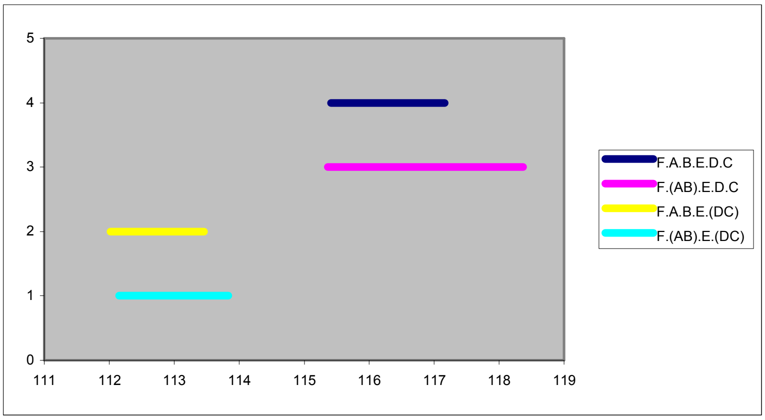
Conclusions model variant C2 (AB-CD-EF, Setup ratio 2):
Combining only tasks A and B leads to a significant reduction of lead time for models with a low and medium arrival rate. Combining tasks D and C or combining any tasks under a high arrival rate does not lead to a decrease in lead time, or can even result in an increase in lead time. None of the models show a significant difference in WIP level. The other measures are only significantly positive affected when tasks A and B are combined in a model with a low arrival rate. All other situations lead to an insignificant difference in these measures.

7.1.3 Analysis model variant C3 (AB-CD-EF, Setup ratio 3)

This model variant is the third variant with resource setup AB-CD-EF, but now with setup ratio 3. The times in this setup ratio are chosen so that according to heuristic 3 and 4 it is unadvisable to combine tasks A and B, but combining tasks D and C should lead to a positive result. The results of the simulations are shown in Table 50 in Appendix E. The following observations can be made.

Lead time: In the graphs of Figure 32 it can be seen that combining tasks D and C leads to lower lead time for the models with low and medium arrival rates. The difference of the model with a high arrival rate is insignificant. This is comparable to the observations of the previous model variant.





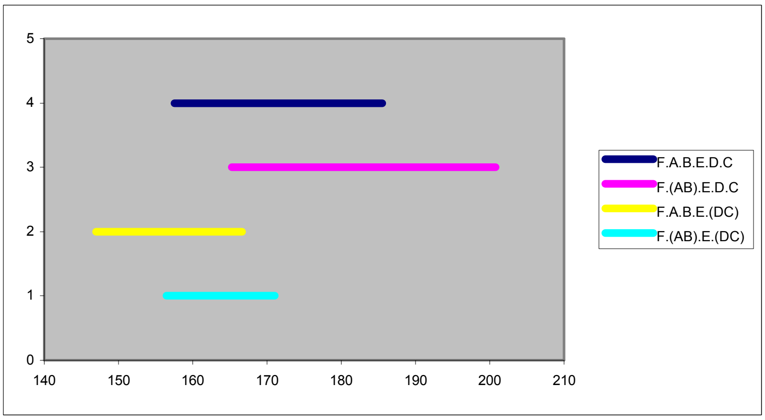


Figure 32: Confidence intervals of the lead times of model variant C3 for arrival rate 23, 36, 42

Utilization: Again, an observation comparable to that of model variant C2 can be made. Combining tasks D and C only leads to significant lower utilization in the model with the lowest arrival rate. All other differences are insignificant.

WIP: Also for this measure, combining tasks D and C does not result in a lower WIP level for any of the three models. This is also equal to the observation of the previous model variant.

Flexibility: Combining tasks D and C does not result in an increase in labour flexibility. However, combining tasks A and B still leads to an increase in labour flexibility for the model with the lowest arrival rate. Concerning volume flexibility, combining D and C only results in an increase in the model with the lowest arrival rate. All other differences are not significant.

Conclusions model variant C3 (AB-CD-EF, Setup ratio 3):
For this model variant it can be concluded that combining tasks D and C results in lower lead times for the models with the low and medium arrival rates. The combination of these tasks does not have a significant impact on the lead time of the model with a high arrival rate and on the WIP level and the utilizations of all models. Furthermore, combining tasks D and C only has a significant positive effect on the volume flexibility in the model with a low arrival rate. These conclusions are all consistent with the conclusions and observations of the previous model variant. The only divergent observation is that of the labour flexibility. Again, only the model with the lowest arrival rate has a significant difference, but now it is not the model with tasks D and C combined, but the model with A and B composed into one task that has the significant difference.

7.1.4 Analysis model variant C4 (AB-CD-EF, Setup ratio 4)

Model variant C4 is the last model variant with a 2 class resource setup and has the settings of setup ratio 4. The setup times of setup ratio 4 are chosen so that heuristic 3 and 4 advise against the composition of tasks A and B as well as D and C. The models in this model variant investigate what the impact is when these tasks are composed anyway. The results of the simulations can be found in Table 51 in Appendix E. The following observations can be made.

Lead time: From Figure 33, showing the confidence intervals of the lead times of this model variant, it can be seen that combining tasks A and B and/or D and C against the statement of heuristic 3 and 4 does not lead to lower lead time. In the model with the highest arrival rate, combining only tasks D and C even leads to an increase in lead time.

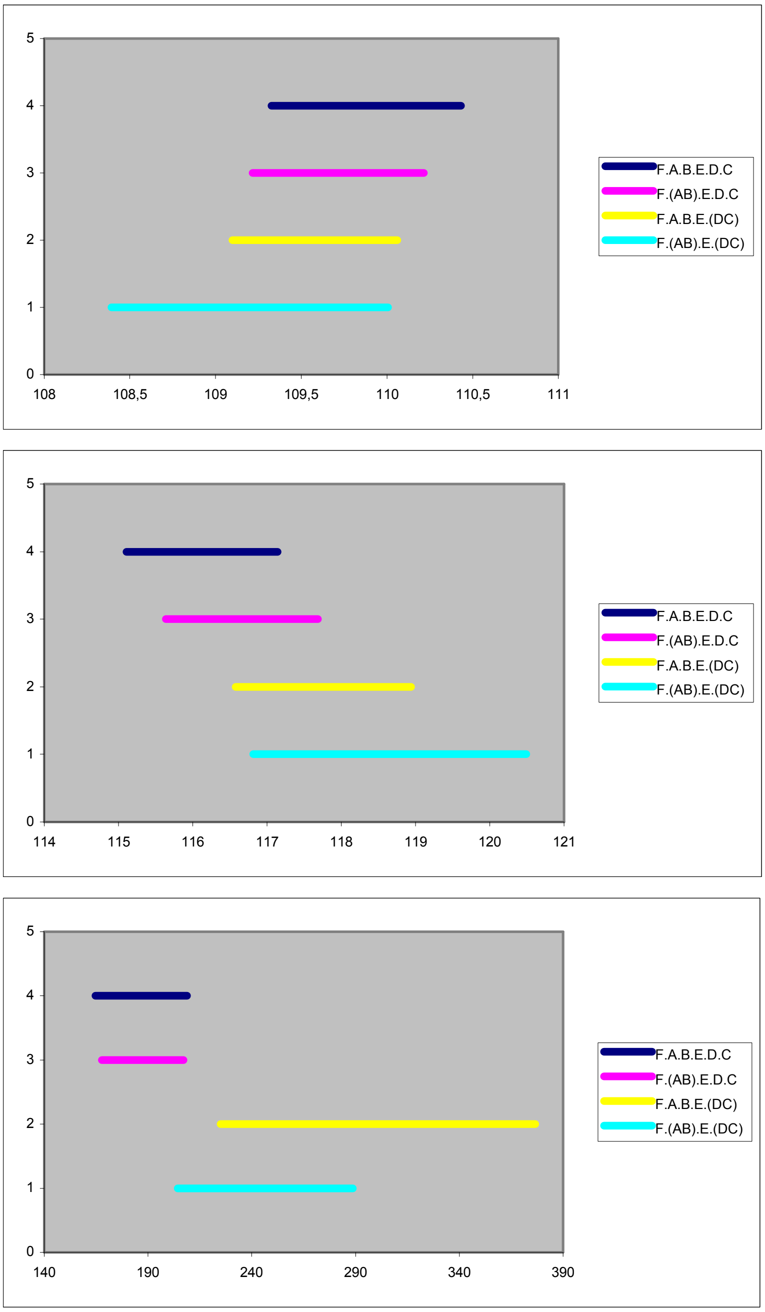


Figure 33: Confidence intervals of the lead times of model variant C4 for arrival rate 23, 36, 42

Utilization: For all three arrival rates, creating two composite tasks results in higher utilizations. The reduction in time of the elimination of one setup time is not high enough to make up for the extra working time of executing subtask 2, while subtask 1 resulted in NOK.

WIP: In this model variant, combining tasks does not lead to lower WIP levels. Combining tasks D and C even leads to higher WIP levels.

Flexibility: Combining tasks A and B leads to an increased labour flexibility under a low arrival rate. The labour flexibility remains the same in the two models with the higher arrival rates. The volume flexibility also remains equal (arrival rate 42) or decreases (arrival rate 23 and 36).

Conclusions model variant C4 (AB-CD-EF, Setup ratio 4):
Combining tasks A and B and/or D and C, in a process with settings comparable to the settings of this model variant leads to no decrease or even an increase in lead time, WIP and utilization. It also does not have a positive effect on the flexibility measures. Therefore it is highly unadvisable to implement the combining tasks rule in a model like model variant C4.

7.1.5 Analysis model variant C5 (ABC-DEF, Setup ratio 1)

This fifth model variant is the first model variant with resource setup ABC-DEF. With this resource setup it is only possible to combine tasks A and B and to combine E and D. As in model variant 1, setup ratio 1 has been used. With this ratio it is advisable to combine tasks A and B as well as tasks E and D. The resulting data of the simulations are reported in Table 52 in Appendix E. The following observations can be made.

Lead time: Looking at all confidence intervals of the lead times of this model variant, shown in Figure 34, it can be seen that the combining tasks rule leads to a decrease in lead times. The decreasing pattern is the same for all three arrival rates. However, the variances of the lead times are higher in the model that has a higher arrival rate. This causes the small or insignificant difference between the confidence intervals of the original combination and that of combinations with only one combined task.

The decrease in lead time of combining tasks A and B is as big as the decrease when combining E and D. From the simulation results of the original model it appears that all six tasks have equal queue times. Combining any two tasks results in the same reduction of lead time. As expected all three redesigned models result in a lower lead time.

Another remark is that the combining tasks rule has a greater impact on the lead time in models with a higher arrival rate, since the differences in averages are bigger (2.1%, 2.5% and 5.8%).

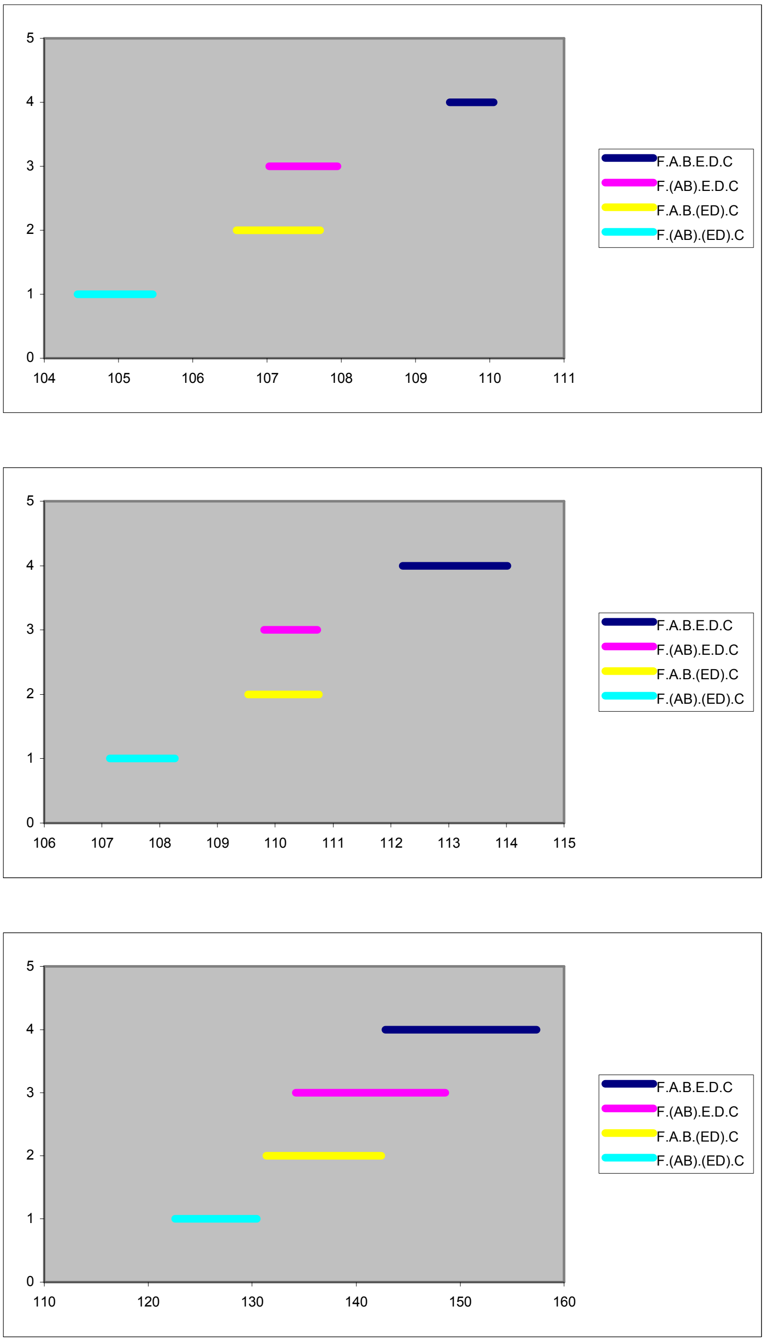


Figure 34: Confidence intervals of the lead times of model variant C5 for arrival rate 23, 36, 42

Utilization: As expected, combining tasks A and B and/or D and E leads to lower utilizations. These utilizations are lower, because resources spend less time on setting up the composite tasks.

WIP: For all three arrival rates, the WIP level of the model with two composed tasks is lower than the WIP level of the original model. The impact is bigger on models with a higher arrival rate. The variances are high, which causes insignificant differences between the WIP levels of the models with one combined tasks and that of the original model.

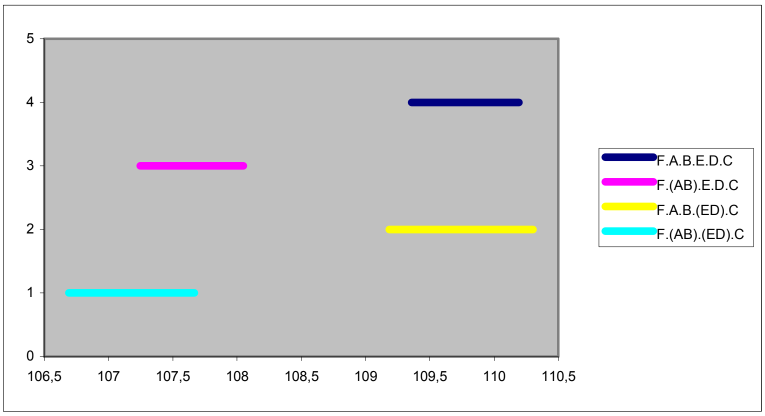
Flexibility: Also in this model variant, combining tasks leads to a higher labour flexibility. For the models with arrival rate 23 and 36, combining A and B has significant more impact on the labour flexibility than combining E and D. Also the volume flexibility increases with the implementation of this rule.

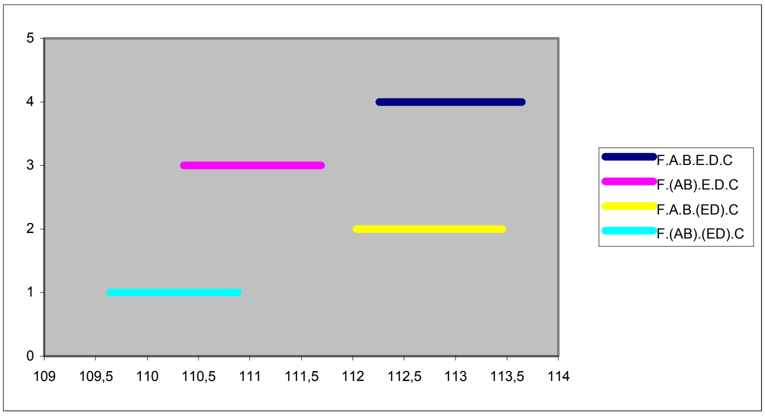
Conclusions model variant C5 (ABC-DEF, Setup ratio 1):
The combining tasks rule has a positive impact on the lead time of completed cases. With this setup ratio, heuristic 3 and 4 propose to combine A and B as well as D and E. The results of this model variant indeed support the proposal of these heuristics. Combing the tasks into two composite tasks results in the lowest lead time. For models with a high arrival rate, combining tasks A and B can lead to an insignificant decrease in lead time. The rule also leads to a decrease in utilization. Combining only two tasks into one composite task leads to a lower WIP level, except in a model with a high arrival rate. Here the differences are small or insignificant. Creating two composite tasks leads to a lower WIP level under all three arrival rates. Finally the rule also leads to an increase in labour flexibility and volume flexibility.

7.1.6 Analysis model variant C6 (ABC-DEF, Setup ratio 2)

Model variant C6 is the second model variant with resource setup ABC-DEF. In this variant, setup ratio 2 has been used. With the setup times in this ratio, it is only advisable according to heuristic 3 and 4 to combine tasks A and B and not tasks E and D. In this model variant it is tested what the impact of combining A and B and/or E and D is on the performance of the workflow. The results of the simulations can be found in Table 53 in Appendix E. The following can be observed.

Lead time: The graphs of Figure 35 show the confidence intervals of the lead times of model variant C6 with the three arrival rates (23, 36 and 42). From these graphs it can be seen that combining tasks A and B results in lower lead times under a low and medium arrival rate. It does not lead to a lower lead time in the model with the highest arrival rate. The graphs show patterns that are comparable to those of model variant C2. Combining tasks E and D does not result in a significantly different lead time.





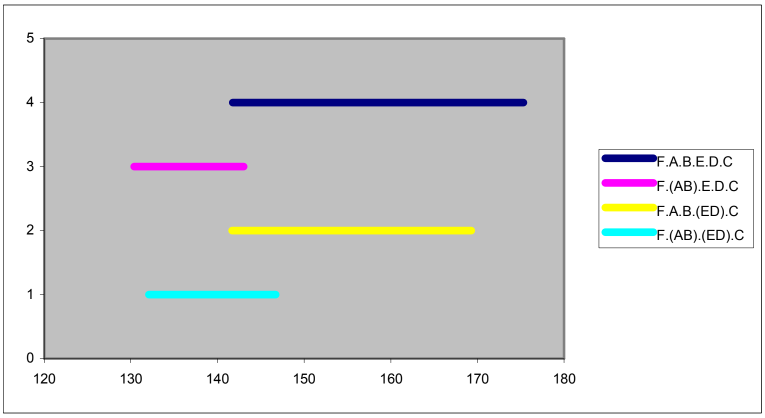


Figure 35: Confidence intervals of the lead times of model variant C6 for arrival rate 23, 36, 42

Utilization: Combining only tasks A and B leads to a lower utilization in the model with arrival rate 36 and 42. Combining E and D as well does lower the impact in results in an insignificant difference. Combining only tasks E and D does not result in a lower utilization.

WIP: None of the redesigns under any of the arrival rates has a significantly different WIP level compared to the original model. Combining tasks does not lead to a difference in WIP level. This is equal to the observations of model variant C2.

Flexibility: Although all three arrival rates show the same pattern, combining tasks A and B only leads to a significant increase in labour flexibility in the model with an arrival rate of 42. The increases are insignificant in both other models. The increase in volume flexibility is only significant in the models with arrival rate of 36 and 42.

Conclusions model variant C6 (ABC-DEF, Setup ratio 2):
As heuristic 3 and 4 predicted, combining tasks A and B results in lower lead times. However the difference is only significant in the models with an arrival rate of 23 and 36. Under the highest arrival rate, the differences in lead time are insignificant. Combining tasks A and B only leads to lower utilizations and higher volume flexibility in the models with an arrival rate 36 and 42. The labour flexibility only increases in the high arrival rate model. The WIP level is not affected by the composition of tasks A and B into one task. So, implementing the combining tasks rule leads to a positive result in lead time. The higher the arrival rate, the more positive the impact of the combining tasks rule is.

7.1.7 Analysis model variant C7 (ABC-DEF, Setup ratio 3)

Model Variant C7 is the third model variant with resource setup ABC-DEF. This model variant has setup ratio 3, with settings for which heuristic 3 and 4 (Van der Aalst, 2000) advise against the combination of tasks A and B, but recommend the composition of task E and D into one composite task. The results of the simulations are stored in Table 54 in Appendix E. The following can be observed form the data in this table.

Lead time: The graphs of Figure 36 show the confidence intervals of the lead times of the models with three different arrival rates. From these graphs it can be observed that combining tasks E and D leads to a decrease in lead time for the model with the low and medium arrival rate. Combining A and B as well leads to an insignificant difference in lead time under the highest arrival rate. This is because the queue times of the tasks AB and C increase, which causes a higher lead time.

