Quantification of the implementation of the parallel heuristic

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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 parallel heuristic (Reijers, 2003). 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 parallel 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 parallel 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	Section 2.1 & 2.2 & 3.1 & 3.2
3. Pilot runs	Section 2.3
4. Validation	Section 2.3
5. Design of experiment	Section 4.1 – 4.4
6. Production runs and results	Section 4.5
7. output analysis	Chapter 5 & 6
8. conclusions	Chapter 7

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 objective of this simulation study is:
The quantification of the impact of the implementation of "the parallel redesign heuristic".

Scope and level of detail
To achieve the objective of this project, a balance must be found in the tradeoff 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 modeling the alternatives it must be clear what indicators and measures are going to be used to measure and express the impact of the redesign effort. The result of the preceding literature review 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 four dimensions of performance that have been used can be found in Table 2. A detailed description of the measures can be found in the report of the preceding literature review.

Performance measures			
Time	**Cost**	**External Quality**	**Flexibility**
Lead time	Total utilization	Percentage 0 res available	Labour flexibility WF
Queue time per task	Utilization per res.	Queue length per task	Labour flexibility Res.
Total queue time	Work in progress		Mix flexibility per task
Setup time		**Internal Quality**	Routing flexibility
Service time		Skill variety	Volume flexibility
Wait time		Task identity	

Table 2: Used performance measures

None of the external quality performance measures of the literature review have been used in this simulation project, because the proposed external quality measures are not suitable for usage in the used simulation models. The proposed external quality measures have therefore been replaced by the following performance measures:

- Percentage '0 resources available': This measure reflects the percentage of all cases that finds no available resources when it arrives at a task
- Queue length per task: This indicator measures per task the number of cases in the queue

A new cost measures has also been introduced:

- Work in progress: This measure depicts the number of cases that is in the complete system

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 "Parallel 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 will describe the original situation and model, and explains the associated parameters.

2.1 Original model

The process of the original situation consists of six sequential tasks and can be seen in Figure 1. All tasks are identical and have an exponentially distributed setup time of 2 minutes and an exponentially distributed service time of 40 minutes for all resources. It is assumed that all resources have equal service times. The difference that is caused by the execution of the task by a specialist or a generalist is left out of consideration. The impact of variation in service times will be investigated and described in Chapter 4. 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.

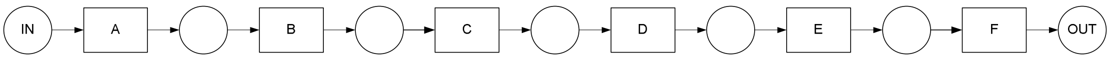

Figure 1: Original situation

As a basis for the comparison with the redesigned situation, a colored Petri net is created in CPN Tools. The main page of the model can be seen in Figure 2 on the next page. 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 will be 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.