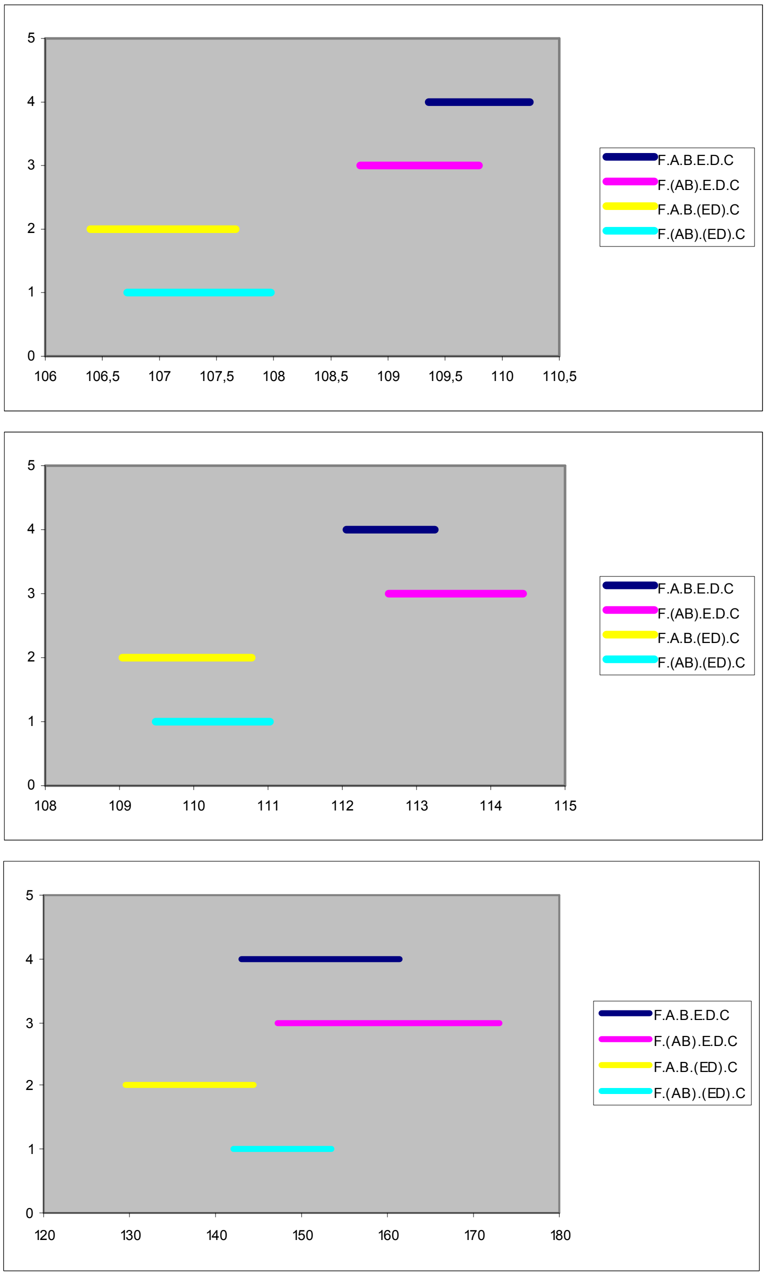


Figure 36: Confidence intervals of the lead times of model variant C7 for arrival rate 23, 36, 42

Utilization: None of the combinations of the three models have a significant different utilization. Combining tasks does not affect the utilizations in this model variant.

WIP: None of the combinations has a significantly different WIP level compared to the original model. Combining tasks again does not lead to a significant difference in WIP level. This observation is in line with the observations of model variant C3.

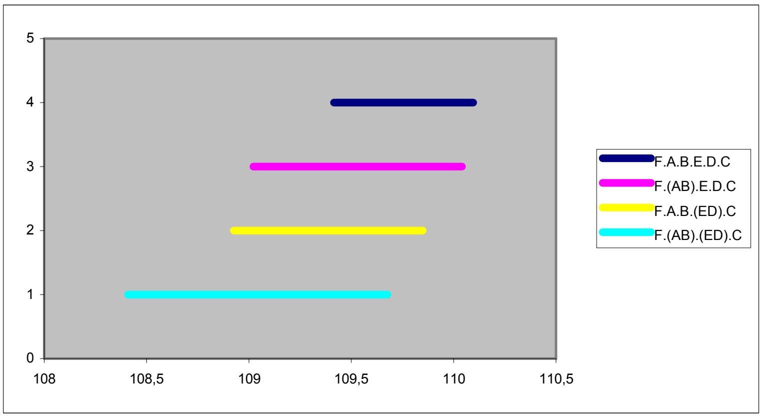
Flexibility: Combining tasks E and D and/or tasks A and B does neither result in a significantly different labour flexibility nor volume flexibility.

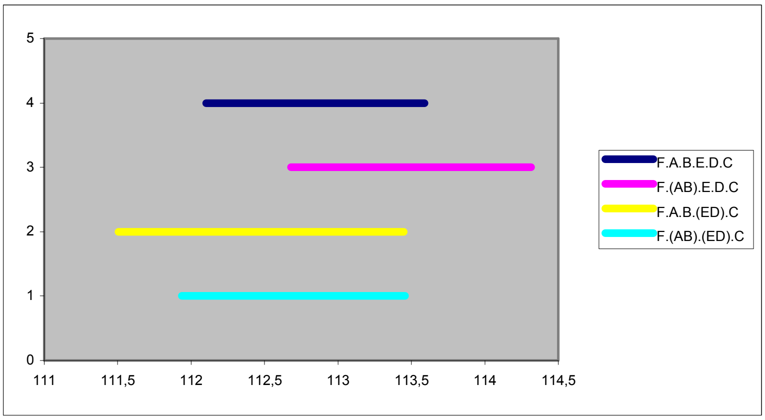
Conclusions model variant C7 (ABC-DEF, Setup ratio 3):
Combining tasks E and D results in a decrease in lead time under low and medium arrival rates. The impact on the lead time under a high arrival rate is insignificant. It does also neither lead to a decrease in utilization or WIP nor to an increase in flexibility. Combining tasks A and B does not result in any significant difference.

7.1.8 Analysis model variant C8 (ABC-DEF, Setup ratio 4)

The last model variant for the combining tasks rule is model variant C8. This is a model variant with a 2 class resource setup (ABC-DEF) and setup ratio 4. This setup ratio is chosen so that heuristic 3 and 4 (Van der Aalst, 2000) advise against the composition of tasks A and B as well the composition of E and D. The simulations in this model variant test what the impact is when one or two composite tasks are created despite the advice against composition. The results of the simulation of the four proposed models are depicted in Table 55 in Appendix E. The following can be observed from the resulting data.

Lead time: From the lead times of the completed cases in this model variant, depicted in Figure 37, it can be seen that the resulting data indeed supports the statement of heuristic 3 and 4. It can be seen that for none of the models with different arrival rates has a significant decrease in lead time when combining tasks A and B and/or tasks E and D.





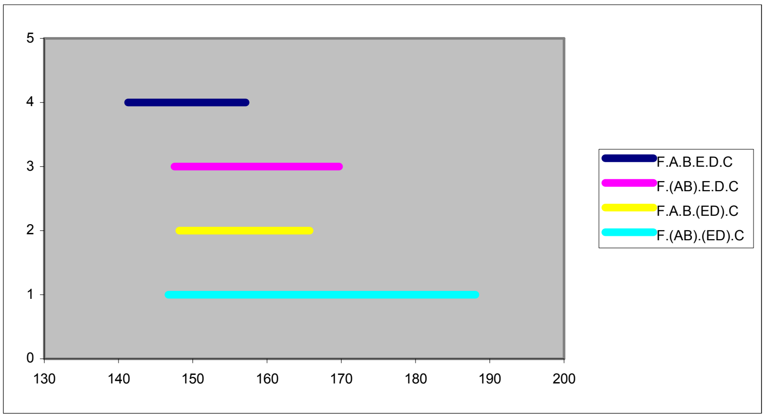


Figure 37: Confidence intervals of the lead times of model variant C8 for arrival rate 23, 36, 42

Utilization: When looking at the data of the utilizations, it can be seen that in the models with arrival rate 23 and 36, combining tasks does not lead to a significant change in utilization. In the model with the highest arrival rate (42) the composition of the tasks even leads to an increase in utilization.

WIP: The pattern of the WIP level is comparable to that of the utilization. The composition of tasks does not result in a significantly changed WIP level.

Flexibility: Implementation of the rule under this setting leads to an equal or even lower labour flexibility. The higher the arrival rate, the more negative the impact on the labour flexibility. The same is true for volume flexibility.

Conclusions model variant C8 (ABC-DEF, Setup ratio 1):
Combining tasks A and B and/or tasks E and D, in a model with the same settings as this model variant, does not lead to a lower lead time nor WIP level. The implementation of the rule can even lead to higher utilizations (more costs) and lower flexibility, in models with a higher arrival rate. According to the data, in this situation it is unadvisable to implement the combining tasks rule.

7.2 Summary of the results of the analysis

This section gives an overview and a summary of all the resulting outcomes of the analysis of Section 7.1. Table 28 gives an overview of the impact of the combining tasks rule on all measures of the model variants under the three arrival rates. The comparisons on which Table 28 is based are between the original model and the model with one or two combined tasks as recommended by heuristic 3 and 4. So, in model variant C1, the original situation has been compared to a model with two combined tasks. In model variant C2, the original situation has been compared to a model in which tasks A and B are combined. A "-" in Table 28 means a decreasing impact, a "o" means no significant impact and a "+" means an increasing impact.

	Lead time			Utilization			WIP			Labour flex			Volume flex		
MV	23	36	42	23	36	42	23	36	42	23	36	42	23	36	42
C1	-	-	-	-	-	-	-	o	o	+	+	+	+	+	+
C2	-	-	o	-	o	o	o	o	o	+	o	o	+	o	o
C3	-	-	o	o	o	o	o	o	o	o	o	o	+	o	o
C4	o	o	o/+	+	+	+	o/+	o/+	o/+	-	o	o	-	o	o
C5	-	-	-	-	-	-	-	-	-	+	+	+	+	+	+
C6	-	-	o	o	-	-	o	o	o	o	o	+	o	+	+
C7	-	-	o	o	o	o	o	o	o	o	o	o	o	o	o
C8	o	o	o	o	o	+	o	o	o	o	o/-	o/-	o	o	o/-

Table 28: Summary of the impact of the combining tasks rule

The following observation can be made from the overview of Table 28.

Lead time:

- In models with setup ratio 1 (MV C1 and C5), creating two composite tasks results in a decrease in lead time under all three arrival rates.
- In models with setup ratio 2 or 3 (MV C2, C6 and C3, C7), creating only one composite task (AB for setup ratio 2 and DC/ED for setup ratio 3) results in a reduction of lead time under arrival rates 23 and 36. The model with the highest arrival rate does not have a significant difference in lead time.
- In models with setup ratio 4 (MV C4 and C8), creating one or two composite tasks results in no difference in lead time under any arrival rate.

The insignificant differences in models with a high arrival rate are caused by the higher variances of the lead times. The average values of the lead times do decrease more than in models with a lower arrival rate. However, the high variances, caused by the higher queue times, make the differences insignificant.

Utilization: Combining tasks into AB and DC/ED results, in model variant 1 and 5 (where heuristic 3 and 4 advise to combine the tasks), in a decreasing utilization, as the decrease in time of creating two composite tasks is big enough. In model variants where only one composite task is created, mostly the decrease of composing only one task is not big enough to lower the utilization. With setup ratio 4, where it is unadvisable to create composite tasks, composing tasks leads to no difference in utilization or even an increase.

WIP: Combining tasks only results in a lower WIP level, when creating two composite tasks in a model with the settings of setup ratio 1. In models with setup ratio 2 and 3, combining two tasks into one composite task result in no significantly different WIP level. In a model with setup ratio 4, combining tasks can even lead to an increase in WIP level.

Labour flexibility: Creating two combined tasks when recommended (in MV C1 and C5) leads to an increase in labour flexibility. When the settings are such that only one combined task should be created (setup ratio 2 and 3), creating that combined task mostly leads to no significant difference in labour flexibility. In some situations the difference is positive and only just significant. Combining tasks when heuristic 3 and 4 advise against it results in no significant difference or a decrease in labour flexibility.

Volume flexibility: The observations for this measure are equal to those of the labour flexibility. Model variant C1 and C5 (setup ratio 1) have higher volume flexibility in the redesigns. In the models with setup ratio 2 and 3, combining tasks into one task results in no significant difference or a just significant positive impact. In models with setup ratio 4, combining tasks can even lead to a decrease in volume flexibility.

In general there are no big differences in impact between the models with resource setup AB-CD-EF and ABC-DEF.

Models with a low arrival rate have outcomes comparable to those of models with a medium arrival rate. The outcomes of models with a high arrival rate are slightly different.

7.3 Conclusions combining tasks rule

This section gives the final conclusions on the results of the combining tasks rule. These conclusions are based on the analyses and summary of the previous sections.

- Creating two composite tasks in a model where heuristic 3 and 4 advise to do so, results in a lower lead time and utilization and an increase in flexibility. It can, in some situations also lead to a decrease in WIP level, with cost advantages.
- Creating one composite task, in a model with settings such that heuristic 3 and 4 recommend to create the combined task, leads to a decrease in lead time in models with low and medium arrival rates. In models with a high arrival rate, the differences are insignificant. It mainly also results in an insignificant impact on the other measures. Only in some situations, a small, just significant positive impact can be expected.
- Creating one or two composite tasks in a model where heuristic 3 and 4 advise not to do so, leads to no positive impact on any measure. It can even result in a negative impact on some measures.

Final conclusion:
Using heuristic 3 and 4, in order to redesign a KO process, can lead to a considerable decrease in lead time. In some settings the utilization, the WIP and flexibility measures are also positively affected.

7.4 Reflection on the analysis of the combining tasks rule

The last section of this chapter gives a reflection on the analysis of the combining tasks rule. A comparison with the results of the KO research project of Van der Aalst (2000) is made. The results of the comparison between the research and research method of Van der Aalst (2000) and those of this project can be found in Section 9.2, giving the overall reflection on the quantification of the KO heuristic.

A comparison between the results of Van der Aalst (2000) and the results of this simulation project results in three differences for the combining tasks rule:

- The results of the research of Van der Aalst (2000) indicate that the rule used in heuristic 3 only leads to lower lead times when the tasks have about the same size. In this study, using the rule of heuristic 3 in processes where the tasks have completely different service times (MV C7, task D (12) and C (36)), does also result in lower lead times. The service times of the combined tasks seem to have no influence on the impact.
- From the results of this study, it can be seen that even when there are multiple resources in a resource class and the combinable tasks have a relevant difference in service times, the rule of proposition 3 and 4 can still be used to lower the lead times.
- From the results of this study, it can also be concluded that heuristic 3 and 4 lead to a reduction of lead time when the arrival rates are not high. In models with a high arrival rate, combining two tasks into one does not lead to a significant decrease of lead time. No difference in impact between models with different arrival rates has been discerned by Van der Aalst (2000).

8 Output analysis parallel tasks rule

This eighth chapter describes the output analyses and the results of the third KO redesign rule, the parallel tasks rule. The chapter starts with the analysis of every separate model variant, like the analysis of the previous two redesign rules. Next, Section 8.2 gives a summary of the results. Finally Section 8.3 concludes the chapter with the final conclusions on the parallel tasks redesign rule and Section 8.4 gives the reflection on the results of the parallel tasks rule.

8.1 Output analysis parallel tasks rule

Each of the following sub-sections describes the output analysis of one of the twelve model variants. The analysis is based on the comparisons of Section 5.1.2.

8.1.1 Analysis model variant P1 (equal st, high Prej, arr rate 19)

The first model variant of the parallel tasks redesign rule is a model variant in which the parallel tasks both have equal service times and high reject probabilities. The first model variant is a model with an arrival rate of 19 cases per hour, which is a low arrival rate for this model. All four models containing the four resource setups of Table 21 have been simulated, analyzed and compared. The resulting output data can be found in Table 56 in Appendix F. The following observations can be made from the data in this table.

Lead time: Figure 38 is showing the confidence intervals of the lead times for this model variant. From this graph it can be seen that implementation of the parallel tasks rule in a model with a low arrival rate results in a decrease in lead time for all four resource setups. The magnitude of the impact on the four resource setups is comparable. This decrease in lead time is caused by the parallel execution of tasks B and C. The high reject probability does not affect the impact on the lead time in a model with a low arrival rate.

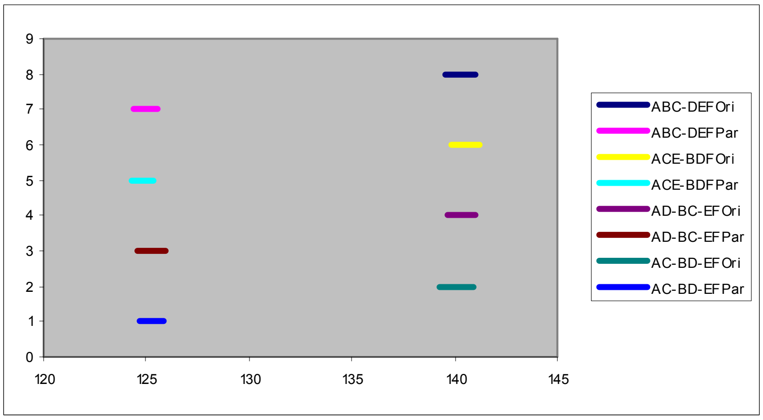


Figure 38: Confidence intervals of the lead times of model variant P1

Utilization: Putting KO tasks B and C in parallel in this model variant leads to higher utilizations. This is because both tasks B and C must be executed completely, even when the other parallel tasks results in a NOK. This results in more working hours for the resources.

WIP: All four models with the resource setups show a decrease in WIP level, after implementation of the parallel tasks rule. The impact on the models with different resource setups is comparable.

Flexibility: The labour flexibility of all parallel models is lower than that of the original models. This means that putting KO tasks in parallel in this setting leads to a decrease in labour flexibility. Also the volume flexibility decreases when the KO tasks are put in parallel. Both decreases are caused by the phenomena that resources have to work more hours.

Conclusions model variant P1 (equal service times, high reject prob., arrival rate 19):
The outcomes of this analysis are clear and consistent for all resource setups; putting KO tasks B and C in parallel in a setting like this model variant, results in a decrease in lead time, WIP level and flexibility and to an increase in utilization. The decrease in lead time and WIP are positive. All other impacts are negative for the performance of the workflow.

8.1.2 Analysis model variant P2 (equal st, high Prej, arr rate 30)

This second model variant has the same settings as the previous model variant, but is now simulated with a medium arrival rate of 30 cases per hour. The parallel tasks have the same service times and a high reject probability. Again the original and redesigned situation of the four models with different resource setups have been simulated and compared. The results are shown in Table 57 in Appendix F. The following observations can be made.

Lead time: Putting tasks B and C in parallel leads to lower lead times in all four setups. The differences of the models with the two class setups are bigger than those of the models with the three resource class setups. This is different from the observations of model variant P1, which also has a higher impact. All confidence intervals of the lead times of this model variant can be seen in Figure 39.

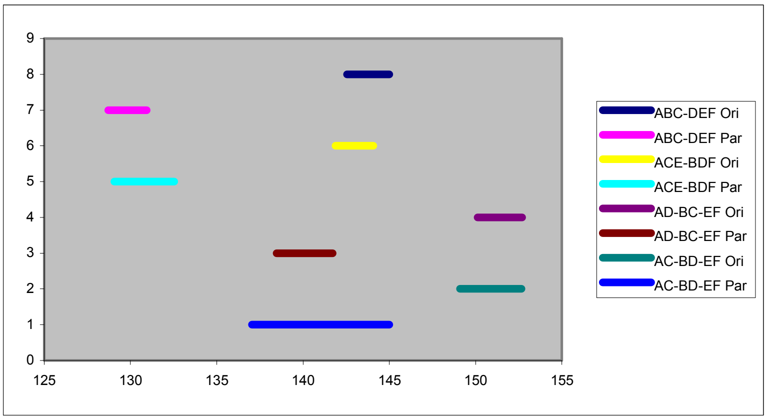


Figure 39: Confidence intervals of the lead times of model variant P2

Utilization: As in model variant P1, putting two tasks in parallel leads an increase in utilization. This is also in this model variant caused by the extra hours a resource has to spend on a case, as tasks B and C must be fully completed, also in case of a NOK in the other parallel branch. The differences are comparable for all four resource setups.

WIP: For the decrease in WIP level, the same graph has been found as for lead time. Putting B and C in parallel leads to a decrease in WIP level, except for the model with resource setup AC-BD-EF. The difference of this setup is insignificant.

Flexibility: Both flexibility measures decrease for all setups when the KO tasks are put in parallel. This is the same observation as in model variant P1. However, the impact on P2 is much higher.

Conclusions model variant P2 (equal service times, high reject prob., arrival rate 30):
Implementation of the parallel tasks rule results in lower lead times and a lower WIP level for all resource setups except for AC-BD-EF. Here the differences are insignificant.

In the models of all resource setups, the parallel tasks rule leads to higher utilizations and lower flexibility.

8.1.3 Analysis model variant P3 (equal st, high Prej, arr rate 32)

Model variant P3 is the first model variant that is simulated with a high arrival rate of 32 cases/h. The model in this model variant has the same settings as the models of the previous model variants; parallel tasks with equal service times and high reject probabilities. The results of simulating the original models and their parallel redesigns for the four resource setups can be found in Table 58 in Appendix F. The following observations can be made.

Lead time: The graph of Figure 40 is showing the confidence intervals of the lead times of the first model variant with a high arrival rate. The only resource setup with a significant decrease in lead time is ABC-DEF. All other differences in lead time are insignificant. The differences in lead time are comparable to those of model variant P2, but lower than those of model variant P1.

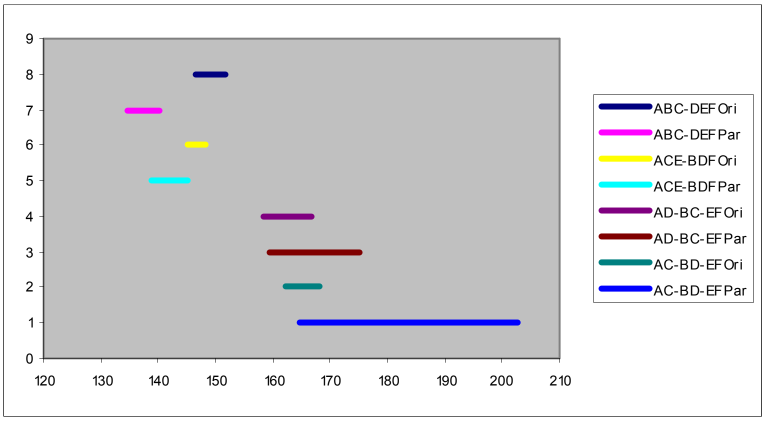


Figure 40: Confidence intervals of the lead times of model variant P3

Utilization: As in the former two model variants, the utilization increases when B and C are put in parallel.

WIP: Only the WIP level of ABC-DEF decreases. Those of ACE-BDF and AD-BC-EF remain the same and that of AC-BD-EF even increases.