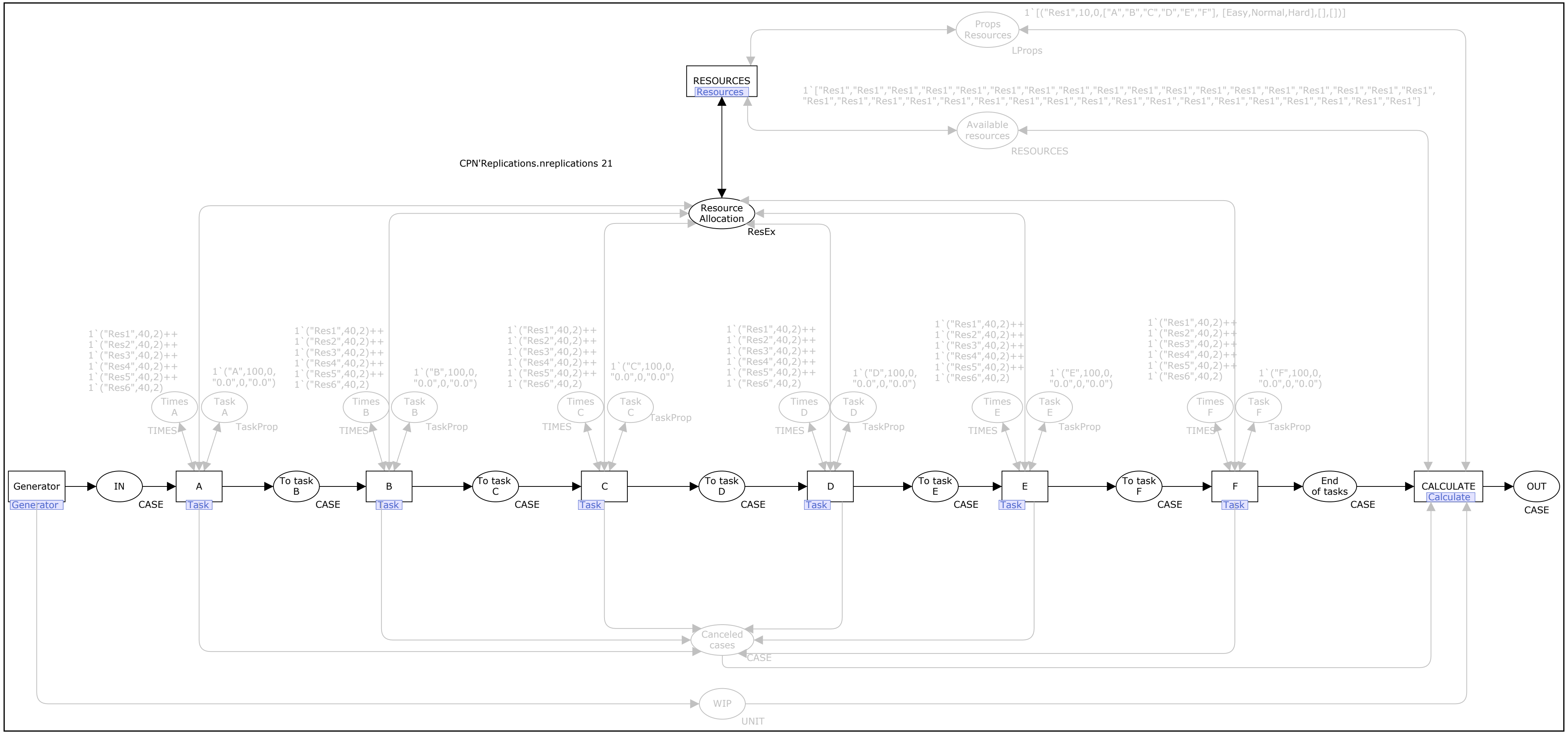

Figure 2: Main page of the original model

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 basic 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 iid Exp(μ_i) random variables
- 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 parallel redesign heuristic to the model of the original situation.

3.1 The parallel heuristic

The complete parallel redesign heuristic is described by Reijers (2003). Berg and Pottjewijd (1997) and Rupp and Russel (1994) also discuss the heuristic in their paper. Van der Aalst and van Hee (2002) refer to parallel routing if more than one task can be carried out at the same time or in any order. Reijers (2003) states that considerable reduction of the lead time may be expected after implementation of the parallel heuristic. As a drawback, Reijers mentions increasing complexity, which may introduce errors or restrict run-time flexibility. Another drawback, also described by van der Aalst (2000), is that applying the heuristic to knock-out processes can have a negative effect on the resource utilization, the lead time and the cost of executing the workflow. This is caused by the fact that cases that are cancelled in one branch claim resource capacity in the other, as they are not cancelled in that branch until synchronization. However, the processes in this study are no knock-out processes.

Van der Aalst (2000) states that putting subsequent knock-out tasks in parallel can only have a considerable positive effect if the following conditions are satisfied:

- Resources from different classes execute the tasks
- The flow times of the parallel sub-processes are of the same order of magnitude
- The reject probabilities are rather small
- There is no overloading of any resource class as a result of putting tasks in parallel
- The time needed to synchronize is limited

Although the tasks in this research project are no knock-out tasks, it has been chosen to use the above mentioned statements as a guide for the setup of the simulation. The parameters and the variations have been chosen so that the above mentioned statements can be investigated. Though, in this study there are no reject probabilities and synchronization time can also be neglected. A detailed explanation of the chosen setup can be found in Section 4.1 and 4.2.

3.2 Redesigned model

The difference between the original model and the redesigned model is that two or more tasks that were sequential in the original model are now put in parallel so they can be executed at the same time. Two alternatives have been modeled and simulated. The alternatives of the redesigned situation can be seen in Figure 3 and Figure 4. The main pages of the simulation models of both alternatives are depicted in Figure 5 and Figure 6. On the main pages of both models, two extra transitions have been added to enable parallel routing. The first transition is the “PAR Split” transition. This transition splits the workflow in two or more branches. The second extra transition is the “PAR Join” transition where the cases from the different branches can wait until all branches are complete in order to synchronize before continuation. The rest of the model and the settings remain the same as in the original situation.