Flexibility: Both flexibility measures decrease after the redesign, like in model variants P1 and P2. The decrease is bigger than on model variant P1.

Conclusions model variant P3 (equal service times, high reject prob., arrival rate 32):
Only the lead times of all ABC-DEF decreases when tasks B and C are put in parallel in this model variant with a high arrival rate. The disadvantage of doing this is an increase in utilization and a decrease in flexibility. The WIP level is only positively influenced for resource setup ABC-DEF. The other WIP levels remain the same or even increase (AC-BD-EF).

8.1.4 Analysis model variant P4 (equal st, low Prej, arr rate 19)

Model variant P4 is the first model variant in which the parallel tasks have low reject probabilities. The service times of the parallel tasks are still equal. The model in this model variant is simulated with a low arrival rate of 19 cases per hour. The four models with their redesigns have been simulated and compared. The results can be found in Table 59 in Appendix F. The following can be concluded.

Lead time: In this model variant, the impact of putting tasks B and C in parallel is equal to that of model variant P1. All lead times are lower in the parallel redesign and there is no difference in impact between models with the different resource setups. The confidence intervals of the lead times for the four models and their redesigns can be found in Figure 41.

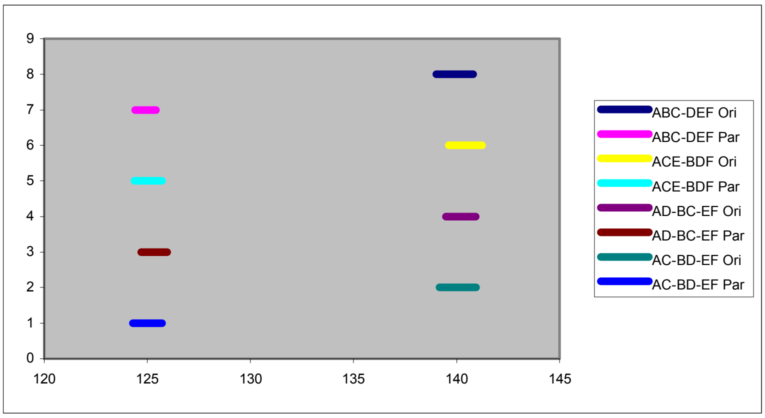


Figure 41: Confidence intervals of the lead times of model variant P4

Utilization: Putting tasks B and C in parallel does not lead to an increase in the utilization, in contrast to model variant P1. The difference between model variant P1 and this model variant is that the reject probabilities of the parallel tasks in this model variant are only low. These low reject probabilities result in a low difference with the original sequential situation, as the chances of rejection in one of the parallel branches are smaller. This causes the insignificant difference in utilization.

WIP: The WIP level is again showing the same decreasing pattern for all resource setups. The impact on the WIP level is comparable for all resource setups.

Flexibility: All differences in both flexibility measures between the sequential and the parallel situations are insignificant. This is a better result than in model variant P1, where both flexibility measures decreased after redesigning.

Conclusions model variant P4 (equal service times, low reject prob., arrival rate 19):
Putting KO tasks B and C in parallel in a model, with the same settings as this model variant results in a decrease in lead time and WIP for all resource setups. The impact on the other measures is insignificant.

8.1.5 Analysis model variant P5 (equal st, low Prej, arr rate 30)

Model variant P5 is the same model as model variant P4 but now simulated with a medium arrival rate of 30 cases/h. The next model variant simulates the model with a high arrival rate. Also here, the service times of the parallel tasks are equal and the reject probabilities low. The outcomes of simulating the models with the different resource setups and their redesigns are reported in Table 60 in Appendix F. The following observations can be made.

Lead time: Figure 42, containing the graph of the confidence intervals of the lead times, shows a significant, equal decrease in lead time for all four resource setups. The differences are slightly lower compared to the previous model variant with the low arrival rate. When comparing the results of this model variant to those of model variant P2 (same settings but then with high reject probabilities) it can be seen that the differences of both model variants are not significantly different.

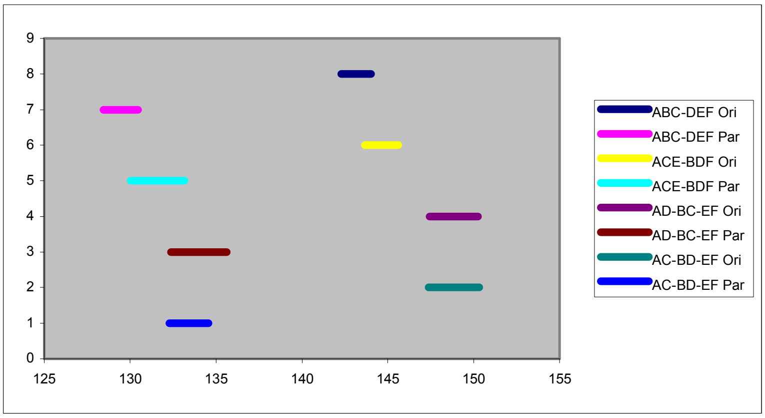


Figure 42: Confidence intervals of the lead times of model variant P5

Utilization: When looking at the utilizations of the resource classes in this model variant it can be seen that all differences in utilizations are only just insignificant, or the utilization is slightly increasing. This is different from the observations of model variant P2, where the utilizations were increasing, but in line with the observation of model variant P4. The differences are comparable for all resource setups.

WIP: Also in this model variant, the WIP level shows a decreasing pattern. Putting tasks B and C in parallel results in lower WIP levels. Again the differences are comparable for the four resource setups. The impact on this model variant is mostly higher than on model variant P2, but equal to that on P4.

Flexibility: For both flexibility measures three of the four setups have insignificant differences. Only ABC-DEF has a just significant decrease in both flexibility measures. This is a more positive outcome compared to model variant P2, where all setups showed a decrease in flexibility.

Conclusions model variant P5 (equal service times, low reject prob., arrival rate 30): Putting tasks in parallel in a model in which the parallel tasks have equal service times and low reject probabilities, with a medium arrival rate of 30 cases/h results in a lower lead time and WIP level. It furthermore has no significant or only a small negative impact on the utilizations and the flexibility measures (only small on ABC-DEF). This is in accordance with the conclusions of the previous model variant. The impact on the utilization, the WIP level and the flexibility measures is more positive in this model variant compared to model variant P2.

8.1.6 Analysis model variant P6 (equal st, low Prej, arr rate 32)

This model variant is the last model variant with parallel tasks that have equal service times and low reject probabilities. The models of the original and redesigned situation have been simulated for four resource setups with a high arrival rate of 32 cases per hour. The results of these simulations can be seen in Table 61 in Appendix F. The following can be observed from the data in this table.

Lead time: Figure 43, depicting the confidence intervals of the lead times, shows a decrease in lead time for all resource setups. The impact on the lead time of this model variant is equal to the impact of model variant P4 and P5.

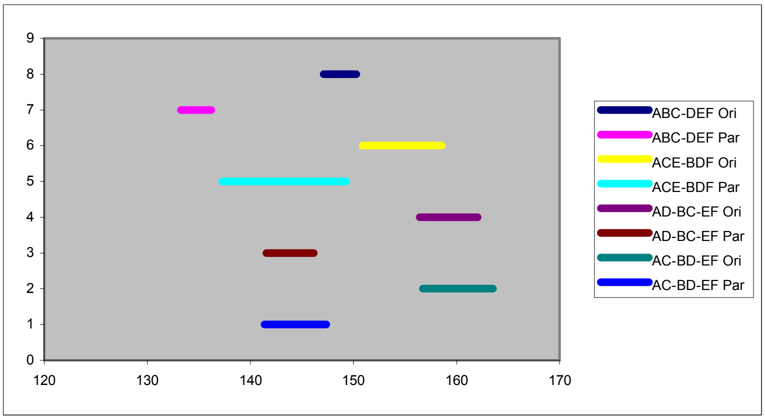


Figure 43: Confidence intervals of the lead times of model variant P6

Utilization: The utilizations of the resource setups increase or the differences are just insignificant. The same pattern as for the utilizations of model variant P5 has been found.

WIP: The implementation of the parallel tasks rule leads to lower WIP levels for all resource setups except ACE-BDF, which has a just insignificant difference. The differences are equal to those of model variants P4 and P5.

Flexibility: The labour flexibility of ABC-DEF and AC-BD-EF are decreasing, as is the volume flexibility of ABC-DEF. The other differences are insignificant. The decreases of P3 are much higher. The values of this model variant are comparable to those of model variant P4 and P5.

Conclusions model variant P6 (equal service times, low reject prob., arrival rate 32):
The parallel execution of B and C leads to a decrease in lead time and WIP level. The disadvantage is that the utilization remains the same or even increases and that the flexibility tends to decrease. The impact on this model variant is comparable to the impact on the same model under lower arrival rates.

8.1.7 Analysis model variant P7 (diff st, high Prej, arr rate 19)

This model variant is the first model variant in which the parallel tasks have completely different service times (55 and 5 minutes). Both parallel tasks have a high reject probability and the model is simulated with a low arrival rate of 19 cases/h. The results of all four resource setups and their redesigns have been analyzed and can be found in Table 62 in Appendix F. The following observations can be made.

Lead time: From Figure 44, showing the confidence intervals of the lead times for this model variant, it can be seen that the parallel tasks rule results in a decrease in lead time for all resource setups. The reductions are comparable for all resource setups. However, the differences are much smaller compared to MV P1 and P4, which have the same arrival rate, but equal parallel service times. The big difference between the service times of tasks B and C leads in this model variant to a limited impact, since the decrease in lead time is only the service time of task C.

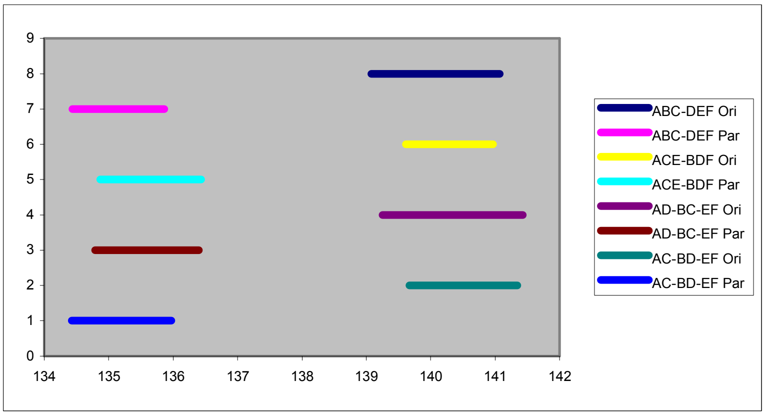


Figure 44: Confidence intervals of the lead times of model variant P7

Utilization: Executing tasks B and C in parallel does not result in a different utilization. All differences between the original model and the parallel model are insignificant.

WIP: The decrease in WIP levels shows the same pattern as that of the lead time. Putting tasks B and C in parallel leads to a significant decrease in WIP level, for all resource setups. These differences are consistent with, but much lower than those of model variant P1 and P4.

Flexibility: Almost all flexibility measures of the resource setups do not change significantly. Only the labour flexibility of ACE-BDF decreases significantly. This observation is in line with the observation of MV P4, except for the deviating labour flexibility of ACE-BDF.

Conclusions model variant P7 (different service times, high reject prob., arrival rate 19):
Putting KO tasks B and C in parallel, in a model with parallel tasks that have different service times and high reject probabilities, leads to a decrease in lead time and WIP level. However, this decrease is smaller compared to models with parallel tasks with equal service times. Implementation of the rule does not result in a difference in utilization or flexibility measure.

8.1.8 Analysis model variant P8 (diff st, high Prej, arr rate 30)

Model variant P8 is the second model variant with completely different service times of the parallel tasks and high reject probabilities. Now the model has been simulated with an arrival rate of 30 cases/h. The results of the simulations are depicted in Table 63 in Appendix F. The following observations can be made.

Lead time: From the confidence intervals of Figure 45 it can be seen that the parallel tasks rule leads to a decrease in lead time for all setups. The magnitude of the differences is comparable to that of model variant P7, which has the same settings but a low arrival rate. However, the differences are much lower compared to those of model variants P2 and P5, which have the same arrival rate and reject probability, but equal service times. These lower differences are due to the completely different service times, since the reduction of lead time is only as big as the service time of the shortest task.

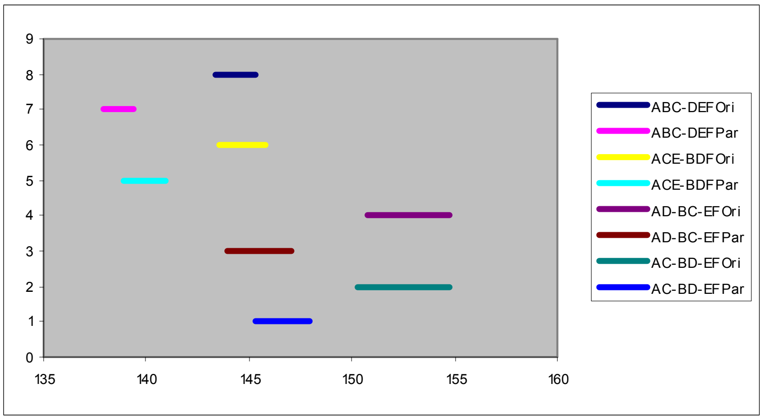


Figure 45: Confidence intervals of the lead times of model variant P8

Utilization: Like in the previous model variant, putting tasks B and C in parallel does not lead to a significant difference in utilizations. These results are different from the results of P2 and P5 where the utilization tended to increase.

WIP: Implementation of the parallel tasks rule does lower the WIP levels of all setups, as expected. The differences are smaller compared to the model variants with parallel tasks with equal service times (P2 and P5), Like with the lead time. The outcomes are comparable to those of the previous model variant.

Flexibility: Both flexibility measures have insignificant differences for all setups. This is consistent with the outcomes of model variant P7.

Conclusions model variant P8 (different service times, high reject prob., arrival rate 30): The parallel execution of tasks B and C leads to a decrease in lead time and WIP level for all four resource setups. The differences are smaller than the differences of the model variants with equal service times (MV P2 and P5). This is caused by the small service time of task C, which is the reduction of lead time. The parallel tasks rule does not affect the utilization and the flexibility measures. This is partly in contrast to model variants P2 and P5. All outcomes are in accordance with those of model variant P7.

8.1.9 Analysis model variant P9 (diff st, high Prej, arr rate 32)

This model variant with the highest arrival rate has the same settings as model variants P7 and P8; parallel tasks with completely different service times and high reject probabilities. The results of the simulations for this model variant are depicted in Table 64 in Appendix F. The following observations can be made.

Lead time: The parallel execution of tasks B and C does not lead to a decrease in lead time in this model variant with a high arrival rate, as can be seen in Figure 46. All the differences in lead time are insignificant. The differences are not significantly different from the differences of model variant P7 and P8, which have the same settings, but lower arrival rates.

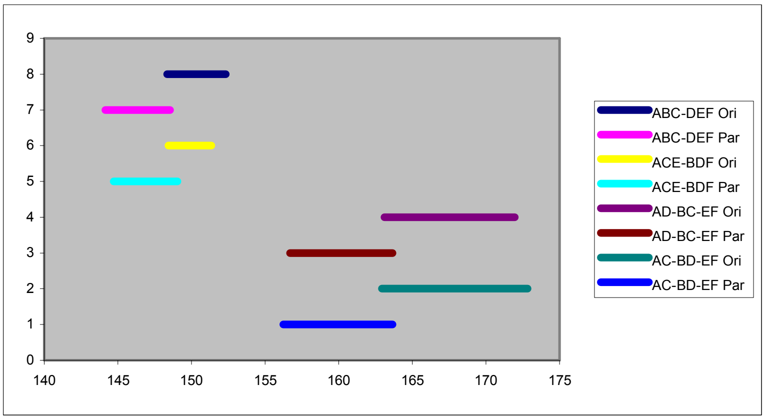


Figure 46: Confidence intervals of the lead times of model variant P9

Utilization: Also in this model variant does the implementation of the parallel tasks rule not lead to different utilizations. This is consistent with the previous two model variants.

WIP: The models of all resource setups have insignificant changes in WIP level, in contrast to the decreasing WIP levels of P7 and P8.

Flexibility: Only the labour flexibility of ABC-DEF decreases. All other differences in flexibility measures are insignificant. This is in accordance with P7 and P8.

Conclusions model variant P9 (different service times, high reject prob., arrival rate 32): Putting two tasks in parallel in a model with the same setting as P9 and a high arrival rate does not affect any of the measures, except for the labour flexibility of ABC-DEF which decreases. It is therefore unadvisable to implement the parallel tasks rule in this model variant.

8.1.10 Analysis model variant P10 (diff st, low Prej, arr rate 19)

Model variant P10 is the fourth variant with an arrival rate of 19 cases/h. The parallel tasks have again completely different service times, but now have low reject probabilities. What the impact of the parallel heuristic is on models with different resource setups has been tested in this model variant. The results of the simulation are reported in Table 65 in Appendix F. The following observation can be made from the results in this table.

Lead time: From the graph of Figure 47, depicting the confidence intervals of the lead times of model variant P10, it can be observed that the lead times of all four resource classes decrease when tasks B and C are put in parallel. It can also be seen that the impact on the lead time of all four resource setups is comparable. This observation is comparable to that of model variants P1, P4 and P7, which all have the same arrival rate. However, the differences of this model variant are significantly smaller than those of model variant P1 and P4.

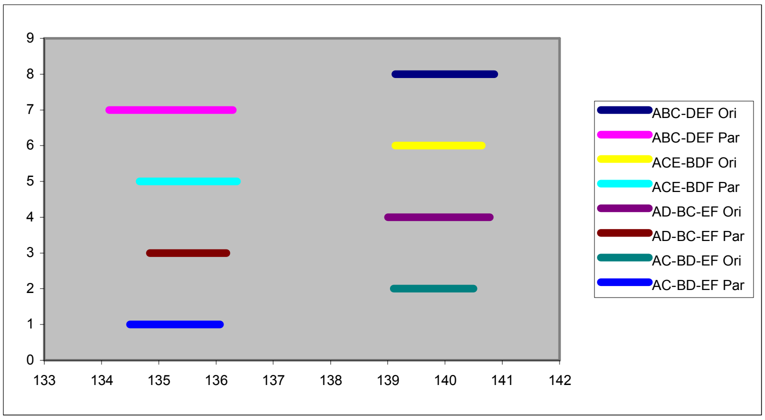


Figure 47: Confidence intervals of the lead times of model variant P10

Utilization: Putting tasks B and C in parallel does not lead to a significant difference in the utilization of the resource classes.

WIP: The WIP levels of the models are all significantly lower in the redesigned situations. This observation is in line with the observations of model variants P1, P4 and P7. The impact on the WIP levels of this model variant is lower than the impact on model variant P1 and P4 and equal to the impact on MV P7.

Flexibility: Like in model variants P4 and P7, both flexibility measures do not change when the two tasks are put in parallel.

Conclusions model variant P10 (different service times, low reject prob., arrival rate 19):
Implementation of the parallel tasks rule results in a decrease in lead time and WIP level in this model variant, but the differences are smaller compared to the model variants with parallel tasks that have equal service times. The utilization and the flexibility measures do not change significantly. For these measures no considerable differences can be found between the results of this model variant and those of MV P4 and P7. The results of P1 are more negative.

8.1.11 Analysis model variant P11 (diff st, low Prej, arr rate 30)

Model variant P11 has the same settings as the previous model variant; parallel tasks with completely different service times and low reject probabilities. The difference is the arrival rate. The model in this model variant is simulated with an arrival rate of 30 cases/h. The results of simulating all four resource setups and their redesigns are depicted in Table 66 in Appendix F. The following observations can be made from this data.

Lead time: Figure 48 shows a significant decrease in lead time for all models. The differences in lead time are bigger for model variants P2 and P5. P8 has comparable lead times. The impact on the lead time of this model variant with an arrival rate of 30 is also equal to the impact on the models with an arrival rate of 19 in the previous model variant.

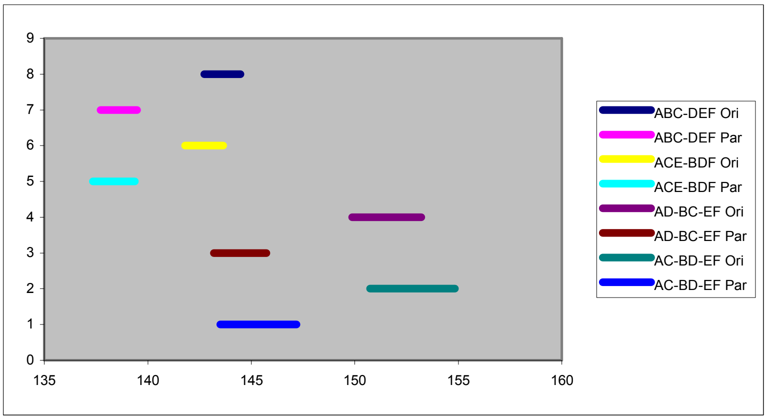


Figure 48: Confidence intervals of the lead times of model variant P11

Utilization: The utilizations of all resource setups remain the same after the redesigning effort. Putting two tasks in parallel has no significant impact on the utilization of this model variant. This is in accordance with the observations of model variants P5 and P8. However the impact on model variant P1 is higher. As for lead time, the impact on the utilization is not different from that of the previous model variant.

WIP: In this model variant, like in model variant P10, the WIP levels are decreasing when tasks B and C are put in parallel. The impact is comparable to that of model variant P2 and P8, however it is lower than on model variant P5.

Flexibility: Again, no significant difference can be found between the flexibility measures of the original situation and the redesigned situation. Only model variant P2 has a different impact with a decrease in flexibility.

Conclusions model variant P11 (different service times, low reject prob., arrival rate 30): The introduction of the parallel tasks rule only results in lower lead times and lower WIP levels. The other measures are not changed by the rule. The impact of the rule is comparable to that on model variant P8, but is bigger on the lead times of model variants P2 and P5 and on the WIP level of P5.

8.1.12 Analysis model variant P12 (diff st, low Prej, arr rate 32)

This last model variant has the same settings as the previous two model variants, but is now simulated with a high arrival rate of 32 cases/h. The parallel tasks have different service times and low reject probabilities. Also in this model variant, the original model has been compared to a parallel redesign for four different resource setups. The results of the simulations can be found in Table 67 in Appendix F. The following observations can be made.

Lead time: From Figure 49 it can be seen that all lead times, except for the lead time of AC-BD-EF, are decreasing. The pattern is equal to that of the previous model variant but the differences between the confidence intervals are now smaller.

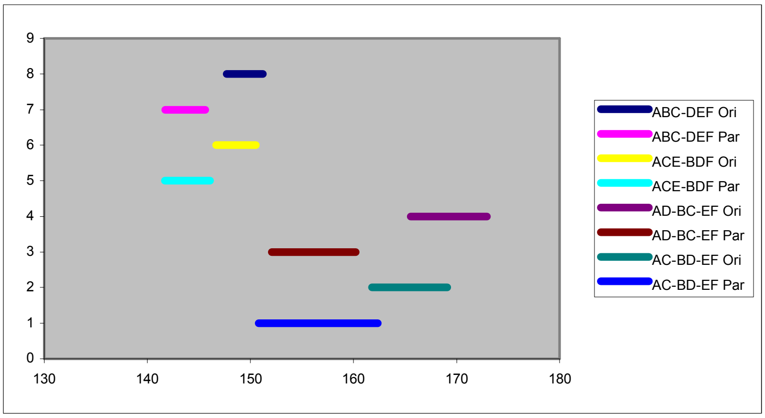


Figure 49: Confidence intervals of the lead times of model variant P12

Utilization: No significant difference in utilization can be found after the implementation of the parallel tasks rule. This is in conformity with the findings of the previous two model variants.

WIP: Only the WIP level of AD-BC-EF is decreasing. All other WIP levels remain equal. This is a more negative outcome compared to model variants P10 and P11.

Flexibility: None of the differences in labour flexibility and volume flexibility are significant. This is also pursuant to model variants P10 and P11.

Conclusions model variant P12 (different service times, low reject prob., arrival rate 32): Putting two tasks in parallel only leads to a small reduction of lead time, except for AC-BD-EF, and to a lower WIP level for AD-BC-EF. All other differences are insignificant. Implementation of the rule does not affect these measures. The findings of this model variant are consistent with those of the same models with lower arrival rates (P10, P11).

8.2 Summary of the results of the analysis

Section 8.2 gives an overview of the outcomes that resulted from the analyses of the previous section. Table 29 gives a summary of the impact that the implementation of the parallel tasks rule has on the different performance measures for all model variants. The data of every model variant is generalized from the output data of every separate resource setup. A detailed overview of the impact per resource setup can be found in Table 68 in Appendix G. A "-" in the table means a decreasing impact, a "0" means no significant impact and a "+" means an increasing impact.

MV	Lead time	Utilization	WIP	Labour flex	Volume flex
P1	-	+	-	-	-
P2	-	+	-	-	-
P3	0	+	0/+	-	-
P4	-	0	-	0	0
P5	-	0/+	-	0	0
P6	-	0/+	-	0/-	0
P7	-	0	-	0	0
P8	-	0	-	0	0
P9	0	0	0	0	0
P10	-	0	-	0	0
P11	-	0	-	0	0
P12	-	0	0	0	0

Table 29: Summary of the impact of the parallel tasks rule

The observations of the impact on all measures are summarized. The first bullet of every measure evaluates the difference in impact between models with equal service times and models with completely different service times. The second bullet compares models with high parallel reject probabilities with models with low parallel reject probabilities. And finally the third bullet compares the models with different arrival rates.

Lead time:

- From the outcomes of the analyses and Table 29, it can be seen that the decrease in lead time is bigger for model variants with parallel tasks that have equal service times compared to the model variants that have different parallel service times. This is as expected, since the time reduction is as big as the sum of the smallest service time of the parallel branches and the queue time of this smallest task, which is bigger in case of equal service times. The decrease in lead time in models with equal service times is on average approximately 9% and that of models with different service is only about 4%.
- Models with parallel tasks with high reject probabilities result in more insignificant decreases in lead time with higher arrival rates compared to models with low parallel reject probabilities.
- The difference between the confidence intervals of the lead time of the original situation and that of the parallel redesign becomes smaller when the arrival rate increases, due to the higher variances and lower differences. The impact of the parallel tasks rule on the lead time is lower on models with a higher arrival rate.

Utilization:

- The impact on the utilization of the resource classes is higher on models with parallel tasks with equal service times. In the models with high reject probabilities the utilization increases under all arrival rates. When the reject probabilities are low, the utilization is negatively affected when the arrival rates are higher. When the service times are different, the parallel tasks rule does not lead to a significant change in utilization. This difference in impact is caused by the small service time of task C. When task B gives a NOK, task C is not executed any more in the original situation. However in the parallel situation, task C is still executed. In the models with a small service time of C, the extra working time is smaller than in models with equal service times.
- The parallel tasks rule has more impact on the utilization of models with parallel tasks that have high reject probabilities. The chance of the occurrence of the just described situation is higher in these models.
- The impact on the utilization is also bigger in models with a higher arrival rate, as queue times increase.

WIP:

- The same conclusions as for lead time can be drawn for the impact on the WIP level. The impact on the WIP level is higher in models with equal parallel service times, for the same reasons as for lead time.
- The impact on the WIP level is higher in models with low parallel reject probabilities.
- The impact gets smaller when the arrival rate increases. The higher the arrival rate, the more differences in WIP level become insignificant.

Flexibility:

The observations for both flexibility measures are equal:

- The flexibility measures are more negatively affected in models with different parallel service times. This change in flexibility is strongly related to the utilization. The extra working hours are higher in the models with equal service times. This results in

lower flexibility. The flexibility of models with equal service times and high reject probabilities decreases. The other model variants have insignificant differences.
- The impact on the flexibility of putting tasks in parallel is higher and more negative when the parallel tasks have high reject probabilities.
- The impact is also higher when the arrival rates are higher.

No remarkable, big differences between the impacts on the different resource setups have been found.

8.3 Conclusions parallel tasks rule

This final section of the chapter concludes the analyses of the parallel tasks rule with the conclusions on this rule, based on the observations of the previous two sections.

- Putting KO tasks in parallel has the highest positive impact on models with equal parallel service times, low reject probabilities and a low arrival rate (the settings of model variant P4). The implementation of the parallel tasks rule results in this situation in a lower lead time and a lower WIP level. This has a positive influence on the customer service and the costs of execution of the workflow, as the inventory costs are lowered by the lower WIP levels. The utilization and the flexibility remains the same.

- The higher the difference in parallel service times, the lower the decrease in lead time and WIP level.
- When the parallel reject probabilities increase, the difference in lead time and WIP decreases and the flexibility even decreases.
- The decreases in lead time and WIP become smaller and the utilizations tend to increase when the arrival rates increases.

Putting KO tasks in parallel has the highest positive effect when
- The service times of the parallel tasks are of the same order of magnitude
- The parallel reject probabilities are only small
- The arrival rates are low
- None of the resource classes is overloaded (an utilization of 100%) as a result of putting tasks in parallel

Final conclusion:
Putting KO tasks in parallel leads to a lower lead time and WIP level in models with equal parallel service times, low reject probabilities and a low arrival rate. Increasing the difference in service times, the reject probability or the arrival rate will result in a lower positive or even more negative result.

8.4 Reflection on the results of the parallel tasks rule

This last section of this chapter gives a reflection on the analysis of the parallel tasks rule. A comparison with the results of the KO research project of Van der Aalst (2000) is made. The differences between the research and research methods of Van der Aalst (2000) and those of this simulation study are described in the last section of the following, concluding chapter.

A comparison between the results of Van der Aalst (2000) and the results of this simulation project results in 2 differences:
- The results of the research of Van der Aalst (2000) indicate that putting KO tasks in parallel can only have a considerable positive effect when resources from different classes execute the tasks. The result of this simulation study do not indicate any

remarkable differences in impact between models with parallel tasks that share a resource class and models with parallel tasks that do not require resources from the same class. This statement of Van der Aalst (2000) is not supported by the results of this study.

- From the results of this simulation project it appeared that one additional condition needs to be satisfied for the parallel tasks rule to have a considerable positive impact; the arrival rates need to be low. The positive impact decreases when the arrival rate increases. This condition has not been considered in heuristic 6 of Van der Aalst (2000).

9 Conclusions

This final chapter concludes this report with conclusions about the implementation of the KO redesign heuristic, based on the analyses of the swapping tasks rule, the composite tasks rule and the parallel tasks rule. Section 9.2 gives a reflection on the impact of the KO redesign heuristic.

9.1 Conclusions on the KO redesign rules

All three rules lead to enhancement of specific measures of performance. The following three conclusions give conditions for every rule under which a certain impact can be expected.

- Using heuristic 2 to redesign a KO process leads to lower, more balanced utilizations, a lower WIP level and increased labour and volume flexibility. When the arrival rate is too low to cause queue times or the utilizations of the resource classes are too unbalanced for the heuristic to balance them, implementation of heuristic 2 does not result in a reduction of lead time. In all other processes, heuristic 2 results in lower lead times.
- Using heuristic 3 and 4 to combine tasks into one or more composite tasks mainly has a positive impact on the lead time. A positive impact on the utilization and the flexibility can also be achieved when creating two combined tasks, when heuristic 3 and 4 advise to do so.
- Putting KO tasks in parallel leads to a lower lead time and WIP level in models with equal parallel service times, low reject probabilities and a low arrival rate. Increasing the difference in service times, the reject probability or the arrival rate will result in a lower positive or even more negative result.

The expected impact of implementing any of the three redesign rules on the performance of a workflow in a specific situation can be found in the analyses sections of this report.

9.2 Reflection on the quantification of the KO heuristic

This last section gives a reflection on the impact of the KO heuristic on the performance of a workflow. Two comparisons with other research projects have been made. The first comparison, described in Section 9.2.1, is a comparison between the research of Van der Aalst (2000) and the research of this project. The second comparison, described in 9.2.2, is a comparison between the generalized results of this simulation study and the qualitative analysis of Reijers and Limam Mansar (2004).

9.2.1 Comparison with the research of Van der Aalst

Five differences can be found, when comparing the research and research method described in this report and that of Van der Aalst (2000):

- More performance measures have been measured in this simulation project. WIP level and two flexibility measures have been analyzed in addition to the lead time and the utilization.
- Van der Aalst (2000) only simulates one process model in order to test the rules in the propositions and heuristics. In this simulation study, multiple variants and process models have been simulated to test the impact of the rules in different settings.
- For all three rules, more variations have been used in this study, in order to test the applicability and the correctness of the propositions and heuristics.

- Van der Aalst (2000) uses a different simulation tool, in order to test the rules in the propositions and heuristics; ExSpect.
- In this simulation study it is assumed that tasks cannot fail, in contrast to the research of Van der Aalst (2000) which considers fail probabilities.

The differences in results for all three redesign rules are given earlier, at the end of each of the three analysis chapters. In these reflections it can be seen that the comparison between the results of Van der Aalst (2000) and the results of this study indicates two differences for the swapping tasks rule and the parallel task rule and three differences for the combining tasks rule.

9.2.2 Comparison with the research of Reijers and Limam Mansar

Reijers and Limam Mansar (2004) have made a qualitative assessment of the impact of the implementation of the KO heuristic. They predict the following impact:

- Time: -0.5
- Cost: +4
- Quality: 0
- Flexibility: 0

However, from the simulations of this study it follows that these impacts are only adequate for the swapping tasks rule. Reijers and Limam Mansar (2004) do not consider the impact of the composite tasks rule and the parallel tasks rule.

The cost advantage is indicated as the biggest advantage when implementing the KO heuristic. When looking at the results of this simulation study it can be generalized that the KO heuristic has the biggest positive impact on the time dimension (lead time) as this dimension is affected by all three rules. The rules can also lead to lower utilizations and WIP levels with obvious cost advantages and increased flexibility.

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Appendix A

Redesigned combinations swapping tasks rule.

Case 1

A-B-C-D-E-F

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
AEDFBC	Optimal heuristic 2
EDAFCB	Nr 10 heuristic 2
DAEBFC	Nr 25 heuristic 2
DCEBAF	Average heuristic 2
BCFDAE	Last heuristic 2
EDBFAC	Decreasing KO ratio 1
EBDFAC	Decreasing KO ratio 2
EDBFCA	Decreasing KO ratio 3
EBDFCA	Decreasing KO ratio 4

AB-CD-EF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
EBDFCA	Optimal heuristic 2
BEDFCA	Nr 10 heuristic 2
DAEBFC	Nr 25 heuristic 2
FCAEBD	Average heuristic 2
CDABFE	Last heuristic 2
EDBFAC	Decreasing KO ratio 1
EBDFAC	Decreasing KO ratio 2
EDBFCA	Decreasing KO ratio 3
EBDFCA	Decreasing KO ratio 4

ABC-DEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
EBDFCA	Optimal heuristic 2
BEDFAC	Nr 10 heuristic 2
EDBFAC	Nr 25 heuristic 2
DBCEFA	Average heuristic 2
CABFDE	Last heuristic 2
EDBFAC	Decreasing KO ratio 1
EBDFAC	Decreasing KO ratio 2
EDBFCA	Decreasing KO ratio 3
EBDFCA	Decreasing KO ratio 4

ABCDEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
EBDFCA	Optimal heuristic 2
EDFBAC	Nr 10 heuristic 2
DEFBCA	Nr 25 heuristic 2
DABCEF	Average heuristic 2
CAFBDE	Last heuristic 2
EDBFAC	Decreasing KO ratio 1
EBDFAC	Decreasing KO ratio 2
EDBFCA	Decreasing KO ratio 3
EBDFCA	Decreasing KO ratio 4

Case 2

A-B-C-D-E-F

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
DAEBFC	Optimal heuristic 2
ADEBCF	Nr 10 heuristic 2
EADFBC	Nr 25 heuristic 2
BDCFAE	Average heuristic 2
FCBAED	Last heuristic 2
DEABFC	Decreasing KO ratio

AB-CD-EF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
DEABFC	Optimal heuristic 2
EDABCF	Nr 10 heuristic 2
EDBFAC	Nr 25 heuristic 2
AFEBDC	Average heuristic 2
CDFEBA	Last heuristic 2
DEABFC	Decreasing KO ratio

ABC-DEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
DEABFC	Optimal heuristic 2
ADEBFC	Nr 10 heuristic 2
EDFABC	Nr 25 heuristic 2
ECDAFB	Average heuristic 2
CBAFED	Last heuristic 2
DEABFC	Decreasing KO ratio

ABCDEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
DEABFC	Optimal heuristic 2
EDBAFC	Nr 10 heuristic 2
DEBCAF	Nr 25 heuristic 2
FDBACE	Average heuristic 2
CFBAED	Last heuristic 2
DEABFC	Decreasing KO ratio

Case 3

A-B-C-D-E-F

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
CFBDEA	Optimal heuristic 2
CFEBDA	Nr 10 heuristic 2
CBDEFA	Nr 25 heuristic 2
ECFDAB	Average heuristic 2
AEDBFC	Last heuristic 2
CFBDEA	Decreasing KO ratio

AB-CD-EF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
CBFEDA	Optimal heuristic 2
FBCDEA	Nr 10 heuristic 2
BCFEAD	Nr 25 heuristic 2
BDEACF	Average heuristic 2
ABEFDC	Last heuristic 2
CFBDEA	Decreasing KO ratio

ABC-DEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
CFDBEA	Optimal heuristic 2
CDFBEA	Nr 10 heuristic 2
CEFBDA	Nr 25 heuristic 2
DFCEAB	Average heuristic 2
ABCEDF	Last heuristic 2
CFBDEA	Decreasing KO ratio

ABCDEF

Redesigned combinations	
Combination	**Remark**
ABCDEF	Original
CFBDEA	Optimal heuristic 2
CFDBEA	Nr 10 heuristic 2
FCDBAE	Nr 25 heuristic 2
FEDBAC	Average heuristic 2
AEDBFC	Last heuristic 2
CFBDEA	Decreasing KO ratio

Appendix B

Model variants and simulated models combining tasks rule.

AB-CD-EF

Task	Rej Prob	Succes prob	Processing time	Ratio	arrival rate	Nr of resources
A	0,07	0,93	0,1667	0,4200	23/36/42	14
B	0,07	0,93	0,2000	0,3500		
C	0,12	0,88	0,6000	0,2000		22
D	0,05	0,95	0,2000	0,2500		
E	0,1	0,9	0,3333	0,3000		26
F	0,17	0,83	0,3333	0,5100		

Model variant 1:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.1667	2	10	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12	0.164	F.A.B.E.(DC)
D	0.1667	2	10	0,05		F.(AB).E.(DC)
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 2:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.1667	2	10	0,07		F.(AB).E.D.C
C	0.0139	0.5	35.5	0,12	0.164	F.A.B.E.(DC)
D	0.1667	2	10	0,05		F.(AB).E.(DC)
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 3:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.0167	0.2	11.8	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12	0.164	F.A.B.E.(DC)
D	0.1667	2	10	0,05		F.(AB).E.(DC)
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 4:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.0167	0.2	11.8	0,07		F.(AB).E.D.C
C	0.0139	0.5	35.5	0,12	0.164	F.A.B.E.(DC)
D	0.1667	2	10	0,05		F.(AB).E.(DC)
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

The reject probabilities of the composite tasks can be calculated with:

$$rp(t_{1,2}) = rp(t_1) + rp(t_2) - (rp(t_1) \cdot rp(t_2))$$

ABC-DEF

Task	Rej Prob	Succes prob	Processing time	Ratio	arrival rate	Nr of resources
A	0,07	0,93	0,1667	0,4200	23/36/42	30
B	0,07	0,93	0,2000	0,3500		
C	0,12	0,88	0,6000	0,2000		
D	0,05	0,95	0,2000	0,2500		32
E	0,1	0,9	0,3333	0,3000		
F	0,17	0,83	0,3333	0,5100		

Model variant 5:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.1667	2	10	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12		F.A.B.(ED).C
D	0.2083	2.5	9.5	0,05	0.145	F.(AB).(ED).C
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 6:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.1667	2	10	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12		F.A.B.(ED).C
D	0.0417	0.5	11.5	0,05	0.145	F.(AB).(ED).C
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 7:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.0167	0.2	11.8	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12		F.A.B.(ED).C
D	0.2083	2.5	9.5	0,05	0.145	F.(AB).(ED).C
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

Model variant 8:

Task	Setup ratio	SetupT	ServiceT	Reject Prob	Reject Prob	Combinations
A	0.1	1	9	0,07	0.1351	F.A.B.E.D.C
B	0.0167	0.2	11.8	0,07		F.(AB).E.D.C
C	0.0833	3	33	0,12		F.A.B.(ED).C
D	0.0417	0.5	11.5	0,05	0.145	F.(AB).(ED).C
E	0.1	2	18	0,1		
F	0.1	2	18	0,17		

The reject probabilities of the composite tasks can be calculated with:

$$rp(t_{1,2}) = rp(t_1) + rp(t_2) - (rp(t_1) \cdot rp(t_2))$$

Appendix C

Model variants and simulated models of the parallel tasks rule.