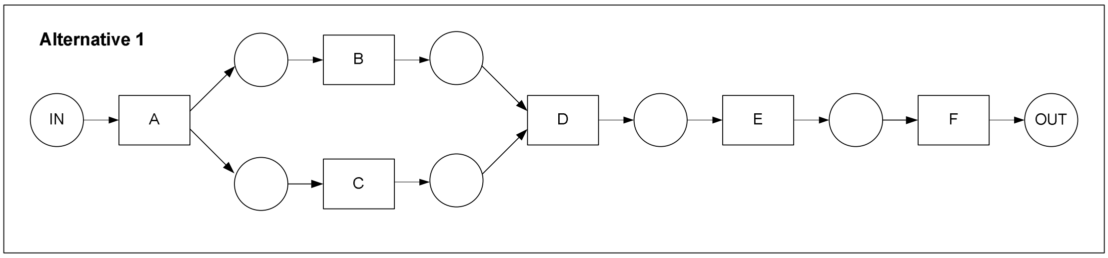

Figure 3: Redesigned situation alternative 1, two tasks parallel

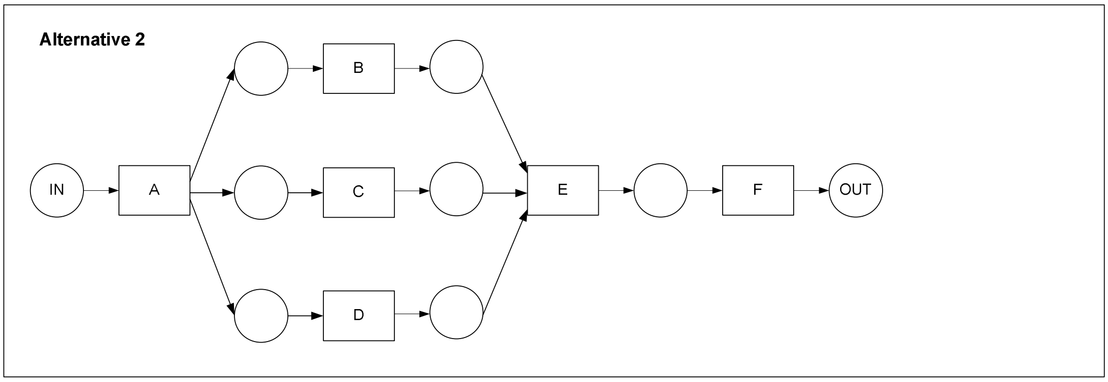

Figure 4: Redesigned situation alternative 2, three tasks parallel

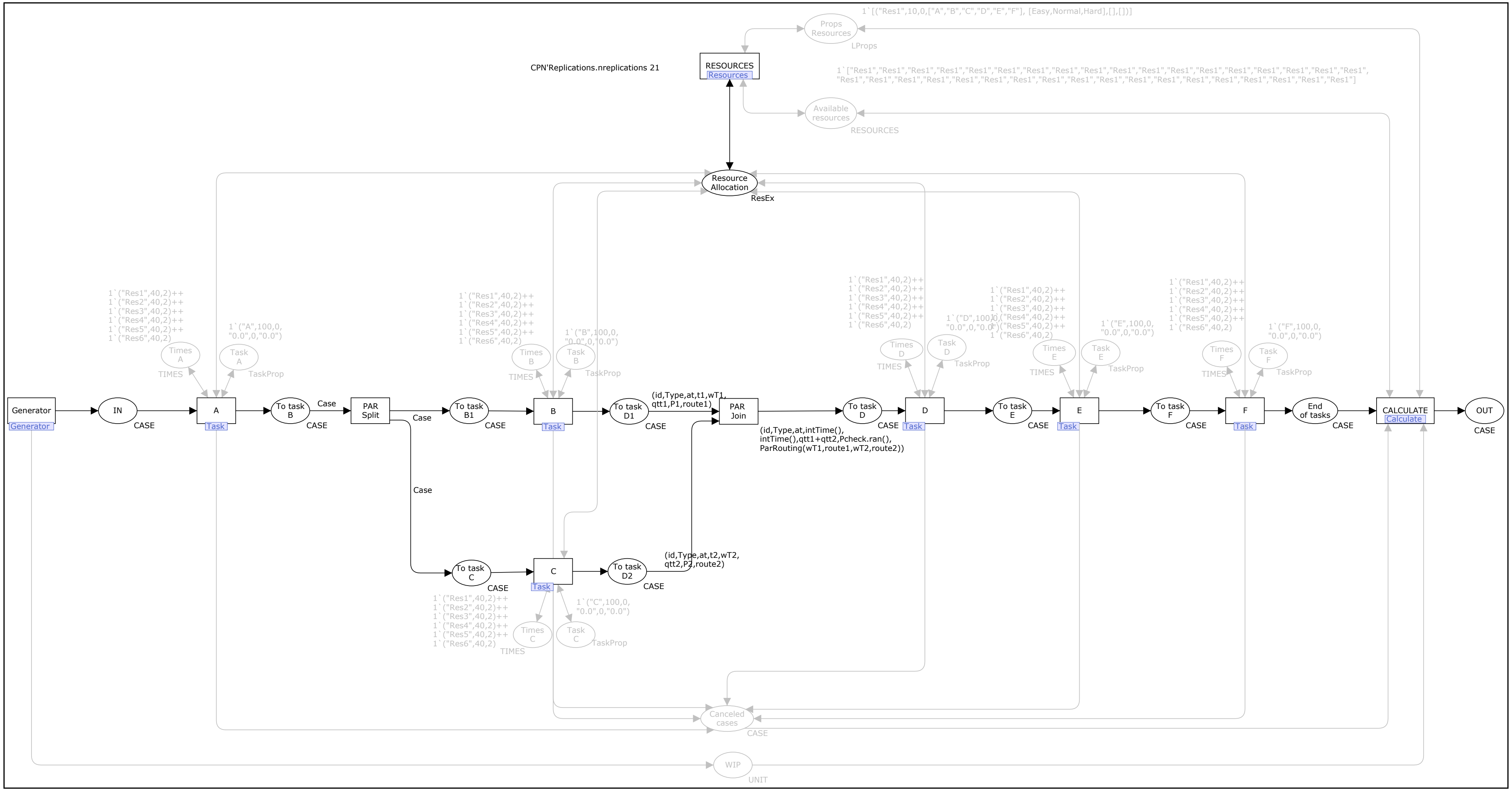

Figure 5: Main page of the 2 task parallel model

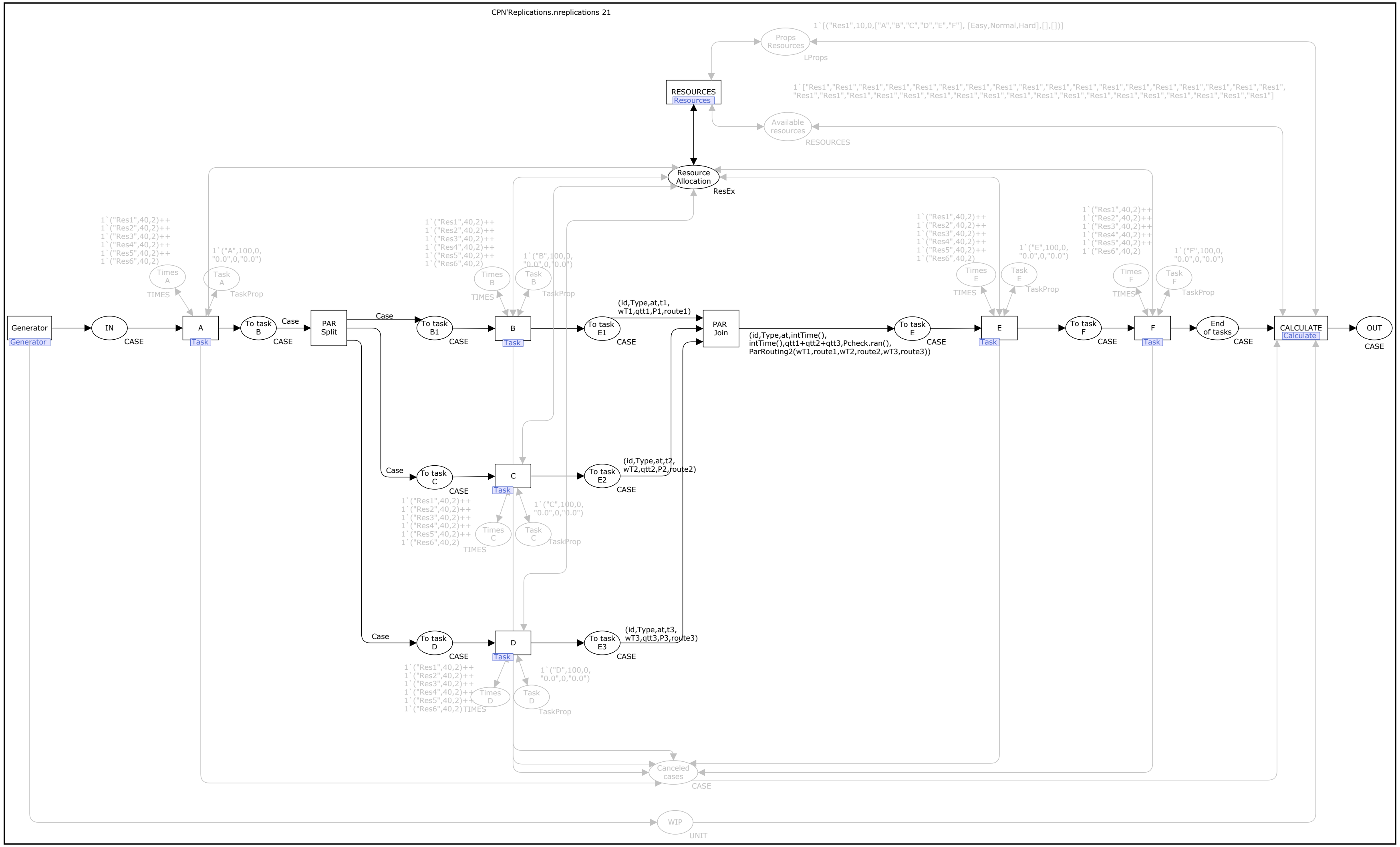

Figure 6: Main page of the 3 task parallel model

4 Experiments

This chapter will describe step 5 of the project plan: the design of the experiments. First it has been decided what variation to use in the models in order to test the statements described in Section 3.1. Next, the warm-up period, the run length and the number of replications have been calculated. This chapter ends with an overview of all the comparisons in the model variants.

4.1 Simulation

In order to test the statements of Van der Aalst (2000), it was necessary to simulate the models of the different alternatives and use different setups and parameters. Different variations are needed to reject or support the statements and to find out in what situations it is advisable to apply the parallel heuristic. In total three kinds of variations have been inserted in the simulations:

- Variations in the arrival rate
- Variations in service times
- Variations in resource classes and allocation

In all alternatives and the model of the original situation, all variants and possible combinations of variants have been tested. The next three sub-sections give an overview of the introduced variations

Variations in the arrival rate

The first variation is a variation in arrival rate. This variation is chosen to see whether the implementation of the heuristic has the same impact on a process with a different arrival rate. The utilization of the resources is directly related to the mean value of the inter-arrival time of the cases. Table 6 gives an overview of the different mean values of the inter-arrival times and the related utilizations.

Inter-arrival time	Utilization	Inter-arrival time	Utilization
6.0	99.41 %	9.0	78.40 %
6.5	99.38 %	10.0	68.66 %
6.7	99.10 %	11.0	63.70 %
6.8	99.00 %	12.0	57.69 %
6.9	98.76 %	13.0	53.41 %
7.0	98.08 %	14.0	49.02 %
8.0	86.41 %	15.0	46.56 %

Table 6: Inter-arrival time - utilization combinations

When the mean value of the inter-arrival time is smaller than 6.5 minutes, the system will overload. This will violate statement 4 in Section 3.1.

To check the impact of different arrival rates, three arrival processes have been chosen to model:

- Poisson process with exponentially distributed inter-arrival times with a mean value of 7 minutes. This value is chosen in order to investigate the system and the differences after redesign at a high utilization rate of the resources. With this mean value, the utilization of the resources is approximately 97-98%.
- Poisson process with exponentially distributed inter-arrival times with a mean value of 8 minutes. 8 minutes is chosen in order to analyze the system at a utilization of approximately 86-87%.
- Poisson process with exponentially distributed inter-arrival times with a mean value of 14 minutes. This process has been chosen in order to investigate the impact in a system with a low utilization (50%).

Variations in service times
The second type of variation is diversity in service times of the different tasks. This variation is needed to test the second statement: "The flow times of the parallel sub-processes are of the same order of magnitude". It has been chosen to model two variants. The variants can be seen in Table 7.

Exponential Service times A-B-C-D-E-F						
Variants	A	B	C	D	E	F
1. Service times equal	40	40	40	40	40	40
2. Service times completely different	40	78	2	40	40	40

Table 7: Service time variants

As stated before, the difference in skills and service times between specialists and generalists is not considered in this study.