Model variant P1 – P3

AC-BD-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.15	19/30/32	AC	27
B	0.2	30	0.40			
C	0.2	30	0.40		BD	25
D	0.05	20	0.15			
E	0.05	20	0.15		EF	14
F	0.05	20	0.15			

AD-BC-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.15	19/30/32	AD	20
B	0.2	30	0.40			
C	0.2	30	0.40		BC	32
D	0.05	20	0.15			
E	0.05	20	0.15		EF	14
F	0.05	20	0.15			

ACE-BDF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.15	19/30/32	ACE	35
B	0.2	30	0.40			
C	0.2	30	0.40			
D	0.05	20	0.15		BDF	33
E	0.05	20	0.15			
F	0.05	20	0.15			

ABC-DEF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.15	19/30/32	ABC	46
B	0.2	30	0.40			
C	0.2	30	0.40			
D	0.05	20	0.15		DEF	22
E	0.05	20	0.15			
F	0.05	20	0.15			

Model variant P4 – P6

AC-BD-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.45	19/30/32	AC	28
B	0.05	30	0.10			
C	0.05	30	0.10		BD	26
D	0.15	20	0.45			
E	0.15	20	0.45		EF	15
F	0.15	20	0.45			

AD-BC-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.45	19/30/32	AD	22
B	0.05	30	0.10			
C	0.05	30	0.10		BC	32
D	0.15	20	0.45			
E	0.15	20	0.45		EF	15
F	0.15	20	0.45			

ACE-BDF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.45	19/30/32	ACE	36
B	0.05	30	0.10			
C	0.05	30	0.10			
D	0.15	20	0.45		BDF	33
E	0.15	20	0.45			
F	0.15	20	0.45			

ABC-DEF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.45	19/30/32	ABC	44
B	0.05	30	0.10			
C	0.05	30	0.10			
D	0.15	20	0.45		DEF	25
E	0.15	20	0.45			
F	0.15	20	0.45			

Model variant P7 – P9

AC-BD-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.1500	19/30/32	AC	15
B	0.2	55	0.2182			
C	0.2	5	2.4000		BD	40
D	0.05	20	0.1500			
E	0.05	20	0.1500		EF	14
F	0.05	20	0.1500			

AD-BC-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.1500	19/30/32	AD	20
B	0.2	55	0.2182			
C	0.2	5	2.4000		BC	35
D	0.05	20	0.1500			
E	0.05	20	0.1500		EF	14
F	0.05	20	0.1500			

ACE-BDF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.1500	19/30/32	ACE	22
B	0.2	55	0.2182			
C	0.2	5	2.4000			
D	0.05	20	0.1500		BDF	48
E	0.05	20	0.1500			
F	0.05	20	0.1500			

ABC-DEF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.05	20	0.1500	19/30/32	ABC	48
B	0.2	55	0.2182			
C	0.2	5	2.4000			
D	0.05	20	0.1500		DEF	22
E	0.05	20	0.1500			
F	0.05	20	0.1500			

Model variant P10 – P12

AC-BD-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.4500	19/30/32	AC	15
B	0.05	55	0.0545			
C	0.05	5	0.6000		BD	39
D	0.15	20	0.4500			
E	0.15	20	0.4500		EF	15
F	0.15	20	0.4500			

AD-BC-EF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.4500	19/30/32	AD	22
B	0.05	55	0.0545			
C	0.05	5	0.6000		BC	32
D	0.15	20	0.4500			
E	0.15	20	0.4500		EF	15
F	0.15	20	0.4500			

ACE-BDF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.4500	19/30/32	ACE	24
B	0.05	55	0.0545			
C	0.05	5	0.6000			
D	0.15	20	0.4500		BDF	46
E	0.15	20	0.4500			
F	0.15	20	0.4500			

ABC-DEF

Task	Reject Prob	ServiceT	KO Ratio	Arrival rate	Class	Nr of resources
A	0.15	20	0.4500	19/30/32	ABC	45
B	0.05	55	0.0545			
C	0.05	5	0.6000			
D	0.15	20	0.4500		DEF	25
E	0.15	20	0.4500			
F	0.15	20	0.4500			

Appendix D

Output data swapping tasks rule:

Model variant SW1 (Case 1, A-B-C-D-E-F):

	Original		AEDFBC		EDAFCB		DAEBFC		DCEBAF	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	184,6323	211,1345	145,8354	148,3840	146,3272	148,6322	150,2818	153,3227	170,3828	203,6714
Queue_time_total	44,6718	70,5584	6,3312	8,1848	7,1285	8,8110	10,5653	12,7105	30,5408	63,2732
Utilisation_Res1	0,5226	0,5356	0,5261	0,5353	0,4144	0,4250	0,4597	0,4716	0,2795	0,2876
Utilisation_Res2	0,9294	0,9533	0,6114	0,6311	0,4826	0,4992	0,7370	0,7553	0,6198	0,6372
Utilisation_Res3	0,8368	0,8559	0,5481	0,5681	0,6533	0,6704	0,5480	0,5654	0,9177	0,9396
Utilisation_Res4	0,4986	0,5148	0,6732	0,6892	0,7070	0,7259	0,7911	0,8077	0,7865	0,8041
Utilisation_Res5	0,3292	0,3365	0,5617	0,5756	0,5876	0,6020	0,4909	0,5041	0,4106	0,4234
Utilisation_Res6	0,4733	0,4838	0,7107	0,7286	0,7111	0,7291	0,6015	0,6155	0,4765	0,4929
WIP_data_col	45,5535	53,8281	33,3555	34,5245	33,6457	34,7288	34,7836	35,6624	40,8269	50,8198
Lab_Flex_WF	2,5516	2,6434	2,8016	2,9099	2,8243	2,9310	2,7927	2,8787	2,5899	2,6901
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	465127,33	477349,72	470688,76	486996,95	471032,66	485152,77	475510,71	489048,15	462786,41	477075,30

	BCFDAE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	290,8055	463,1621	148,9316	151,9577	159,9603	169,0593	149,5574	152,8101	157,1471	172,5378
Queue_time_total	150,9978	322,6266	10,0313	12,1173	19,9975	28,5819	9,7079	12,4752	18,0074	32,0237
Utilisation_Res1	0,2538	0,2634	0,2889	0,2981	0,2900	0,2988	0,2292	0,2375	0,2310	0,2394
Utilisation_Res2	0,9785	0,9931	0,7760	0,7916	0,8835	0,9012	0,7714	0,7896	0,8810	0,9012
Utilisation_Res3	0,8844	0,9025	0,5469	0,5635	0,5531	0,5667	0,5766	0,5963	0,5840	0,6026
Utilisation_Res4	0,4369	0,4484	0,7049	0,7201	0,6004	0,6167	0,6989	0,7187	0,5960	0,6145
Utilisation_Res5	0,2708	0,2814	0,5911	0,6004	0,5876	0,6043	0,5884	0,6029	0,5853	0,6019
Utilisation_Res6	0,6295	0,6476	0,6283	0,6436	0,6300	0,6476	0,6267	0,6480	0,6283	0,6514
WIP_data_col	79,8023	134,5617	33,9895	34,9654	37,3295	40,1816	33,8855	35,2521	36,6610	41,1252
Lab_Flex_WF	2,4258	2,5117	2,8373	2,9112	2,7757	2,8683	2,7863	2,9166	2,7533	2,8792
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	466377,52	479365,62	485401,31	497599,83	481332,27	495505,92	482937,85	501457,58	479248,58	497538,95

Table 30: Output data model variant SW1

Model variant SW2 (Case 1, AB-CD-EF):

	Original		EBDFCA		BEDFCA		DAEBFC		FCAEBD	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	142,4833	145,9184	139,9092	141,9706	141,0135	142,3895	140,0401	141,8716	141,1361	142,8485
Queue_time_total	3,2252	5,1266	0,8624	1,1753	1,2643	1,6719	0,8188	1,1791	1,6010	2,4569
Utilisation_Res1	0,7567	0,7707	0,6037	0,6156	0,6667	0,6768	0,6174	0,6306	0,4617	0,4762
Utilisation_Res2	0,7051	0,7233	0,5862	0,6016	0,5940	0,6062	0,6442	0,6604	0,6722	0,6858
Utilisation_Res3	0,4122	0,4239	0,6090	0,6090	0,5800	0,5800	0,5527	0,5672	0,6900	0,6900
WIP_data_col	33,1333	34,3955	31,5832	32,2925	31,9896	32,5403	31,9044	32,6880	32,8792	33,6230
Lab_Flex_WF	5,3255	5,5935	6,3127	6,5207	6,2570	6,4180	6,1636	6,3904	5,8779	6,0823
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	459968,54	475902,79	484220,15	497531,85	477845,55	489488,74	475276,76	491293,62	457208,13	472368,83

	CDABFE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	154,3802	163,5797	140,0274	141,5719	140,3439	142,1819	140,0245	141,5298	139,9092	141,9706
Queue_time_total	14,4707	23,3325	0,6706	1,0220	0,9189	1,3840	0,7136	0,9672	0,8624	1,1753
Utilisation_Res1	0,5299	0,5407	0,5635	0,5805	0,6307	0,6433	0,5429	0,5535	0,6037	0,6156
Utilisation_Res2	0,8826	0,8994	0,6133	0,6276	0,5713	0,5860	0,6302	0,6442	0,5862	0,6016
Utilisation_Res3	0,4203	0,4299	0,6100	0,6100	0,6150	0,6150	0,6150	0,6150	0,6100	0,6100
WIP_data_col	37,0528	40,0729	31,5492	32,3043	31,6963	32,4017	31,5650	32,2322	31,5832	32,2925
Lab_Flex_WF	5,1148	5,3268	6,3138	6,5533	6,2455	6,4616	6,3529	6,5592	6,3127	6,5207
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	450067,48	463495,95	483224,29	497899,05	480685,75	495205,87	482994,93	497000,69	484220,15	497531,85

Table 31: Output data model variant SW2

Model variant SW3 (Case 1, ABC-DEF):

	Original		EBDFCA		BEDFAC		EDBFAC		DBCEFA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	141,5751	144,0443	139,0489	140,5051	138,9639	141,2425	139,6349	140,8553	139,7974	141,7422
Queue_time_total	2,3164	3,4030	0,1260	0,2264	0,1145	0,2371	0,1583	0,3233	0,4525	0,8613
Utilisation_Res1	0,7978	0,8134	0,5919	0,6041	0,6201	0,6339	0,5628	0,5730	0,6826	0,6958
Utilisation_Res2	0,4425	0,4558	0,6090	0,6196	0,5798	0,5938	0,6402	0,6544	0,5435	0,5574
WIP_data_col	33,1708	34,0463	31,3504	32,0059	31,3473	32,0458	31,3652	32,0378	32,2644	32,8590
Lab_Flex_WF	8,0945	8,4451	9,6568	9,9833	9,6421	10,0014	9,5231	9,8628	9,3468	9,6267
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	456704,56	473328,77	484991,71	498090,01	482369,11	498730,99	482416,36	496947,17	466465,01	482395,56

	CABFDE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	142,8735	145,5352	139,6349	140,8553	139,6916	141,2210	140,1783	141,2567	139,0489	140,5051
Queue_time_total	3,4913	5,2774	0,1583	0,3233	0,1344	0,2984	0,1253	0,2879	0,1260	0,2264
Utilisation_Res1	0,8084	0,8248	0,5628	0,5730	0,5954	0,6092	0,5628	0,5760	0,5919	0,6041
Utilisation_Res2	0,4462	0,4602	0,6402	0,6544	0,6123	0,6234	0,6432	0,6541	0,6090	0,6196
WIP_data_col	33,6988	34,8862	31,3652	32,0378	31,5444	32,2582	31,5269	32,2312	31,3504	32,0059
Lab_Flex_WF	7,9374	8,3268	9,5231	9,8628	9,5237	9,8859	9,4181	9,7608	9,6568	9,9833
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	446979,90	464237,62	482416,36	496947,17	479350,42	493876,91	480999,32	494748,11	484991,71	498090,01

Table 32: Output data model variant SW3

Model variant SW4 (Case 1, ABCDEF):

	Original		EBDFCA		EDFBAC		DEFBCA		DABCEF	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,1170	140,9373	139,4248	140,6714	138,6888	140,5530	138,7870	140,5675	139,2799	141,1431
Queue_time_total	-0,0166	0,0462	-0,0002	0,0036	-0,0074	0,0169	-0,0028	0,0111	-0,0012	0,0108
Utilisation_Res1	0,6239	0,6357	0,6015	0,6136	0,6014	0,6122	0,6043	0,6153	0,6160	0,6270
WIP_data_col	32,5331	33,1731	31,3897	32,0637	31,4035	31,9859	31,3804	32,1070	32,1014	32,7574
Lab_Flex_WF	18,6187	19,2440	19,7340	20,3570	19,8063	20,4043	19,6833	20,3875	19,0196	19,6926
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	454608,14	469358,81	482203,59	497259,74	483899,29	497412,90	480060,81	493849,48	465449,33	479210,01

	CAFBDE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,1298	140,8428	138,8757	140,6997	139,3271	141,1108	139,4194	140,9258	139,4248	140,6714
Queue_time_total	-0,0028	0,0271	-0,0016	0,0086	-0,0043	0,0157	-0,0026	0,0131	-0,0002	0,0036
Utilisation_Res1	0,6332	0,6482	0,6020	0,6159	0,6024	0,6144	0,6026	0,6128	0,6015	0,6136
WIP_data_col	32,9678	33,7985	31,3344	32,0832	31,3712	32,1295	31,4197	32,0051	31,3897	32,0637
Lab_Flex_WF	17,9455	18,7994	19,6651	20,4389	19,6428	20,3515	19,7382	20,3426	19,7340	20,3570
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	438974,71	457690,44	479366,70	496716,63	481166,99	496163,68	483149,88	495944,98	482203,59	497259,74

Table 33: Output data model variant SW4

Model variant SW5 (Case 2, A-B-C-D-E-F):

	Original		DAEBFC		ADEBCF		EADFBC	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	155,4368	164,1285	136,9559	139,2475	137,4672	139,7725	138,1430	140,4268
Queue_time_total	22,0841	29,2632	3,4146	4,6154	3,9978	5,0716	4,5702	6,0898
Utilisation_Res1	0,3271	0,3352	0,2891	0,2956	0,3277	0,3360	0,2950	0,3021
Utilisation_Res2	0,8335	0,8574	0,6557	0,6745	0,6611	0,6814	0,5488	0,5639
Utilisation_Res3	0,8477	0,8701	0,5557	0,5728	0,6672	0,6888	0,5504	0,5678
Utilisation_Res4	0,2241	0,2319	0,3518	0,3599	0,3341	0,3425	0,3006	0,3081
Utilisation_Res5	0,2378	0,2463	0,3523	0,3606	0,3514	0,3598	0,4216	0,4336
Utilisation_Res6	0,4961	0,5147	0,6247	0,6410	0,5002	0,5143	0,7377	0,7570
WIP_data_col	33,2277	35,6370	26,4016	27,0846	26,7325	27,5351	26,9964	27,8230
Lab_Flex_WF	3,2857	3,3924	3,9382	4,0083	3,8751	3,9703	3,8662	3,9550
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	571565,03	586563,83	620910,65	633103,45	614026,78	628122,55	610702,08	623792,59

	BDCFAE		FCBAED		DEABFC	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	158,9335	165,7991	250,3009	434,3383	136,9777	138,9584
Queue_time_total	24,6757	31,1466	117,3041	300,6837	3,5254	4,5713
Utilisation_Res1	0,1603	0,1673	0,1806	0,1862	0,2609	0,2684
Utilisation_Res2	0,8822	0,8974	0,5728	0,5883	0,6592	0,6743
Utilisation_Res3	0,7844	0,8046	0,8525	0,8753	0,5510	0,5690
Utilisation_Res4	0,2973	0,3053	0,1660	0,1705	0,3526	0,3598
Utilisation_Res5	0,1961	0,2035	0,2198	0,2265	0,3704	0,3766
Utilisation_Res6	0,5843	0,6024	0,9737	0,9870	0,6243	0,6429
WIP_data_col	34,1529	36,2299	61,8228	115,5817	26,3365	27,1201
Lab_Flex_WF	3,3237	3,4208	2,8709	2,9574	3,9398	4,0325
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	579443,58	592804,13	546189,05	555506,85	622513,84	634299,97

Table 34: Output data model variant SW5

Model variant SW6 (Case 2, AB-CD-EF):

	Original		DEABFC		EDABCF		EDBFAC	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	133,5777	135,2384	133,4944	134,8134	133,5355	135,3017	133,4321	135,7034
Queue_time_total	0,5999	0,9376	0,0759	0,1384	0,0921	0,1370	0,1557	0,2809
Utilisation_Res1	0,6135	0,6276	0,4903	0,5010	0,4898	0,4977	0,4789	0,4881
Utilisation_Res2	0,5975	0,6110	0,4773	0,4861	0,5294	0,5409	0,4638	0,4737
Utilisation_Res3	0,3806	0,3920	0,5159	0,5272	0,4654	0,4741	0,5563	0,5697
WIP_data_col	27,6352	28,3558	25,7733	26,2499	25,9703	26,4838	26,1960	26,7023
Lab_Flex_WF	6,9649	7,1819	8,2029	8,3569	8,1150	8,2814	8,0476	8,2214
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	575490,68	589614,46	619586,39	630227,99	618224,67	626367,81	611976,03	622607,02

	AFEBDC		CDFEBA		DEABFC	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	133,5836	135,4970	135,3656	138,2025	133,4944	134,8134
Queue_time_total	0,6803	1,0683	2,3174	4,0255	0,0759	0,1384
Utilisation_Res1	0,4946	0,5067	0,3269	0,3349	0,4903	0,5010
Utilisation_Res2	0,4151	0,4282	0,7450	0,7616	0,4773	0,4861
Utilisation_Res3	0,6646	0,6798	0,4929	0,5040	0,5159	0,5272
WIP_data_col	27,4002	28,1275	29,1058	29,9524	25,7733	26,2499
Lab_Flex_WF	7,2150	7,4305	6,7366	6,9709	8,2029	8,3569
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	579907,94	594058,44	553844,23	565877,68	619586,39	630227,99

Table 35: Output data model variant SW6

Model variant SW7 (Case 2, ABC-DEF):

	Original		DEABFC		ADEBFC		EDFABC	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	134,3932	135,9542	133,3299	134,9442	132,8096	134,4790	133,3346	134,9804
Queue_time_total	0,8118	1,1690	0,0039	0,0305	0,0037	0,0314	-0,0029	0,0310
Utilisation_Res1	0,7245	0,7391	0,5176	0,5308	0,5350	0,5460	0,4729	0,4817
Utilisation_Res2	0,3328	0,3411	0,4616	0,4731	0,4519	0,4630	0,5235	0,5350
WIP_data_col	27,7734	28,4277	25,5460	26,2167	25,8121	26,3471	25,9262	26,5937
Lab_Flex_WF	10,3607	10,6760	12,6134	12,9320	12,4984	12,7772	12,1604	12,5083
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	574794,25	587356,99	622055,51	636426,01	618788,36	631721,74	614235,90	625546,48

	ECDAFB		CBAFED		DEABFC	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	133,0014	134,6820	135,1242	137,0348	133,4944	134,8134
Queue_time_total	0,1314	0,2686	1,7714	3,1524	0,0759	0,1384
Utilisation_Res1	0,6211	0,6365	0,7498	0,7676	0,4903	0,5010
Utilisation_Res2	0,4359	0,4464	0,3621	0,3711	0,4773	0,4861
WIP_data_col	27,6036	28,2980	29,4989	30,5880	25,7733	26,2499
Lab_Flex_WF	11,7103	12,0517	9,6800	10,0714	8,2029	8,3569
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	572826,21	587877,69	537882,28	553712,20	619586,39	630227,99

Table 36: Output data model variant SW7

Model variant SW8 (Case 2, ABCDEF):

	Original		DEABFC		EDBAFC		DEBCAF	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	133,5007	135,2755	133,3924	135,2401	133,1413	134,9829	133,1614	134,8454
Queue_time_total	-0,0065	0,0134	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
Utilisation_Res1	0,5281	0,5405	0,4904	0,5015	0,4971	0,5075	0,4976	0,5085
WIP_data_col	27,5940	28,2440	25,4796	26,1574	25,9557	26,4237	25,9240	26,4558
Lab_Flex_WF	23,4903	24,1168	25,6014	26,2557	25,2835	25,7421	25,2529	25,8221
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	573395,34	588882,66	622143,02	635985,65	614671,77	627548,89	613318,41	627029,98

	FDBACE		CFBAED		DEABFC	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	132,3684	134,1479	133,2018	135,0093	133,3924	135,2401
Queue_time_total	-0,0002	0,0004	-0,0016	0,0035	0,0000	0,0000
Utilisation_Res1	0,5287	0,5393	0,5633	0,5774	0,4904	0,5015
WIP_data_col	27,4106	28,1308	29,4448	30,2559	25,4796	26,1574
Lab_Flex_WF	23,5791	24,3025	21,4876	22,2798	25,6014	26,2557
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	574919,30	588152,79	527374,91	544998,04	622143,02	635985,65

Table 37: Output data model variant SW8

Model variant SW9 (Case 3, A-B-C-D-E-F):

	Original		CFBDEA		CFEBDA		CBDEFA	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	275,0889	293,4590	267,2781	282,4785	266,8463	286,2644	265,8417	284,6074
Queue_time_total	35,4494	53,4248	28,0956	41,6947	26,5438	45,2017	26,5772	43,3753
Utilisation_Res1	0,8696	0,8943	0,3820	0,3975	0,3894	0,4040	0,3895	0,4034
Utilisation_Res2	0,8254	0,8529	0,5774	0,5943	0,5195	0,5369	0,7011	0,7173
Utilisation_Res3	0,7012	0,7240	0,8745	0,8979	0,8853	0,9039	0,8779	0,9046
Utilisation_Res4	0,5615	0,5793	0,4869	0,5034	0,4423	0,4606	0,5928	0,6113
Utilisation_Res5	0,4922	0,5105	0,4271	0,4410	0,5806	0,6017	0,5172	0,5342
Utilisation_Res6	0,4382	0,4574	0,6948	0,7141	0,7023	0,7253	0,4688	0,4862
WIP_data_col	42,1786	46,4817	36,8357	39,9946	37,0952	41,6195	37,3239	41,2881
Lab_Flex_WF	2,3239	2,4643	2,8952	2,9976	2,7833	2,9263	2,7781	2,9374
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	432766,60	451360,26	533966,82	547961,27	513630,35	533518,13	509050,42	526763,30

	ECFDAB		AEDBFC		CFBDEA	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	272,5553	288,0050	284,3914	304,3079	267,2781	282,4785
Queue_time_total	33,7979	46,3626	44,4675	64,4718	28,0956	41,6947
Utilisation_Res1	0,4516	0,4674	0,8800	0,9027	0,3820	0,3975
Utilisation_Res2	0,4279	0,4414	0,6577	0,6760	0,5774	0,5943
Utilisation_Res3	0,7867	0,8023	0,4595	0,4745	0,8745	0,8979
Utilisation_Res4	0,5171	0,5356	0,7470	0,7687	0,4869	0,5034
Utilisation_Res5	0,8780	0,9000	0,8297	0,8542	0,4271	0,4410
Utilisation_Res6	0,6212	0,6388	0,5537	0,5725	0,6948	0,7141
WIP_data_col	39,9434	43,1332	45,9892	50,8656	36,8357	39,9946
Lab_Flex_WF	2,5827	2,7126	2,0699	2,1985	2,8952	2,9976
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	482339,44	496499,13	381827,04	400821,53	533966,82	547961,27

Table 38: Output data model variant SW9

Model variant SW10 (Case 3, AB-CD-EF):

	Original		CBFEDA		FBCDEA		BCFEAD	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	252,3210	260,5947	238,7546	242,1334	239,0672	242,3351	239,8108	243,5964
Queue_time_total	12,8319	19,1187	0,9821	1,5348	1,0158	1,6472	0,9721	1,9357
Utilisation_Res1	0,8561	0,8724	0,5421	0,5548	0,5577	0,5710	0,6579	0,6755
Utilisation_Res2	0,6328	0,6477	0,6584	0,6763	0,5507	0,5666	0,5779	0,5960
Utilisation_Res3	0,4674	0,4828	0,5410	0,5587	0,6527	0,6698	0,5431	0,5577
WIP_data_col	38,0732	39,8547	31,5965	32,6113	32,1717	32,9334	32,3963	33,3176
Lab_Flex_WF	4,9262	5,1737	6,7103	7,0164	6,6205	6,8696	6,5096	6,7837
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	432688,15	448919,66	523981,45	542455,88	517070,29	533341,14	507394,04	525873,38

	BDEACF		ABEFDC		CFBDEA	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	242,3282	246,0618	251,8139	261,0942	240,6560	243,3928
Queue_time_total	3,5488	4,7370	11,9997	21,1390	1,5163	2,2630
Utilisation_Res1	0,7322	0,7493	0,8545	0,8775	0,4867	0,4994
Utilisation_Res2	0,6552	0,6711	0,4941	0,5113	0,6857	0,7034
Utilisation_Res3	0,5505	0,5654	0,6720	0,6880	0,5673	0,5809
WIP_data_col	35,8783	36,6667	39,1218	41,4345	31,8390	32,5421
Lab_Flex_WF	5,5377	5,7473	4,6440	4,8853	6,6805	6,8911
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	439614,08	457290,77	400810,03	421104,26	527273,30	542481,55