Variations in resource classes and allocation
The last type of variation is variation in the resource classes and the allocation of resources. This diversity has been implemented in order to test the first statement; "Resources from different classes execute the tasks". Therefore different resource classes have been defined and a varying number of resource classes per model have been introduced. The categorization into the different resource classes for the two alternatives and the executable tasks per resource class are shown in Table 8 and Table 9.

Alternative 1: 2 Tasks parallel							
# Classes	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**	
2 Resource classes	ABC	DEF					B and C in same class
	ACE	BDF					B and C in different class
3 Resource classes	AB	CE	DF				B and C in different class
	AD	BC	EF				B and C in same class

Table 8: Resource classes alternative 1

Alternative 2: 3 Tasks parallel							
# Classes	**Class 1**	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**	
2 Resource classes	AEF	BCD					B,C,D in same class
	ABC	DEF					B,C,D in different class
3 Resource classes	AB	CE	DF				B,C,D in different class
	AD	BC	EF				B,C,D in same class
	AB	CD	EF				B,C,D in same class
	AC	BD	EF				B,C,D in same class

Table 9: Resource classes alternative 2

The division of the tasks 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 of the same magnitude.

4.2 Model variants

A Combination of the three variations of section 4.1 leads to 6 different model variants. The variants are summed up in Table 10.

Model variants			
	Arrival process	Service times (A-F)	Resources classes
Model variant 1	Exponential (7)	40-40-40-40-40-40	All
Model variant 2	Exponential (8)	40-40-40-40-40-40	All
Model variant 3	Exponential (14)	40-40-40-40-40-40	All
Model variant 4	Exponential (7)	40-78-2-40-40-40	All
Model variant 5	Exponential (8)	40-78-2-40-40-40	All
Model variant 6	Exponential (14)	40-78-2-40-40-40	All

Table 10: Model variants

4.2.1 Model variant 1 & 2 & 3

The only difference between model variant 1, 2 and 3 is the mean value of the inter-arrival time of the cases. The service times are equal in all variants and all resource classes are modelled and simulated. This leads to the resource classes of Table 11 and Table 12. The numbers behind the executable tasks represents the number of resources per resource class.

Alternative 1: 2 Tasks parallel						
# Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
2 Resource classes	ABC (18)	DEF (18)				
	ACE (18)	BDF (18)				
3 Resource classes	AB (12)	CE (12)	DF (12)			
	AD (12)	BC (12)	EF (12)			

Table 11: Resource classes of model variant 1 & 2 & 3 for alternative 1 (2 tasks parallel)

Alternative 2: 3 Tasks parallel						
# Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
2 Resource classes	AEF (18)	BCD (18)				
	ABC (18)	DEF (18)				
3 Resource classes	AB (12)	CE (12)	DF (12)			
	AD (12)	BC (12)	EF (12)			
	AB (12)	CD (12)	EF (12)			
	AC (12)	BD (12)	EF (12)			

Table 12: Resource classes of model variant 1 & 2 & 3 for alternative 2 (3 tasks parallel)

4.2.2 Model variant 4 & 5 & 6

Again, variant 4, 5 and 6 only differ in arrival process. The service times in these variants are completely different for the parallel tasks. All resource classes are modelled. Table 13 and Table 14 show the resource classes and the number of resources per class for both alternatives for model variant 4, 5 and 6. The number of resources per class has been adapted in order to keep a constant utilization for all resource classes.

Alternative 1: 2 Tasks parallel						
# Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
2 Resource classes	ABC (18)	DEF (18)				
	ACE (13)	BDF (23)				
3 Resource classes	AB (17)	CE (7)	DF (12)			
	AD (12)	BC (12)	EF (12)			

Table 13: Resource classes of model variant 4 & 5 & 6 for alternative 1 (2 tasks parallel)

Alternative 2: 3 Tasks parallel						
# Classes	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
2 Resource classes	AEF (18)	BCD (18)				
	ABC (18)	DEF (18)				
3 Resource classes	AB (17)	CE (7)	DF (12)			
	AD (12)	BC (12)	EF (12)			
	AB (17)	CD (7)	EF (12)			
	AC (7)	BD (17)	EF (12)			

Table 14: Resource classes of model variant 4 & 5 & 6 for alternative 2 (3 tasks parallel)

4.3 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 7. 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).

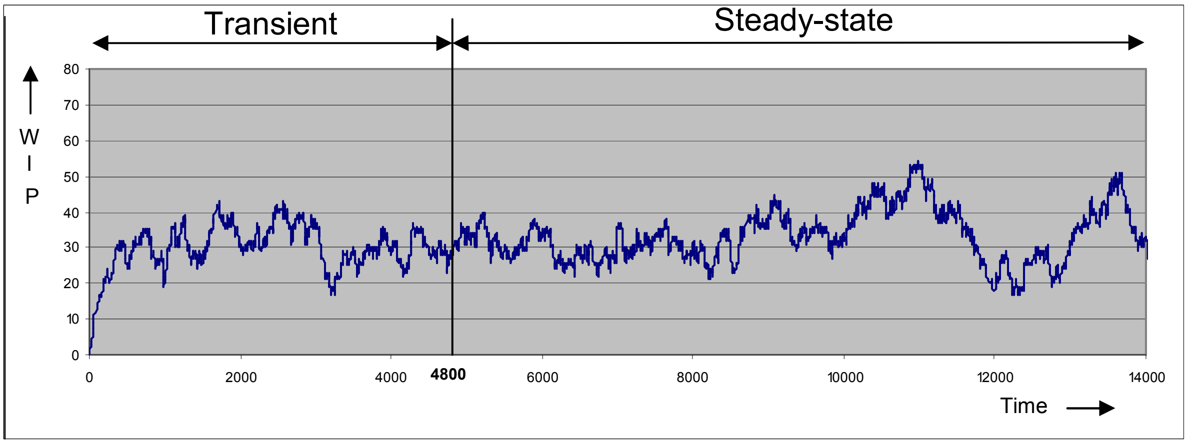

Figure 7: Example of the warm-up period for one of the replications

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).

4.4 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 8.

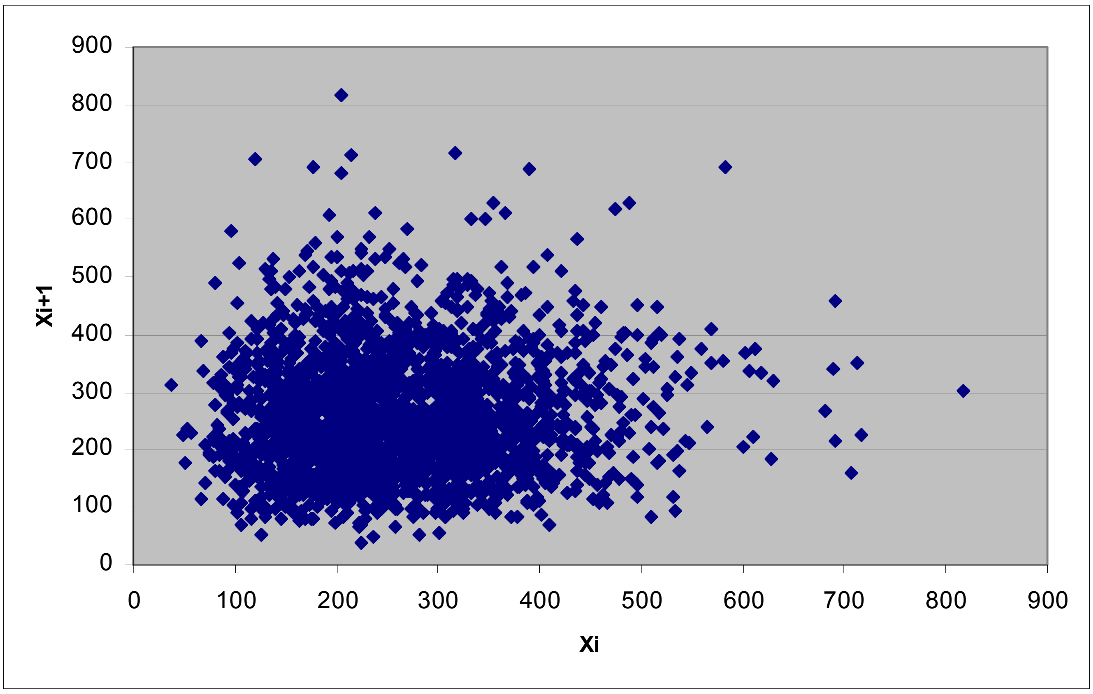

Figure 8: Scatter plot for lead time, run length = 10 weeks

From Figure 8 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.

4.5 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 modeler 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 15: 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.

4.6 Simulation results

The results of the simulation of the different model variants can be found in the excel sheets. Table 16 shows what setups have been used in the different comparisons.

	Original vs. alternative 1	Original vs. alternative 2
ABC-DEF	√	√
ACE-BDF	√	
AEF-BCD		√
AB-CE-DF	√	√
AD-BC-EF	√	√
AB-CD-EF		√
AC-BD-EF		√

Table 16: Comparisons setups

5 Output analysis

This chapter will describe the analysis of the output data. First, the comparisons and the procedure for the calculations are described. Then the outputs of the six model variants are separately analyzed and compared to each other and sub-conclusions are drawn for every variant. The final conclusions can be found in Chapter 7. Chapter 6 describes the setups and analyses of the additional measurements.

5.1 Comparisons

To test the statements, named in section 3.1, different setups and variants have been compared and analyzed. This section describes what output has been compared, to get to the final conclusions. An extra statement (statement 3) has been added in order to investigate the impact of a varying arrival rate.

Statement 1:
To test statement 1 (“Resources from different classes should execute the tasks”) different setups within the model variants have been investigated and compared. Setups with tasks that require resources from the same resource class have been compared to setups containing parallel tasks that require resources from differing resource classes. The comparisons for every model variant are:

Alternative 1:
- ABC-DEF vs. ACE-BDF
- AB-CE-DF vs. AD-BC-EF

Alternative 2:
- ABC-DEF vs. AEF-BCD
- AB-CE-DF vs. AD-BC-EF vs. AB-CD-EF vs. AC-BD-EF

Statement 2:
In order to reject or support statement 2 (“The flow times of the parallel sub-processes must be of the same order of magnitude”), data has been gathered by comparing different model variants. As the setups within the model variants are equal, it is easy to compare the model variants. The comparisons are:
- Model variant 1 vs. model variant 4
- Model variant 2 vs. model variant 5
- Model variant 3 vs. model variant 6

Statement 3: A varying arrival rate leads to different results
To test the impact of different arrival rates, model variants with differing arrival rates have been compared and statement 3 is tested. The following comparisons have been made:
- Model variant 1 vs. model variant 2 vs. model variant 3
- Model variant 4 vs. model variant 5 vs. model variant 6

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 parallel 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 a 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_o is rejected (and the difference in means is significantly different from 0) when $|t_o|> t_{f,\alpha/2}$, 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). 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 - α/c), so that the overall confidence level associated with all intervals' covering their targets will be at least (1 – α) (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 alternative 1, the differences of 4 setups have been compared. Therefore, the α of the separate comparisons is 0.05 / 4 = 0.0125.