Table 39: Output data model variant SW10

Model variant SW11 (Case 3, ABC-DEF):

	Original		CFDBEA		CDFBEA		CEFBDA	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	244,3604	248,8687	237,3542	240,6668	239,1547	241,3673	239,2748	242,0250
Queue_time_total	5,0014	8,5713	0,1041	0,3560	0,1706	0,3538	0,1081	0,3005
Utilisation_Res1	0,8104	0,8247	0,5903	0,6032	0,5916	0,6076	0,6000	0,6128
Utilisation_Res2	0,5019	0,5128	0,5675	0,5842	0,5815	0,6005	0,5906	0,6070
WIP_data_col	36,7701	37,8214	31,4835	32,3529	31,8663	32,8222	32,2648	33,1423
Lab_Flex_WF	7,4728	7,8492	10,4425	10,8864	10,1976	10,6933	10,0646	10,5024
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	430490,36	444410,21	527588,05	544650,90	514200,75	534778,77	506365,30	523583,36

	DFCEAB		ABCEDF		CFBDEA	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	240,2917	243,1056	244,4145	246,9844	239,2291	241,4208
Queue_time_total	1,0823	1,9423	4,5865	7,3734	0,0999	0,2968
Utilisation_Res1	0,5146	0,5271	0,8040	0,8229	0,6188	0,6300
Utilisation_Res2	0,7249	0,7425	0,5041	0,5159	0,5446	0,5559
WIP_data_col	33,9530	34,8617	36,4522	37,7146	31,4548	32,2545
Lab_Flex_WF	8,8376	9,2884	7,5474	7,9693	10,4508	10,8595
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	474058,40	491988,55	429310,76	447403,05	527953,27	541631,39

Table 40: Output data model variant SW11

Model variant SW12 (Case 3, ABCDEF):

	Original		CFBDEA		CFDBEA		FCDBAE	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	238,7313	241,5536	237,8518	240,4989	238,0570	241,0917	237,1390	241,1615
Queue_time_total	-0,0014	0,0722	-0,0060	0,0133	0,0000	0,0000	-0,0147	0,0354
Utilisation_Res1	0,6567	0,6705	0,5776	0,5933	0,5805	0,5921	0,5878	0,5998
WIP_data_col	35,5763	36,3474	31,3650	32,3118	31,3477	32,1235	31,9633	32,6196
Lab_Flex_WF	17,3383	18,1205	21,3784	22,3081	21,5840	22,3500	20,9776	21,6939
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	427004,64	444858,21	527108,74	547428,88	528638,10	543673,99	518677,15	534151,33

	FEDBAC		AEDBFC		CFBDEA	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	238,5194	241,3286	238,9917	241,8424	237,8518	240,4989
Queue_time_total	-0,0079	0,0656	0,0256	0,1099	-0,0060	0,0133
Utilisation_Res1	0,6362	0,6473	0,6900	0,7041	0,5776	0,5933
WIP_data_col	34,5202	35,1630	37,3561	38,2213	31,3650	32,3118
Lab_Flex_WF	18,4841	19,0943	15,5290	16,3384	21,3784	22,3081
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	457048,45	471393,27	383485,94	401752,25	527108,74	547428,88

Table 41: Output data model variant SW12

Additional measurement 1 (Case 1, AB-CD-EF):

	Original		EBDFCA		BEDFCA		DAEBFC		FCAEBD	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	207,1397	263,2858	147,8185	150,8825	151,7297	155,4240	148,6475	152,6595	161,1538	168,9499
Queue_time_total	66,9158	122,7887	7,6816	10,4262	11,8337	15,3976	9,1646	12,4270	21,1780	28,4470
Utilisation_Res1	0,9625	0,9793	0,7672	0,7809	0,8400	0,8533	0,7810	0,7967	0,5902	0,6032
Utilisation_Res2	0,9000	0,9169	0,7473	0,7636	0,7524	0,7672	0,8213	0,8336	0,8512	0,8669
Utilisation_Res3	0,5296	0,5384	0,7798	0,7957	0,7309	0,7431	0,6991	0,7119	0,8512	0,8669
WIP_data_col	65,6143	88,3069	42,0137	43,7754	43,6972	45,2048	43,0179	44,7445	47,6113	50,3985
Lab_Flex_WF	2,5244	2,7475	3,5434	3,8512	3,5344	3,7264	3,4992	3,7236	3,0281	3,2654
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	247262,73	262760,99	276358,92	293533,27	273357,80	287469,44	273388,98	288528,07	246145,78	261801,65

	DBCAFE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	290,2952	579,4803	147,3586	150,3437	148,8134	153,3452	147,3317	150,9416	147,8185	150,8825
Queue_time_total	150,5828	439,2627	7,8579	9,7963	8,9012	13,0514	7,9093	10,8085	7,6816	10,4262
Utilisation_Res1	0,7926	0,8086	0,7233	0,7344	0,7979	0,8170	0,6927	0,7024	0,7672	0,7809
Utilisation_Res2	0,9851	0,9941	0,7757	0,7950	0,7197	0,7422	0,8040	0,8169	0,7473	0,7636
Utilisation_Res3	0,5229	0,5367	0,7800	0,7949	0,7801	0,7990	0,7828	0,7969	0,7798	0,7957
WIP_data_col	93,4944	196,4518	42,3209	43,4967	42,5328	44,7092	42,4909	43,7938	42,0137	43,7754
Lab_Flex_WF	2,5244	2,7475	3,5900	3,8008	3,4755	3,7983	3,5675	3,7510	3,5434	3,8512
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	247262,73	262760,99	277102,88	294729,88	272868,83	296572,79	276541,34	290178,57	276358,92	293533,27

Table 42: Output data additional measurement 1 AB-CD-EF

Additional measurement 1 (Case 1, ABC-DEF):

	Original		EBDFCA		BEDFAC		EDBFAC		DBCEFA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	192,0321	334,7870	141,5801	143,7021	141,4334	143,2687	141,3419	143,2023	144,0967	147,6840
Queue_time_total	52,4153	194,7701	1,8158	2,9359	1,8185	2,7696	1,9620	3,1386	4,6833	7,1650
Utilisation_Res1	0,9667	0,9847	0,7192	0,7317	0,7618	0,7747	0,6777	0,6972	0,8229	0,8409
Utilisation_Res2	0,5337	0,5461	0,7402	0,7520	0,7075	0,7202	0,7759	0,7962	0,6578	0,6713
WIP_data_col	58,0419	110,8673	38,6938	39,5674	38,8932	39,6975	38,5460	39,9338	39,9441	41,2235
Lab_Flex_WF	4,6988	5,0410	6,3160	6,6237	6,2842	6,6076	6,0842	6,6091	6,1149	6,4601
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	293383,81	311031,53	322824,25	336623,94	316302,40	329939,12	316752,25	340295,18	304968,34	323372,90

	CABFDE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	278,9783	611,2845	141,3419	143,2023	140,9654	142,8125	141,9259	143,8886	141,5801	143,7021
Queue_time_total	139,2125	470,8840	1,9620	3,1386	1,5844	2,4885	2,1701	3,3174	1,8158	2,9359
Utilisation_Res1	0,9793	0,9940	0,6777	0,6972	0,7237	0,7385	0,6836	0,6986	0,7192	0,7317
Utilisation_Res2	0,5343	0,5451	0,7759	0,7962	0,7410	0,7562	0,7807	0,7945	0,7402	0,7520
WIP_data_col	85,7491	197,3697	38,5460	39,9338	38,6761	39,6981	38,8530	40,0138	38,6938	39,5674
Lab_Flex_WF	4,5581	4,8652	6,0842	6,6091	6,2479	6,6493	6,0386	6,4629	6,3160	6,6237
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	289445,34	301575,89	316752,25	340295,18	316179,84	333071,78	317088,23	333375,96	322824,25	336623,94

Table 43: Output data additional measurement 1 ABC-DEF

Additional measurement 1 (Case 1, ABCDEF):

	Original		EBDFCA		EDFBAC		DEFBCA		DABCEF	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	180,9845	241,7402	156,8091	168,8378	153,5879	165,6742	159,2746	168,4850	166,8362	206,3844
Queue_time_total	40,9720	100,9777	16,7621	28,4810	13,9966	25,3155	19,6472	28,0198	27,1798	65,9350
Utilisation_Res1	0,9535	0,9713	0,9235	0,9379	0,9237	0,9397	0,9307	0,9447	0,9451	0,9579
WIP_data_col	64,6753	87,6915	54,2514	59,0602	53,1670	58,2891	55,3880	59,3279	59,3581	74,3426
Lab_Flex_WF	1,6788	2,5797	3,2331	3,9999	3,2112	4,1390	2,9361	3,7677	2,1902	2,9569
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	35795,12	58020,21	77510,42	95365,58	75264,70	95149,40	68915,44	86448,75	52471,39	68501,37

	CAFBDE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	209,3075	303,7891	155,1567	167,1307	155,2222	166,5312	154,9392	162,4663	156,8091	168,8378
Queue_time_total	69,6836	164,0894	15,3794	27,3425	15,3272	26,6596	15,7820	22,3150	16,7621	28,4810
Utilisation_Res1	0,9674	0,9806	0,9283	0,9416	0,9254	0,9398	0,9259	0,9379	0,9235	0,9379
WIP_data_col	74,4116	109,2234	54,1527	59,1459	54,0477	58,4150	53,9970	56,8108	54,2514	59,0602
Lab_Flex_WF	1,0622	1,7908	3,0909	3,7767	3,1749	3,9339	3,2436	3,9402	3,2331	3,9999
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	24139,41	40682,68	72869,47	89478,06	75102,40	93090,65	77469,52	92400,29	77510,42	95365,58

Table 44: Output data additional measurement 1 ABCDEF

Additional measurement 2 (Case 1, A-B-C-D-E-F, arrival rate 15):

	Original		AEDFBC		EDAFCB		DAEBFC		DCEBAF	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	145,9225	148,3256	140,5152	142,6452	140,6401	143,0316	141,7022	143,3574	143,8036	146,6133
Queue_time_total	5,3553	7,2437	1,3419	1,9661	1,3846	2,0853	2,4148	3,0234	4,1406	5,5114
Utilisation_Res1	0,4141	0,4229	0,4128	0,4260	0,3280	0,3356	0,3619	0,3705	0,2182	0,2253
Utilisation_Res2	0,7402	0,7574	0,4777	0,5010	0,3895	0,4005	0,5819	0,5968	0,4855	0,4983
Utilisation_Res3	0,6725	0,6853	0,4316	0,4504	0,5150	0,5295	0,4366	0,4486	0,7237	0,7443
Utilisation_Res4	0,4034	0,4152	0,5299	0,5436	0,5559	0,5770	0,6198	0,6332	0,6194	0,6339
Utilisation_Res5	0,2656	0,2721	0,4395	0,4500	0,4655	0,4779	0,3891	0,3950	0,3246	0,3334
Utilisation_Res6	0,3804	0,3922	0,5547	0,5709	0,5607	0,5750	0,4737	0,4860	0,3759	0,3889
WIP_data_col	27,0273	27,8474	25,2111	26,0959	25,4480	26,3034	25,5785	26,0790	26,3307	27,1982
Lab_Flex_WF	3,6026	3,6849	3,8150	3,9373	3,8448	3,9670	3,8096	3,8763	3,7057	3,8189
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	620798,80	630179,20	634703,74	651465,97	631759,50	644926,31	639369,12	648419,46	628705,99	641169,34

	BCFDAE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	146,7818	150,2826	141,7934	143,7425	142,4932	144,9200	141,7566	143,5514	142,3623	144,1200
Queue_time_total	7,2924	9,6076	2,2514	2,9095	3,0415	4,1806	2,3267	2,8660	3,4740	4,4577
Utilisation_Res1	0,2010	0,2102	0,2274	0,2347	0,2259	0,2336	0,1822	0,1897	0,1839	0,1913
Utilisation_Res2	0,7726	0,7907	0,6105	0,6237	0,6926	0,7092	0,6113	0,6338	0,7017	0,7172
Utilisation_Res3	0,6937	0,7092	0,4329	0,4445	0,4329	0,4484	0,4570	0,4715	0,4539	0,4697
Utilisation_Res4	0,3442	0,3574	0,5595	0,5724	0,4695	0,4807	0,5560	0,5681	0,4730	0,4877
Utilisation_Res5	0,2153	0,2251	0,4639	0,4729	0,4630	0,4736	0,4627	0,4765	0,4658	0,4767
Utilisation_Res6	0,4995	0,5162	0,4986	0,5091	0,4926	0,5096	0,4993	0,5113	0,4992	0,5119
WIP_data_col	27,1778	28,2138	25,2080	25,7040	25,2779	26,1094	25,3730	25,7991	25,6381	26,3399
Lab_Flex_WF	3,5923	3,6875	3,8798	3,9548	3,8585	3,9572	3,8781	3,9413	3,8284	3,9232
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	628417,05	641094,67	646141,30	654571,27	645419,74	658602,83	642676,93	654545,36	641423,58	654028,13

Table 45: Output data additional measurement 2 A-B-C-D-E-F, arrival rate 15

Additional measurement 2 (Case 1, A-B-C-D-E-F, arrival rate 12):

	Original		AEDFBC		EDAFCB		DAEBFC		DCEBAF	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	140,5155	142,2961	138,6569	141,2671	138,7258	140,9159	140,0518	141,9109	139,9975	142,1377
Queue_time_total	1,2279	1,6668	0,3003	0,4349	0,3139	0,4831	0,5241	0,7846	0,8055	1,0960
Utilisation_Res1	0,3283	0,3356	0,3264	0,3374	0,2601	0,2695	0,2905	0,3029	0,1765	0,1806
Utilisation_Res2	0,5882	0,6042	0,3817	0,3929	0,3027	0,3128	0,4601	0,4789	0,3874	0,3998
Utilisation_Res3	0,5288	0,5433	0,3439	0,3552	0,4070	0,4196	0,3484	0,3617	0,5799	0,5977
Utilisation_Res4	0,3167	0,3249	0,4199	0,4354	0,4427	0,4539	0,4962	0,5131	0,4951	0,5090
Utilisation_Res5	0,2075	0,2140	0,3470	0,3600	0,3701	0,3796	0,3086	0,3193	0,2595	0,2662
Utilisation_Res6	0,3003	0,3122	0,4423	0,4567	0,4420	0,4555	0,3800	0,3958	0,3013	0,3135
WIP_data_col	20,6340	21,0772	19,8838	20,4288	20,0908	20,4686	20,1445	20,7416	20,4408	21,0571
Lab_Flex_WF	4,4855	4,5512	4,6409	4,7208	4,7160	4,7781	4,5689	4,6618	4,5989	4,6974
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	751130,44	760433,56	761231,03	773343,35	761766,58	770180,56	755440,42	769716,34	750853,91	762142,66

	BCFDAE		EDBFAC		EBDFAC		EDBFCA		EBDFCA	
	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	140,9888	142,6824	138,9044	141,2895	141,0272	141,9495	139,2172	141,3417	139,9834	141,6697
Queue_time_total	1,6377	2,0878	0,4776	0,6880	0,7667	1,1845	0,4915	0,6961	0,6909	1,0763
Utilisation_Res1	0,1619	0,1674	0,1830	0,1912	0,1834	0,1921	0,1454	0,1495	0,1449	0,1517
Utilisation_Res2	0,6210	0,6346	0,4892	0,5002	0,5560	0,5720	0,4848	0,5004	0,5536	0,5709
Utilisation_Res3	0,5587	0,5730	0,3434	0,3608	0,3493	0,3633	0,3654	0,3785	0,3622	0,3761
Utilisation_Res4	0,2765	0,2861	0,4408	0,4570	0,3777	0,3898	0,4397	0,4570	0,3735	0,3873
Utilisation_Res5	0,1704	0,1765	0,3688	0,3797	0,3708	0,3827	0,3698	0,3826	0,3713	0,3797
Utilisation_Res6	0,3985	0,4079	0,3926	0,4077	0,4013	0,4144	0,3955	0,4096	0,3946	0,4065
WIP_data_col	20,6610	21,1020	19,7151	20,3364	19,9951	20,5611	19,7958	20,3154	19,8357	20,3699
Lab_Flex_WF	4,5384	4,6070	4,6892	4,7867	4,6473	4,7345	4,7064	4,7899	4,6839	4,7732
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	753028,49	760324,74	764171,15	776952,00	760431,27	771822,63	763735,12	776496,69	765680,01	776445,70

Table 46: Output data additional measurement 2 A-B-C-D-E-F, arrival rate 12

Additional measurement 3 (Case 3, A-B-C-D-E-F)

	Original		CFBDEA		CFEBDA		CBDEFA	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	483,0458	684,0081	245,8011	249,7354	246,7793	250,8321	256,5211	261,9988
Queue_time_total	241,6409	442,1155	7,1410	9,0629	7,4950	9,4030	15,8710	21,6476
Utilisation_Res1	0,9761	0,9891	0,4364	0,4522	0,4331	0,4466	0,4351	0,4463
Utilisation_Res2	0,9140	0,9385	0,6558	0,6745	0,5783	0,5967	0,7881	0,8123
Utilisation_Res3	0,5188	0,5329	0,6611	0,6738	0,6553	0,6750	0,6537	0,6677
Utilisation_Res4	0,6213	0,6375	0,5543	0,5717	0,4963	0,5109	0,6658	0,6886
Utilisation_Res5	0,5427	0,5634	0,4803	0,4998	0,6445	0,6661	0,5806	0,6082
Utilisation_Res6	0,3877	0,4053	0,6274	0,6462	0,6243	0,6454	0,4203	0,4367
WIP_data_col	83,9067	125,8749	32,4578	33,4691	32,8466	33,7382	34,7022	36,2112
Lab_Flex_WF	2,4030	2,5008	3,2311	3,3466	3,1986	3,3082	3,0383	3,1557
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	448707,21	462949,27	528556,05	542851,95	524000,34	540585,18	511843,19	529050,14

	ECFDAB		AEDBFC		CFBDEA	
	LB	UB	LB	UB	LB	UB
Lead_Time_complete	418,9566	696,7367	474,1505	668,0774	245,8011	249,7354
Queue_time_total	179,2422	456,7228	234,5698	428,3475	7,1410	9,0629
Utilisation_Res1	0,5030	0,5223	0,9744	0,9882	0,4364	0,4522
Utilisation_Res2	0,4766	0,4948	0,7301	0,7482	0,6558	0,6745
Utilisation_Res3	0,5798	0,5931	0,3374	0,3483	0,6611	0,6738
Utilisation_Res4	0,5696	0,5899	0,8214	0,8471	0,5543	0,5717
Utilisation_Res5	0,9764	0,9912	0,9190	0,9447	0,4803	0,4998
Utilisation_Res6	0,5573	0,5710	0,4918	0,5082	0,6274	0,6462
WIP_data_col	69,5695	127,4974	83,1334	122,9878	32,4578	33,4691
Lab_Flex_WF	2,8833	2,9583	1,9647	2,0574	3,2311	3,3466
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	493105,16	506451,99	400972,56	414616,01	528556,05	542851,95

Table 47: Output data additional measurement 3 A-B-C-D-E-F

Appendix E

Output data combining tasks rule:

Model variant C1 (AB-CD-EF, setup ratio 1):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.E.(DC) [23]		F.(AB).E.(DC) [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,4274	110,3066	107,7194	108,3947	106,3806	107,3908	104,4490	105,4800
Queue_time_total	0,0382	0,0731	0,0204	0,0716	0,0286	0,0523	0,0205	0,0595
Utilisation_Res1	0,4782	0,4864	0,4522	0,4637	0,4765	0,4830	0,4481	0,4604
Utilisation_Res2	0,5167	0,5283	0,5163	0,5265	0,4984	0,5100	0,4962	0,5123
Utilisation_Res3	0,5047	0,5146	0,5052	0,5126	0,5010	0,5100	0,5018	0,5114
WIP_data_col	31,2625	31,9574	31,0178	31,4846	30,7496	31,2820	30,3374	30,9889
Lab_Flex_WF	9,6751	9,9113	10,4070	10,5565	9,8213	10,0001	10,6216	10,8427
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	724922,65	739054,40	735956,90	746575,48	739428,11	750775,12	744988,89	761018,92

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.E.(DC) [36]		F.(AB).E.(DC) [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	115,3926	117,1009	112,6083	114,2420	111,6022	113,6211	108,9158	112,2096
Queue_time_total	5,6094	7,1382	4,9146	6,3077	5,0186	6,4617	4,4360	6,9664
Utilisation_Res1	0,7531	0,7614	0,7083	0,7217	0,7528	0,7660	0,7127	0,7269
Utilisation_Res2	0,8123	0,8246	0,8089	0,8231	0,7919	0,8086	0,7915	0,8067
Utilisation_Res3	0,7910	0,8033	0,7945	0,8051	0,7967	0,8095	0,7987	0,8113
WIP_data_col	51,7736	52,8652	50,8444	52,0339	51,1461	52,6337	50,5238	52,3445
Lab_Flex_WF	3,9418	4,1421	4,1965	4,4221	3,9571	4,2236	4,2403	4,5219
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	297037,68	310848,13	310336,66	325236,20	299174,45	319078,22	312673,26	331027,98

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.E.(DC) [42]		F.(AB).E.(DC) [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	174,5352	212,6316	169,3988	219,4803	148,8871	165,6833	141,3788	169,0680
Queue_time_total	64,8540	102,7112	61,8462	111,5253	42,1287	58,7778	36,4496	63,7915
Utilisation_Res1	0,8905	0,8998	0,8388	0,8506	0,8862	0,8971	0,8372	0,8542
Utilisation_Res2	0,9589	0,9726	0,9569	0,9739	0,9308	0,9462	0,9272	0,9482
Utilisation_Res3	0,9389	0,9495	0,9386	0,9499	0,9354	0,9474	0,9350	0,9469
WIP_data_col	91,6114	110,0379	88,9812	113,9722	80,0467	89,4272	76,6062	91,3079
Lab_Flex_WF	1,1914	1,3695	1,2239	1,5155	1,4081	1,6230	1,4518	1,7671
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	80673,99	95387,82	96587,35	113724,93	97200,10	113556,37	111018,21	132060,84

Table 48: Output data model variant C1

Model variant C2 (AB-CD-EF, setup ratio 2):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.E.(DC) [23]		F.(AB).E.(DC) [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,2352	110,1443	107,1718	108,2009	109,1984	110,0977	106,7021	107,7263
Queue_time_total	0,0417	0,0674	0,0212	0,0571	0,0395	0,0788	0,0273	0,0651
Utilisation_Res1	0,4799	0,4870	0,4513	0,4594	0,4783	0,4872	0,4552	0,4637
Utilisation_Res2	0,5136	0,5237	0,5121	0,5236	0,5318	0,5443	0,5299	0,5404
Utilisation_Res3	0,5069	0,5133	0,5047	0,5105	0,5058	0,5152	0,5042	0,5124
WIP_data_col	31,3933	31,8218	30,8730	31,3847	31,6969	32,3094	31,1983	31,7387
Lab_Flex_WF	9,7364	9,8538	10,4262	10,6132	9,5950	9,7919	10,4389	10,6448
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	728999,48	737806,99	739830,46	749785,06	716871,48	729355,28	728520,04	739172,44

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.E.(DC) [36]		F.(AB).E.(DC) [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	114,9854	116,8803	112,8438	114,4807	116,1932	118,8628	112,8438	114,4807
Queue_time_total	5,3119	7,1359	5,1301	6,4325	6,9921	9,3635	5,1301	6,4325
Utilisation_Res1	0,7530	0,7643	0,7173	0,7258	0,7563	0,7694	0,7173	0,7258
Utilisation_Res2	0,8134	0,8261	0,8139	0,8282	0,8382	0,8567	0,8139	0,8282
Utilisation_Res3	0,7945	0,8084	0,7996	0,8105	0,7978	0,8094	0,7996	0,8105
WIP_data_col	51,7143	53,1394	51,2265	52,4732	53,0407	54,7234	51,2265	52,4732
Lab_Flex_WF	3,8830	4,1255	4,0808	4,3296	3,8154	4,0476	4,0808	4,3296
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	291536,56	308720,86	302279,59	317030,60	273370,51	292051,59	302279,59	317030,60

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.E.(DC) [42]		F.(AB).E.(DC) [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	165,8219	200,9423	155,3560	193,3900	207,4972	333,8400	204,0402	286,8881
Queue_time_total	55,9102	90,7522	47,6023	85,3705	98,2356	224,2496	93,4739	183,3678
Utilisation_Res1	0,8830	0,8953	0,8372	0,8544	0,8841	0,8940	0,8409	0,8561
Utilisation_Res2	0,9498	0,9684	0,9533	0,9682	0,9754	0,9865	0,9765	0,9862
Utilisation_Res3	0,9351	0,9469	0,9326	0,9471	0,9338	0,9433	0,9350	0,9489
WIP_data_col	87,0420	104,2280	81,1594	100,5122	106,6612	165,9947	106,2289	146,7733
Lab_Flex_WF	1,2679	1,5074	1,3150	1,6436	1,3251	1,4913	1,2548	1,5174
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	86239,37	104897,78	99565,79	120429,26	79608,97	91615,60	88738,76	105109,43

Table 49: Output data model variant C2

Model variant C3 (AB-CD-EF, setup ratio 3):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.E.(DC) [23]		F.(AB).E.(DC) [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,4176	110,6217	109,2079	110,3621	106,0481	107,4509	106,3055	107,0491
Queue_time_total	0,0375	0,0768	0,0370	0,0819	0,0326	0,0675	0,0409	0,0769
Utilisation_Res1	0,4765	0,4845	0,4931	0,5041	0,4758	0,4854	0,4903	0,5012
Utilisation_Res2	0,5184	0,5305	0,5140	0,5286	0,4983	0,5108	0,5011	0,5120
Utilisation_Res3	0,5056	0,5169	0,5047	0,5118	0,5033	0,5116	0,5036	0,5111
WIP_data_col	31,3365	31,9418	31,5304	32,0933	30,8062	31,3359	31,1200	31,6360
Lab_Flex_WF	9,6908	9,8970	10,2627	10,4577	9,7901	9,9614	10,4345	10,6198
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	724027,02	737112,89	720934,54	735127,65	737138,29	749746,57	731818,77	742903,80

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.E.(DC) [36]		F.(AB).E.(DC) [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	115,4111	117,1650	115,3610	118,3662	112,0225	113,4583	112,1546	113,8310
Queue_time_total	5,7326	7,4023	5,8983	8,5182	5,1227	6,2793	5,5496	6,8622
Utilisation_Res1	0,7519	0,7599	0,7763	0,7924	0,7501	0,7613	0,7792	0,7927
Utilisation_Res2	0,8163	0,8279	0,8132	0,8296	0,7948	0,8073	0,7911	0,8064
Utilisation_Res3	0,7975	0,8089	0,7939	0,8080	0,7964	0,8083	0,7967	0,8078
WIP_data_col	52,0473	53,3483	52,1128	54,2089	51,2679	52,4583	51,8023	53,0874
Lab_Flex_WF	3,8644	4,0656	3,9617	4,2789	3,9875	4,2161	4,1187	4,3671
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	291763,53	305674,38	280375,91	301410,28	302882,09	317965,44	293233,26	309844,64

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.E.(DC) [42]		F.(AB).E.(DC) [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	157,5210	185,5130	165,2494	200,7799	146,9755	166,6453	156,4603	171,0281
Queue_time_total	47,9054	75,3950	55,8756	90,8714	40,2663	59,6789	49,5756	64,0732
Utilisation_Res1	0,8794	0,8905	0,9122	0,9267	0,8782	0,8906	0,9130	0,9244
Utilisation_Res2	0,9511	0,9639	0,9527	0,9690	0,9252	0,9451	0,9287	0,9429
Utilisation_Res3	0,9316	0,9420	0,9321	0,9455	0,9333	0,9478	0,9350	0,9439
WIP_data_col	82,4267	96,2761	87,4045	104,8976	78,8385	90,1315	85,1890	92,7529
Lab_Flex_WF	1,3839	1,5765	1,1300	1,4221	1,4304	1,6831	1,3127	1,4757
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	93154,01	107798,56	75676,79	96015,30	99602,04	120613,39	92115,27	105782,45

Table 50: Output data model variant C3

Model variant C4 (AB-CD-EF, setup ratio 4):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.E.(DC) [23]		F.(AB).E.(DC) [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,3273	110,4318	109,2165	110,2160	109,0980	110,0610	108,3927	110,0055
Queue_time_total	0,0318	0,0684	0,0422	0,0988	0,0394	0,0886	0,0562	0,1223
Utilisation_Res1	0,4752	0,4813	0,4892	0,5016	0,4752	0,4828	0,4907	0,5001
Utilisation_Res2	0,5138	0,5249	0,5135	0,5250	0,5308	0,5438	0,5274	0,5389
Utilisation_Res3	0,5034	0,5111	0,5047	0,5125	0,5045	0,5118	0,5040	0,5110
WIP_data_col	31,1156	31,6497	31,4966	32,0523	31,6470	32,1544	31,6333	32,2317
Lab_Flex_WF	9,79	9,95	10,27	10,48	9,66	9,81	10,34	10,53
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	731302,65	741758,21	724037,86	735908,24	720496,20	732055,90	717443,60	729208,02

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.E.(DC) [36]		F.(AB).E.(DC) [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	115,1108	117,1425	115,6366	117,6845	116,5772	118,9387	116,8134	120,4925
Queue_time_total	5,5908	7,4303	6,1990	7,8553	7,4369	9,3684	7,6229	10,8047
Utilisation_Res1	0,7505	0,7626	0,7783	0,7918	0,7489	0,7615	0,7805	0,7933
Utilisation_Res2	0,8138	0,8274	0,8170	0,8263	0,8378	0,8511	0,8387	0,8578
Utilisation_Res3	0,7981	0,8072	0,7991	0,8096	0,7964	0,8093	0,7996	0,8087
WIP_data_col	51,7894	53,1249	52,6892	53,9890	53,2767	54,6007	53,8278	55,9242
Lab_Flex_WF	3,92	4,11	3,94	4,15	3,83	4,05	3,86	4,12
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	292658,22	306604,54	281804,48	295036,19	279272,42	295429,39	265275,59	282491,36

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.E.(DC) [42]		F.(AB).E.(DC) [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	164,7106	208,7324	167,8366	207,0572	224,9445	376,6026	204,2767	288,6049
Queue_time_total	55,1120	98,8773	57,9518	97,3048	115,7009	266,9526	95,3655	179,3022
Utilisation_Res1	0,8835	0,8966	0,9111	0,9258	0,8764	0,8885	0,9089	0,9216
Utilisation_Res2	0,9556	0,9684	0,9525	0,9670	0,9737	0,9873	0,9710	0,9835
Utilisation_Res3	0,9369	0,9483	0,9357	0,9478	0,9305	0,9449	0,9324	0,9455
WIP_data_col	86,1050	108,9099	89,0458	108,3612	115,0664	185,9991	106,2627	147,9080
Lab_Flex_WF	1,27	1,48	1,10	1,33	1,32	1,57	1,12	1,39
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	85570,11	99959,42	75772,06	94091,94	80002,71	97190,91	70408,36	86592,02

Table 51: Output data model variant C4

Model variant C5 (ABC-DEF, setup ratio 1):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.(ED).C [23]		F.(AB).(ED).C [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,4597	110,0513	107,0307	107,9483	106,5909	107,7153	104,4472	105,4601
Queue_time_total	0,0010	0,0084	-0,0009	0,0077	0,0001	0,0102	-0,0001	0,0031
Utilisation_Res1	0,5040	0,5156	0,4866	0,4971	0,5031	0,5121	0,4888	0,4967
Utilisation_Res2	0,5026	0,5126	0,5003	0,5078	0,4910	0,4994	0,4899	0,4984
WIP_data_col	31,2281	31,9832	30,7629	31,2294	30,8989	31,4246	30,3840	30,9294
Lab_Flex_WF	14,7088	15,0981	15,1486	15,3722	14,8447	15,1296	15,2460	15,5212
Routing_Flex	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Volume_Flex	723428,83	738729,37	740737,50	752748,50	735998,55	748286,60	747990,55	759388,40

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.(ED).C [36]		F.(AB).(ED).C [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	112,2077	114,0169	109,8079	110,7263	109,5311	110,7526	107,1396	108,2588
Queue_time_total	2,6998	3,7955	2,3108	2,9468	2,2162	3,0543	1,9130	2,7856
Utilisation_Res1	0,7938	0,8071	0,7706	0,7829	0,7914	0,8033	0,7785	0,7885
Utilisation_Res2	0,7935	0,8037	0,7915	0,8021	0,7746	0,7844	0,7774	0,7876
WIP_data_col	50,6047	52,0240	49,6528	50,6574	49,8942	50,8384	49,2336	50,4275
Lab_Flex_WF	5,7790	6,2199	6,1701	6,5408	6,0690	6,3986	6,2835	6,6826
Routing_Flex	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Volume_Flex	290216,85	306384,68	308670,84	324785,44	308267,42	322167,06	316266,27	329580,50

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.(ED).C [42]		F.(AB).(ED).C [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	142,8167	157,3411	134,1766	148,5802	131,3834	142,4331	122,5908	130,4471
Queue_time_total	33,0243	47,4174	26,4757	40,6826	24,3319	34,8182	17,6801	25,0474
Utilisation_Res1	0,9312	0,9417	0,9084	0,9225	0,9331	0,9449	0,9088	0,9222
Utilisation_Res2	0,9327	0,9425	0,9306	0,9457	0,9096	0,9197	0,9086	0,9178
WIP_data_col	76,1306	84,4838	71,5968	80,5286	70,8079	77,3385	66,2933	71,4018
Lab_Flex_WF	1,8879	2,1602	1,9557	2,4345	2,1048	2,4513	2,4227	2,8406
Routing_Flex	1,00	1,00	1,00	1,00	1,00	1,00	1,00	1,00
Volume_Flex	87055,40	100195,08	98232,91	118415,57	102057,25	116786,18	119691,32	135164,97

Table 52: Output data model variant C5

Model variant C6 (AB-CD-EF, setup ratio 2):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.(ED).C [23]		F.(AB).(ED).C [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,3592	110,1922	107,2486	108,0507	109,1840	110,3034	106,6921	107,6689
Queue_time_total	-0,0003	0,0104	-0,0003	0,0061	0,0022	0,0091	-0,0005	0,0049
Utilisation_Res1	0,5019	0,5100	0,4911	0,5009	0,5037	0,5154	0,4886	0,4977
Utilisation_Res2	0,5002	0,5085	0,5010	0,5096	0,5094	0,5201	0,5074	0,5131
WIP_data_col	31,1699	31,7308	30,8942	31,4800	31,6231	32,2776	31,0116	31,4776
Lab_Flex_WF	14,8297	15,1082	15,0479	15,3368	14,4873	14,8176	14,9614	15,1984
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	730630,57	741948,19	736615,15	748883,43	718054,32	733484,34	736491,85	745558,34

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.(ED).C [36]		F.(AB).(ED).C [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	112,2588	113,6447	110,3580	111,6927	112,0369	113,4544	109,6451	110,8854
Queue_time_total	2,8268	3,6346	2,6359	3,6305	2,7460	3,7159	2,4087	3,2400
Utilisation_Res1	0,7977	0,8074	0,7793	0,7889	0,7961	0,8092	0,7757	0,7860
Utilisation_Res2	0,7940	0,8036	0,7950	0,8036	0,8060	0,8137	0,8058	0,8135
WIP_data_col	50,8850	51,8022	50,1767	51,1864	51,2219	52,3055	50,5398	51,3221
Lab_Flex_WF	5,8356	6,1558	6,0655	6,3990	5,6045	5,9518	5,9352	6,1622
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	290117,65	303137,30	303382,90	315682,24	281274,00	294856,95	298046,42	309763,49

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.(ED).C [42]		F.(AB).(ED).C [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	143,4089	173,6697	130,9984	142,4232	143,0348	167,9396	132,7674	146,0250
Queue_time_total	33,6201	63,7235	23,2866	34,8259	33,7666	58,5278	25,7064	38,8115
Utilisation_Res1	0,9322	0,9487	0,9050	0,9161	0,9370	0,9481	0,9028	0,9183
Utilisation_Res2	0,9297	0,9445	0,9261	0,9363	0,9424	0,9555	0,9373	0,9508
WIP_data_col	76,3274	93,9012	69,7173	76,4331	77,9157	92,7714	72,1879	80,8274
Lab_Flex_WF	1,6953	2,1997	2,2298	2,5349	1,6085	1,9471	1,9344	2,3551
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	80000,16	102264,60	110141,83	124256,93	72319,69	88731,35	97359,90	117264,48

Table 53: Output data model variant C6

Model variant C7 (ABC-DEF, setup ratio 3):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.(ED).C [23]		F.(AB).(ED).C [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,4006	110,1976	108,8062	109,7440	106,4572	107,6052	106,7806	107,9165
Queue_time_total	-0,0001	0,0057	0,0003	0,0092	-0,0010	0,0066	-0,0003	0,0075
Utilisation_Res1	0,5030	0,5133	0,5097	0,5195	0,5038	0,5146	0,5078	0,5180
Utilisation_Res2	0,5028	0,5132	0,5038	0,5102	0,4899	0,4980	0,4893	0,4998
WIP_data_col	31,2408	31,9877	31,4703	31,9497	30,8233	31,4186	31,0279	31,6570
Lab_Flex_WF	14,7045	15,0687	14,8749	15,1100	14,8618	15,1719	14,9180	15,2272
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	724717,19	739164,05	722722,62	733395,47	735407,51	748565,92	731937,46	745850,63

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.(ED).C [36]		F.(AB).(ED).C [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	112,1126	113,1883	112,7141	114,3485	109,1273	110,6985	109,5623	110,9535
Queue_time_total	2,4116	3,3232	2,9852	4,4878	2,2048	3,1088	2,5905	3,4481
Utilisation_Res1	0,7957	0,8036	0,8040	0,8198	0,7940	0,8074	0,8060	0,8185
Utilisation_Res2	0,7923	0,8016	0,7927	0,8059	0,7762	0,7867	0,7765	0,7890
WIP_data_col	50,4024	51,4425	51,0625	52,5597	49,8186	51,0324	50,4212	51,5611
Lab_Flex_WF	5,9439	6,2892	5,7087	6,1449	6,0218	6,4243	5,9258	6,2956
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	294087,67	306217,19	279288,42	299716,15	303085,33	319415,24	293410,54	310549,84

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.(ED).C [42]		F.(AB).(ED).C [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	143,4765	161,2137	147,2697	173,1312	128,7022	143,3237	142,1948	153,5537
Queue_time_total	33,7653	51,9197	37,5285	63,3784	22,3249	37,1073	34,8906	46,2343
Utilisation_Res1	0,9275	0,9399	0,9432	0,9587	0,9282	0,9459	0,9467	0,9571
Utilisation_Res2	0,9318	0,9412	0,9281	0,9402	0,9090	0,9227	0,9100	0,9215
WIP_data_col	76,4089	87,0146	78,4104	92,7215	69,6649	79,0194	76,7310	83,7678
Lab_Flex_WF	1,9134	2,2139	1,7273	2,0956	2,0446	2,4923	1,8953	2,2385
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	89082,64	103846,89	76355,81	95274,00	98863,45	121001,12	91907,42	106711,44

Table 54: Output data model variant C7

Model variant C8 (AB-CD-EF, setup ratio 4):

	F.A.B.E.D.C [23]		F.(AB).E.D.C [23]		F.A.B.(ED).C [23]		F.(AB).(ED).C [23]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	109,4154	110,0948	109,0219	110,0400	108,9270	109,8484	108,4102	109,6761
Queue_time_total	0,0012	0,0042	0,0009	0,0038	-0,0010	0,0124	0,0007	0,0079
Utilisation_Res1	0,5019	0,5102	0,5103	0,5191	0,4985	0,5088	0,5083	0,5186
Utilisation_Res2	0,5013	0,5093	0,5000	0,5084	0,5073	0,5155	0,5052	0,5151
WIP_data_col	31,2423	31,7414	31,3499	31,9674	31,3022	31,8235	31,6650	32,1567
Lab_Flex_WF	14,8266	15,0652	14,8652	15,1807	14,6956	14,9866	14,6382	14,8882
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	730226,96	740840,66	724243,53	736097,80	726426,93	738775,83	719848,67	733142,09

	F.A.B.E.D.C [36]		F.(AB).E.D.C [36]		F.A.B.(ED).C [36]		F.(AB).(ED).C [36]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	112,1020	113,5885	112,6802	114,3148	111,5057	113,4485	111,9362	113,4572
Queue_time_total	2,5402	3,6112	3,1244	4,6048	2,5946	3,9203	2,9389	3,9570
Utilisation_Res1	0,7930	0,8060	0,8045	0,8209	0,7908	0,8035	0,8049	0,8165
Utilisation_Res2	0,7893	0,8019	0,7953	0,8074	0,8020	0,8153	0,8006	0,8120
WIP_data_col	50,3413	51,5001	51,1959	52,7245	50,9470	52,1892	51,4313	52,5416
Lab_Flex_WF	5,9629	6,3346	5,6598	6,1052	5,6820	6,0763	5,5267	5,8719
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	292109,35	310471,51	277350,69	297410,36	284003,17	301969,40	277248,75	292755,53

	F.A.B.E.D.C [42]		F.(AB).E.D.C [42]		F.A.B.(ED).C [42]		F.(AB).(ED).C [42]	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	141,2955	157,1035	147,5433	169,6794	148,1861	165,7044	146,7002	188,0327
Queue_time_total	31,7883	47,0650	37,9791	60,1206	38,9203	56,2276	37,4699	78,5009
Utilisation_Res1	0,9276	0,9428	0,9450	0,9571	0,9313	0,9438	0,9448	0,9623
Utilisation_Res2	0,9289	0,9381	0,9336	0,9403	0,9431	0,9537	0,9430	0,9567
WIP_data_col	74,9873	84,3545	78,7970	91,2096	80,9015	91,5713	79,7118	102,9811
Lab_Flex_WF	1,8825	2,3053	1,7408	2,0167	1,5470	1,8907	1,2760	1,7576
Routing_Flex	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000	1,0000
Volume_Flex	89344,84	105999,64	77778,91	89442,71	76773,80	92330,97	60812,57	83020,29

Table 55: Output data model variant C8

Appendix F

Output data parallel tasks rule:

Model variant P1 (equal service times, high reject probability, arrival rate 19):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,5135	140,9825	124,4249	125,5666	139,7973	141,1735	124,2411	125,3341
Queue_time_total	0,0051	0,0228	0,0074	0,0227	-0,0017	0,0092	-0,0075	0,0360
Utilisation_Res1	0,4850	0,4969	0,5246	0,5340	0,4863	0,4977	0,5403	0,5483
Utilisation_Res2	0,4935	0,5045	0,4924	0,5019	0,4909	0,5017	0,4908	0,4979
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	33,2697	34,0595	30,6402	31,1387	33,3371	34,0341	30,7663	31,3548
Lab_Flex_WF	17,9084	18,3495	16,9437	17,2381	16,7142	17,0619	15,7272	16,0570
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	817740,03	835301,59	778301,33	792078,96	817145,50	834071,07	778136,23	788420,91

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,6654	140,9794	124,6190	125,9497	139,2978	140,9215	124,6402	125,8721
Queue_time_total	0,0859	0,1994	0,1394	0,2443	0,0711	0,1834	0,1324	0,2414
Utilisation_Res1	0,5060	0,5169	0,5014	0,5106	0,4983	0,5114	0,5664	0,5749
Utilisation_Res2	0,5072	0,5156	0,5567	0,5685	0,5110	0,5251	0,5132	0,5203
Utilisation_Res3	0,5039	0,5155	0,4992	0,5108	0,5025	0,5186	0,5058	0,5183
WIP_data_col	33,5692	34,1164	30,4748	31,0978	33,4702	34,4156	30,8977	31,3901
Lab_Flex_WF	10,7752	10,9531	10,1480	10,4212	10,6619	10,9963	10,0602	10,2592
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	768324,05	780620,43	731611,44	747067,70	764056,04	784856,72	726675,61	737450,96