For alternative 2, an α of 0.05 / 6 = 0.0083 has been used.

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
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
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 9. From this picture it can be seen that the difference between setup AD-BC-EF and AB-CE-DF for this measure is not significant, as the confidence intervals overlap. The differences between all other setups are significant.

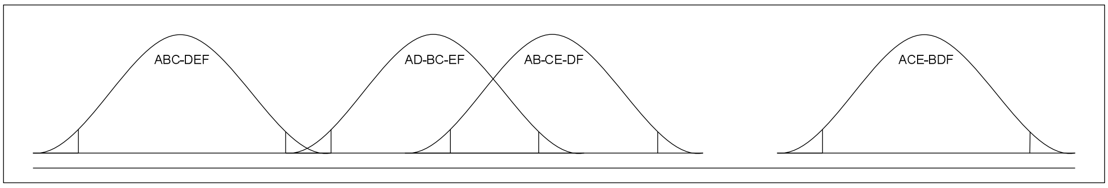

Figure 9: Example of s setup comparison

As confidence levels of 98.75% 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 10 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.

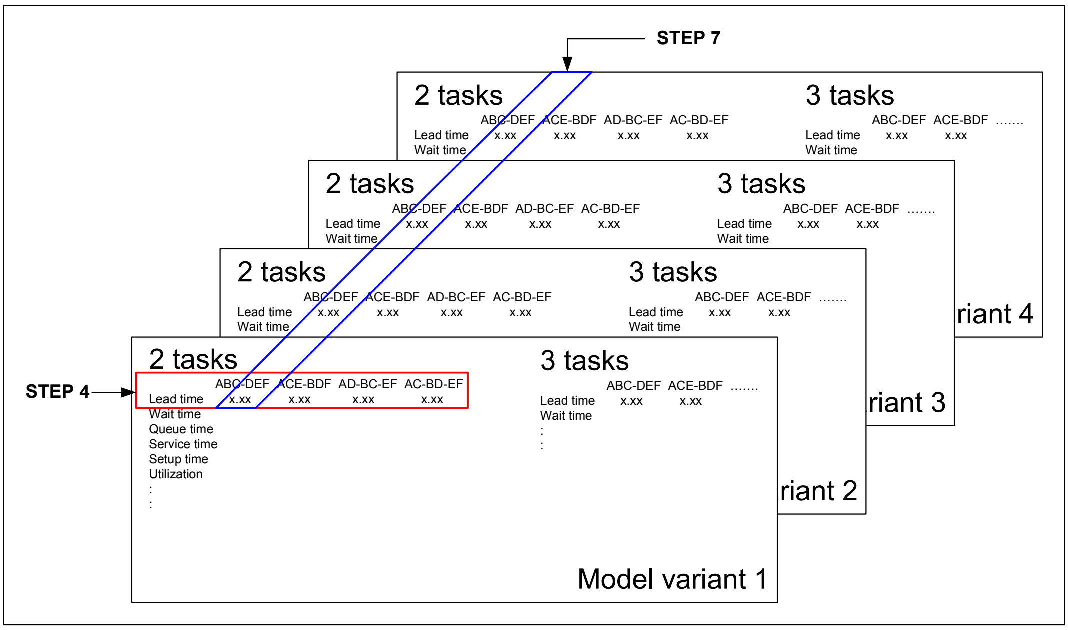

Figure 10: Comparisons in and between model variants

The remainder of this chapter is organized as follows. The following Sections 5.3 to 5.8 explain the analyses of every separate model variant. This analysis is step 4 of the above sketched analysis plan, and has been performed in order to test statement 1: "Resources from different classes should execute the tasks". Within a model variant it has been assessed whether a measure changes significantly after the redesigning effort and whether a difference in measure is significantly different in one setup compared to another setup. Based on these analyses, a conclusion has been drawn about statement 1. Then Section 5.9 describes the results of the comparisons between model variants. The different model variants have been compared in order to test statement 2: "The flow times of the parallel sub-processes must be of the same order of magnitude", and statement 3: "A varying arrival rate leads to different results". This analysis equals step 7 of the above explained analysis plan. Eventually conclusions have been drawn, based on these comparisons between the model variants.

5.3 Analysis model variant 1 (Exp (7) 40-40)

To investigate what measures change significantly and should be analyzed, the analysis of model variant 1 started with the hypothesis tests. The results of the significance tests for all measures can be found in the tables of Appendix A. From these tables it appeared that for the following measures H_0 is rejected, which means that they change significantly:

Measures with significant differences model variant 1		
Lead time	Queue time total	Queue length C
Queue time C	Wait time	Queue length E
Queue time E	Percentage 0 resources available	WIP

Table 17: Significantly changed performance measures model variant 1

To reduce the amount of data to process, Queue times and Queue lengths have been omitted as both types of measures are very specific for every task. Routing flexibility increase is for every model variant the same, since the original model has 1 route, alternative 1 has 2 routes and alternative 2 has 6 routes.