Table 56: Output data model variant P1

Model variant P2 (equal service times, high reject probability, arrival rate 30):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	142,5506	145,0072	128,7198	130,9263	141,8690	144,0777	129,0667	132,5359
Queue_time_total	2,9268	5,0087	4,8140	7,3036	2,3572	3,5759	5,3973	8,6069
Utilisation_Res1	0,7794	0,7895	0,8366	0,8474	0,7758	0,7897	0,8595	0,8715
Utilisation_Res2	0,7860	0,8036	0,7819	0,7980	0,7806	0,7933	0,7838	0,7971
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	54,3133	55,7005	50,2028	51,5788	53,9246	55,3891	50,8374	52,6082
Lab_Flex_WF	7,3009	7,7508	5,8087	6,2084	6,8345	7,3683	5,3760	5,8003
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	337305,84	355209,59	275995,90	294563,72	340881,68	361466,99	269740,75	288018,78

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	150,1189	152,6893	138,4739	141,7163	149,0956	152,6499	137,0364	145,0040
Queue_time_total	10,1904	12,3243	20,1642	25,1909	9,5235	12,7639	14,5196	22,9344
Utilisation_Res1	0,8038	0,8158	0,8043	0,8184	0,7900	0,8041	0,8983	0,9106
Utilisation_Res2	0,8027	0,8166	0,8921	0,9049	0,8081	0,8247	0,8117	0,8269
Utilisation_Res3	0,7998	0,8164	0,7967	0,8151	0,7983	0,8172	0,7988	0,8157
WIP_data_col	56,8396	58,2692	54,3718	56,5006	56,3060	58,3590	53,7592	57,6411
Lab_Flex_WF	3,9817	4,2814	2,9193	3,2159	4,0417	4,3686	2,9994	3,3015
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	292898,32	310872,44	224326,33	242964,33	294631,91	317796,57	225689,74	244365,50

Table 57: Output data model variant P2

Model variant P3 (equal service times, high reject probability, arrival rate 32):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	146,6167	151,7312	134,7559	140,2873	145,2769	148,2306	138,8565	145,2732
Queue_time_total	7,0240	11,9030	12,8726	19,5597	5,8824	8,3045	16,3308	23,2724
Utilisation_Res1	0,8293	0,8424	0,8943	0,9043	0,8240	0,8388	0,9178	0,9328
Utilisation_Res2	0,8382	0,8555	0,8383	0,8514	0,8320	0,8468	0,8355	0,8516
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	59,4279	61,8484	56,5439	59,3603	58,8152	60,8523	58,3150	61,8040
Lab_Flex_WF	5,4304	5,9314	3,7795	4,1905	5,1736	5,6907	3,4716	3,9675
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	250791,73	273189,89	185771,28	200391,00	257255,82	280312,85	174267,41	198962,69

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	158,4099	166,8032	159,4964	175,2089	162,2125	168,2911	164,5396	202,5105
Queue_time_total	18,9665	26,3815	54,4348	81,8205	22,3348	28,2045	46,4764	87,0581
Utilisation_Res1	0,8554	0,8683	0,8592	0,8719	0,8475	0,8577	0,9620	0,9744
Utilisation_Res2	0,8526	0,8660	0,9525	0,9632	0,8709	0,8811	0,8696	0,8817
Utilisation_Res3	0,8516	0,8685	0,8501	0,8685	0,8581	0,8740	0,8548	0,8726
WIP_data_col	63,7523	67,5262	67,4814	75,7600	65,3951	68,0998	70,2861	90,6568
Lab_Flex_WF	2,8591	3,1971	1,7198	1,9992	2,8605	3,0690	1,7128	1,9922
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	211880,06	230823,56	135546,85	152721,43	207810,01	221905,61	131461,83	150410,36

Table 58: Output data model variant P3

Model variant P4 (equal service times, low reject probability, arrival rate 19):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	139,0193	140,7988	124,4169	125,4167	139,6148	141,2418	124,3801	125,7104
Queue_time_total	0,0008	0,0148	-0,0008	0,0236	0,0004	0,0037	0,0010	0,0046
Utilisation_Res1	0,4969	0,5063	0,5062	0,5164	0,5319	0,5413	0,5381	0,5499
Utilisation_Res2	0,4930	0,5023	0,4928	0,5061	0,4967	0,5064	0,4897	0,5021
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	34,3264	34,9223	30,7269	31,4302	34,5902	35,2777	30,6027	31,3436
Lab_Flex_WF	17,3420	17,6614	16,9254	17,3563	15,5519	15,8924	15,4835	15,8860
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	820553,26	834890,45	807558,81	825140,14	766196,88	779573,60	762454,76	780196,96

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	139,4861	140,9314	124,6941	125,9564	139,1784	140,9377	124,3106	125,7084
Queue_time_total	0,0579	0,1151	0,0767	0,1384	0,0492	0,1384	0,0624	0,1365
Utilisation_Res1	0,5073	0,5184	0,5056	0,5132	0,4960	0,5083	0,5097	0,5189
Utilisation_Res2	0,4897	0,5019	0,5002	0,5101	0,4931	0,5029	0,4932	0,5026
Utilisation_Res3	0,5019	0,5167	0,5042	0,5155	0,5014	0,5172	0,5005	0,5115
WIP_data_col	34,5081	35,3179	30,8651	31,3544	34,3974	35,1917	30,7166	31,2411
Lab_Flex_WF	11,1964	11,4926	11,0914	11,2646	11,3622	11,6365	11,2923	11,5354
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	811631,48	830476,80	809187,38	821846,43	815670,46	833178,02	810890,58	824157,70

Table 59: Output data model variant P4

Model variant P5 (equal service times, low reject probability, arrival rate 30):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	142,2828	144,0283	128,4535	130,4715	143,6598	145,6114	130,0331	133,1620
Queue_time_total	2,9445	4,1923	4,3758	6,0477	3,8905	5,2499	6,3872	9,0028
Utilisation_Res1	0,7942	0,8043	0,8097	0,8189	0,8382	0,8528	0,8620	0,8745
Utilisation_Res2	0,7901	0,8002	0,7908	0,8027	0,7849	0,7965	0,7839	0,7975
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	56,0661	57,1244	50,5976	51,6517	56,0054	57,4239	51,1117	52,8724
Lab_Flex_WF	6,7431	7,1354	6,3523	6,6959	5,6921	6,1312	5,2490	5,7101
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	327421,58	342228,61	310097,76	325910,53	281738,03	301893,40	263132,82	283292,13

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	147,4477	150,2435	132,3800	135,6215	147,3876	150,3093	132,2889	134,5670
Queue_time_total	7,8787	10,3710	9,1226	12,4466	7,4989	10,0022	8,1318	10,4029
Utilisation_Res1	0,8059	0,8164	0,8036	0,8152	0,7890	0,8018	0,8153	0,8272
Utilisation_Res2	0,7804	0,7921	0,7961	0,8116	0,7853	0,7961	0,7853	0,7973
Utilisation_Res3	0,8022	0,8182	0,8045	0,8174	0,7998	0,8140	0,8003	0,8180
WIP_data_col	57,8159	59,5405	51,9315	53,5647	57,5142	59,0233	51,6692	53,1869
Lab_Flex_WF	4,3648	4,6843	4,1461	4,4255	4,5049	4,7795	4,2331	4,5288
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	323479,54	340827,70	309780,69	328805,22	329238,71	345805,09	310419,73	327616,84

Table 60: Output data model variant P5

Model variant P6 (equal service times, low reject probability, arrival rate 32):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	147,0904	150,2618	133,2394	136,2138	150,8830	158,5773	137,2803	149,2690
Queue_time_total	7,2968	9,8999	10,1950	13,7001	11,3406	18,4253	14,5368	27,7043
Utilisation_Res1	0,8472	0,8596	0,8636	0,8743	0,8990	0,9097	0,9193	0,9325
Utilisation_Res2	0,8424	0,8557	0,8422	0,8551	0,8401	0,8508	0,8383	0,8520
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	61,4010	63,1448	55,9748	57,6325	63,2893	67,0268	57,6925	63,7739
Lab_Flex_WF	4,9599	5,3490	4,5453	4,8924	3,8728	4,2467	3,4368	3,9285
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	235908,02	254794,93	221232,64	237112,70	192879,49	207909,09	173267,39	192798,23

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	156,4381	162,0424	141,5516	146,1222	156,7378	163,5346	141,3886	147,3605
Queue_time_total	16,6885	22,0141	20,3333	25,3088	16,4338	23,3543	18,6040	24,9898
Utilisation_Res1	0,8572	0,8720	0,8571	0,8723	0,8470	0,8570	0,8718	0,8855
Utilisation_Res2	0,8292	0,8422	0,8478	0,8610	0,8417	0,8508	0,8435	0,8605
Utilisation_Res3	0,8543	0,8714	0,8485	0,8690	0,8519	0,8691	0,8596	0,8792
WIP_data_col	64,9142	68,0012	58,7542	61,5321	65,0794	68,2419	59,2003	62,3935
Lab_Flex_WF	3,2074	3,5437	2,9668	3,3022	3,2815	3,5074	2,8780	3,2183
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	236684,64	257281,74	222304,75	245806,39	237610,69	253556,45	208650,12	233028,93

Table 61: Output data model variant P6

Model variant P7 (different service times, high reject probability, arrival rate 19):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	139,0779	141,0710	134,4388	135,8598	139,6145	140,9665	134,8711	136,4332
Queue_time_total	0,0029	0,0316	0,0033	0,0264	0,0032	0,0270	0,0096	0,0273
Utilisation_Res1	0,4985	0,5102	0,5038	0,5118	0,5030	0,5114	0,5188	0,5265
Utilisation_Res2	0,4943	0,5071	0,4925	0,5054	0,4911	0,4991	0,4923	0,5018
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	34,9096	35,7990	33,7963	34,3780	34,8503	35,4273	33,7867	34,4847
Lab_Flex_WF	18,0525	18,5742	18,1199	18,4697	16,6406	16,9265	16,1423	16,5146
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	825141,16	843928,08	824631,84	838356,16	835535,07	848199,21	824725,01	838125,56

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	139,2540	141,4275	134,7909	136,4014	139,6686	141,3413	134,4289	135,9691
Queue_time_total	0,0914	0,1753	0,0840	0,1675	0,1275	0,2092	0,1314	0,2433
Utilisation_Res1	0,5043	0,5150	0,5068	0,5167	0,4991	0,5089	0,5216	0,5290
Utilisation_Res2	0,5030	0,5132	0,5131	0,5236	0,5047	0,5160	0,5024	0,5092
Utilisation_Res3	0,4991	0,5126	0,5022	0,5154	0,5008	0,5112	0,4990	0,5087
WIP_data_col	34,8690	35,5299	33,9386	34,4978	34,9953	35,6578	33,5840	34,2361
Lab_Flex_WF	11,3593	11,6127	11,2992	11,5096	10,9805	11,2084	10,8182	11,0369
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	806633,69	822448,02	797177,80	810670,39	806807,85	822372,15	806887,89	817096,96

Table 62: Output data model variant P7

Model variant P8 (different service times, high reject probability, arrival rate 30):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	143,3686	145,3039	137,8827	139,4186	143,5688	145,7895	138,9025	140,9061
Queue_time_total	3,4300	5,1669	3,5380	5,0614	3,8438	5,3463	4,8447	6,7547
Utilisation_Res1	0,7911	0,8006	0,8006	0,8090	0,8051	0,8182	0,8222	0,8336
Utilisation_Res2	0,7833	0,8004	0,7821	0,7938	0,7830	0,7983	0,7790	0,7943
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	56,5940	57,8774	54,7852	55,6525	57,1098	58,6610	55,0264	56,5055
Lab_Flex_WF	7,2474	7,6766	7,0943	7,4125	6,4243	6,9209	6,2864	6,7770
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	336697,73	353413,89	330455,09	343082,71	328979,26	352095,89	325417,18	347738,34

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	150,7642	154,7910	143,9199	147,0599	150,3000	154,7007	145,2756	147,9182
Queue_time_total	10,8736	14,5514	10,3751	14,0078	10,6993	14,5126	12,2291	14,8578
Utilisation_Res1	0,8034	0,8181	0,8020	0,8135	0,7933	0,8073	0,8231	0,8347
Utilisation_Res2	0,7980	0,8110	0,8087	0,8240	0,8006	0,8175	0,8035	0,8171
Utilisation_Res3	0,7984	0,8159	0,7941	0,8117	0,8000	0,8180	0,8021	0,8160
WIP_data_col	59,2682	61,4281	56,8196	58,6907	59,4157	61,5482	57,5277	58,9170
Lab_Flex_WF	4,2315	4,5312	4,0819	4,4095	4,0831	4,4006	3,9727	4,1943
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	309908,67	329707,14	302350,08	323044,58	307307,78	331384,88	298856,63	316766,90

Table 63: Output data model variant P8

Model variant P9 (different service times, high reject probability, arrival rate 32):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	148,3353	152,3271	144,1498	148,5418	148,4377	151,3386	144,7297	149,0446
Queue_time_total	8,6564	12,6211	10,2949	14,8419	8,7993	11,5107	12,2269	17,0523
Utilisation_Res1	0,8454	0,8573	0,8601	0,8722	0,8559	0,8696	0,8791	0,8951
Utilisation_Res2	0,8411	0,8543	0,8433	0,8545	0,8347	0,8456	0,8360	0,8509
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	62,5055	64,6825	61,2205	63,1680	62,7484	64,6270	61,4026	63,9893
Lab_Flex_WF	5,2151	5,7094	4,8023	5,2020	4,8631	5,2823	4,4035	4,9104
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	242070,78	261167,70	224792,89	243010,16	247662,71	265468,34	227620,95	252158,38

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	163,1092	171,9537	156,6970	163,6625	162,9338	172,8122	156,2394	163,6481
Queue_time_total	23,4972	31,7433	26,1247	34,5732	23,2288	32,7904	26,1700	34,1062
Utilisation_Res1	0,8575	0,8682	0,8608	0,8748	0,8468	0,8587	0,8804	0,8971
Utilisation_Res2	0,8547	0,8669	0,8698	0,8840	0,8557	0,8709	0,8536	0,8723
Utilisation_Res3	0,8495	0,8654	0,8560	0,8720	0,8507	0,8687	0,8503	0,8722
WIP_data_col	68,2735	71,8686	65,9103	69,2893	68,0588	72,3833	65,9537	69,5375
Lab_Flex_WF	3,0734	3,3115	2,7852	3,0745	2,9076	3,2561	2,6923	3,0476
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	222250,07	238957,36	202042,10	222941,05	220033,63	242617,13	204427,65	231971,59

Table 64: Output data model variant P9

Model variant P10 (different service times, low reject probability, arrival rate 19):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,1303	140,8553	134,1393	136,2939	139,1321	140,6372	134,6709	136,3654
Queue_time_total	0,0000	0,0095	0,0003	0,0193	0,0002	0,0142	0,0013	0,0112
Utilisation_Res1	0,4966	0,5062	0,4933	0,5025	0,4855	0,4945	0,4855	0,4967
Utilisation_Res2	0,4948	0,5082	0,4936	0,5031	0,4961	0,5065	0,4960	0,5058
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	34,8766	35,6381	33,3854	34,0210	34,6495	35,3878	33,3872	34,1711
Lab_Flex_WF	17,5368	17,9203	17,6319	17,9672	16,6842	17,0390	16,6170	17,0310
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	829606,49	845506,46	836314,76	850142,95	836526,16	852001,93	835994,81	852191,00

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	139,0021	140,7785	134,8445	136,1812	139,1026	140,4937	134,4984	136,0684
Queue_time_total	0,0509	0,0946	0,0669	0,1378	0,0870	0,1613	0,1108	0,2044
Utilisation_Res1	0,5032	0,5117	0,5050	0,5154	0,5021	0,5123	0,5100	0,5174
Utilisation_Res2	0,4956	0,5067	0,5029	0,5118	0,4963	0,5085	0,4978	0,5093
Utilisation_Res3	0,5004	0,5134	0,5062	0,5163	0,4987	0,5146	0,5037	0,5143
WIP_data_col	34,6059	35,3667	33,7296	34,3194	34,5304	35,4182	33,5259	34,2416
Lab_Flex_WF	11,1982	11,4443	11,0325	11,2427	11,0166	11,3240	10,9417	11,2005
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	813110,76	828112,38	806150,19	819579,81	811627,10	829869,18	809308,25	823639,37

Table 65: Output data model variant P10

Model variant P11 (different service times, low reject probability, arrival rate 30):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	142,7296	144,4747	137,7200	139,4976	141,7958	143,6490	137,3510	139,3899
Queue_time_total	3,1009	4,5130	3,0952	4,4639	2,5725	3,8694	2,7379	4,1678
Utilisation_Res1	0,7810	0,7947	0,7860	0,7977	0,7740	0,7831	0,7764	0,7912
Utilisation_Res2	0,7820	0,7973	0,7832	0,8003	0,7924	0,8049	0,7924	0,8091
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	56,1039	57,4511	54,3226	55,6143	56,2478	57,5627	54,2073	55,8460
Lab_Flex_WF	7,1664	7,6544	6,9465	7,4299	6,7099	7,1406	6,5343	7,1222
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	344010,30	366521,80	339055,25	360390,37	341545,23	358067,91	331690,37	357232,59

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	**UB**	**LB**	**UB**	**LB**	**UB**	**LB**	**UB**
Lead_Time_complete	149,8704	153,2156	143,1866	145,7387	150,7336	154,8216	143,5112	147,1954
Queue_time_total	10,1899	12,8877	9,6241	11,7998	10,8308	14,5355	10,0472	13,6998
Utilisation_Res1	0,8055	0,8192	0,8010	0,8159	0,8009	0,8127	0,8089	0,8185
Utilisation_Res2	0,7891	0,8056	0,7952	0,8129	0,7941	0,8077	0,7946	0,8058
Utilisation_Res3	0,8007	0,8162	0,8009	0,8154	0,7972	0,8150	0,7947	0,8095
WIP_data_col	59,0967	61,0031	56,3161	57,8776	59,2452	61,5939	56,6516	58,3255
Lab_Flex_WF	4,1859	4,5212	4,1163	4,4750	4,1563	4,4778	4,1671	4,4144
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	311709,24	335544,67	308789,55	332582,83	315498,92	335924,89	317394,45	333068,59

Table 66: Output data model variant P11

Model variant P12 (different service times, low reject probability, arrival rate 32):

	ABC-DEF Original		ABC-DEF Parallel		ACE-BDF Original		ACE-BDF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	147,7041	151,2202	141,7398	145,6249	146,6827	150,5330	141,6834	146,0711
Queue_time_total	7,9421	11,3146	7,9909	11,9879	7,0100	10,2902	7,9601	11,9115
Utilisation_Res1	0,8362	0,8500	0,8454	0,8563	0,8250	0,8395	0,8347	0,8441
Utilisation_Res2	0,8390	0,8514	0,8417	0,8568	0,8456	0,8604	0,8490	0,8621
Utilisation_Res3	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
WIP_data_col	62,1855	63,8989	60,0732	62,2724	61,9069	64,2862	60,0858	61,9684
Lab_Flex_WF	5,2796	5,7037	4,9356	5,3882	4,8560	5,3719	4,8471	5,2396
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	252104,43	272385,10	241926,29	261105,52	246946,25	270733,56	243061,08	260777,49

	AD-BC-EF Original		AD-BC-EF Parallel		AC-BD-EF Original		AC-BD-EF Parallel	
	LB	UB	LB	UB	LB	UB	LB	UB
Lead_Time_complete	165,5544	172,9294	152,0907	160,2178	161,8086	169,0938	150,8090	162,3601
Queue_time_total	25,5125	32,5377	20,8654	30,2839	22,0962	28,9215	19,5201	31,2941
Utilisation_Res1	0,8619	0,8737	0,8589	0,8733	0,8599	0,8710	0,8645	0,8758
Utilisation_Res2	0,8504	0,8632	0,8493	0,8644	0,8476	0,8601	0,8438	0,8602
Utilisation_Res3	0,8604	0,8761	0,8557	0,8733	0,8568	0,8741	0,8539	0,8665
WIP_data_col	69,6363	73,1507	64,1179	67,9168	67,9519	71,4662	63,1919	68,6086
Lab_Flex_WF	2,9059	3,1787	2,8809	3,1944	3,0017	3,2880	2,9834	3,3361
Routing_Flex	1,0000	1,0000	2,0000	2,0000	1,0000	1,0000	2,0000	2,0000
Volume_Flex	217789,13	236513,34	217923,90	240850,67	224165,74	243072,36	224931,71	246169,82

Table 67: Output data model variant P12

Appendix G

MV	Resource setup	Lead time	Utilization	WIP	Labour flex	Volume flex
P1	ABC-DEF	-	+	-	-	-
	ACE-BDF	-	+	-	-	-
	AD-BC-EF	-	+	-	-	-
	AC-BD-EF	-	+	-	-	-
P2	ABC-DEF	-	+	-	-	-
	ACE-BDF	-	+	-	-	-
	AD-BC-EF	-	+	-	-	-
	AC-BD-EF	o	+	o	-	-
P3	ABC-DEF	-	+	-	-	-
	ACE-BDF	o	+	o	-	-
	AD-BC-EF	o	+	o	-	-
	AC-BD-EF	o	+	+	-	-
P4	ABC-DEF	-	o	-	o	o
	ACE-BDF	-	o	-	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	o	-	o	o
P5	ABC-DEF	-	o/+	-	-	-
	ACE-BDF	-	o/+	-	o	o
	AD-BC-EF	-	o/+	-	o	o
	AC-BD-EF	-	o/+	-	o	o
P6	ABC-DEF	-	o	-	-	o
	ACE-BDF	-	+	o	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	+	-	-	-
P7	ABC-DEF	-	o	-	o	o
	ACE-BDF	-	o	-	-	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	o	-	o	o
P8	ABC-DEF	-	o	-	o	o
	ACE-BDF	-	o	-	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	o	-	o	o
P9	ABC-DEF	o	o	o	-	o
	ACE-BDF	o	o	o	o	o
	AD-BC-EF	o	o	o	o	o
	AC-BD-EF	o	o	o	o	o
P10	ABC-DEF	-	o	-	o	o
	ACE-BDF	-	o	-	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	o	-	o	o
P11	ABC-DEF	-	o	-	o	o
	ACE-BDF	-	o	-	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	-	o	-	o	o
P12	ABC-DEF	-	o	o	o	o
	ACE-BDF	-	o	o	o	o
	AD-BC-EF	-	o	-	o	o
	AC-BD-EF	o	o	o	o	o

Table 68: Detailed overview of the impact of the parallel tasks rule