The measures that have been analyzed are:

- Lead time
- Queue time total
- Wait time
- Percentage 0 resources available
- WIP

5.3.1 Alternative 1.1

The confidence intervals of the relative difference for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 18. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0. Per setup a lower bound (LB) and an upper bound (UB) of the confidence interval have been calculated.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-56,6074	-0,7489	-30,4932	2,5856	-27,8097	3,3772	-42,1811	-2,1417
Q time total	-51,9088	60,1461	-27,4014	53,1192	-16,1806	58,1221	-20,1814	44,3598
Wait time	39,8695	40,8660	82,3841	131,6085	91,6613	168,8400	40,0204	40,9663
% 0 res avail	-2,0607	6,0076	-4,6427	1,8479	-0,3825	5,1067	0,5225	6,6239
WIP	-61,1404	3,0719	-40,1491	11,8198	-34,2636	8,5609	-44,2100	-2,4527

Table 18: Confidence intervals for the relative differences in means alternative 1.1

A negative value means that the value of that measure is lower in the redesigned, parallel system. A positive value means the opposite. Whether a lower or higher value is better depends on the measure. Note that all differences are given in % except for the wait time, these are shown in minutes, because the wait time in the original model is 0 minutes.

Observations
From Table 18 the following observations can be made:

- Lead time: For lead time, the differences of AD-BC-EF and ABC-DEF are negative and are the only significant differences. However, they do not significantly differ from the differences of the other setups.
- Queue time total: The differences of all setups appear to be insignificant. Therefore there is also no significant difference between the setups.
- Wait time: All wait time differences are significant. The differences of ABC-DEF and AD-BC-EF are significantly smaller compared to the differences in wait time of ACE-BDF and AB-CE-DF.
- 'Percentage 0 resources available': For this measure, the differences of all setups, except AD-BC-EF, are insignificant. Also no significant difference between the setups can be found.
- WIP: Only the difference of AD-BC-EF appears to be significant. It does not differ significantly from the other setups, though.

5.3.2 Alternative 1.2

The confidence intervals for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in Table 19. The fields that are marked red contain a difference that is not significant. This can be seen from the confidence intervals, as these intervals include 0. The Welch confidence intervals have been calculated with the formula of Section 5.2.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-52,9486	12,8380	-46,6032	-3,2981	-42,4041	0,4982
Q time total	-0,5756	136,9530	6,0476	117,8425	-13,3246	86,6792
Wait time	101,7787	178,8347	59,7133	60,9657	133,6143	256,4852
% 0 res avail	4,4794	13,6089	4,6282	11,6244	0,1103	6,8879
WIP	-55,2734	14,7399	-47,7783	-2,4654	-44,5780	0,4714

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-57,7909	-12,4057	-44,1391	5,7001	-41,9764	2,4945
Q time total	-22,7300	82,6450	16,8388	130,1865	15,9714	126,5459
Wait time	106,9360	212,3728	136,0399	215,8753	117,1176	286,9706
% 0 res avail	-0,1165	6,6835	3,8642	10,0664	-1,6861	5,1351
WIP	-59,3639	-12,3582	-44,2002	7,1918	-42,7664	2,6143

Table 19: Confidence intervals for the relative differences in means alternative 1.2

Note that all differences are given in % except for the wait time, these are shown in minutes.

Observations
From Table 19 the following observations can be made:

- Lead time: The differences of AEF-BCD and AD-BC-EF are significant. There is no significant difference between the differences of the setups.
- Queue time total: The differences in queue times of AEF-BCD, AB-CD-EF and AC-BD-EF are significant. There are no significant differences between the setups.

- Wait time: All differences in wait time are positive and significant. Only the wait time of setup AEF-BCD is significantly lower than that of the other setups.
- 'Percentage 0 resources available': The differences of both 2 class setups are significant. Of the 3 class setups, AB-CE-DF and AB-CD-EF have significant differences in this measure. There is no significant difference between the setups.
- WIP: For WIP the same setups as for lead time have significant differences. The differences between the setups are not significant.

5.3.3 Conclusions model variant 1

For alternative 1, setup ABC-DEF and AD-BC-EF are the only setups with significant differences on lead time, % 0 resources available and/or WIP compared to the other setups. There are no significant differences between the setups except for wait time. Here the differences of ABC-DEF and AD-BC-EF are significantly lower compared to the other setups. So, putting two tasks in parallel only has a significant impact on the setups where B and C share a resource class.

For alternative 2, no significant differences exist between the setups, except for wait time. Here the setups with parallel tasks that require resources from the same class have significantly lower wait times. For lead time and WIP, Putting three tasks in parallel only decreases these measures in setups where the parallel tasks require resources from the same resource class. The measure % 0 resources available is significant in 4 of the 6 setups.

5.4 *Analysis model variant 2 (Exp (8) 40-40)*

The analysis of the data of model variant 2 also started with the hypothesis tests. The results of the significance test are depicted in the tables of Appendix B. From the results of these hypothesis tests in general it can be concluded that only the following performance measures change significantly in the redesign of model variant 2:

Measures with significant differences model variant 2		
Lead time	Queue time F	Queue length C
Queue time B	Queue time total	Queue length D
Queue time C	Wait time	Queue length E
Queue time D	Percentage 0 resources available	Queue length F
Queue time E	Queue length B	WIP

Table 20: Significantly changed performance measures model variant 2

The measures indicated in red have again been omitted.

5.4.1 Alternative 2.1

The confidence intervals for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 21. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-16,3504	-8,0533	-15,2739	-8,6078	-16,4177	-5,3804	-17,7172	-2,8980
Q time total	-15,2230	37,7460	-19,9131	21,0429	-13,2966	39,1758	-4,9691	58,7116
Wait time	39,9626	40,7615	42,2211	43,7968	44,2754	49,3464	39,6432	40,6136
% 0 res avail	-7,5797	6,7109	-10,0334	1,3931	-4,4617	6,8726	-2,8069	12,3197
WIP	-17,6315	-8,0294	-16,4140	-8,4153	-17,3368	-4,6189	-19,5553	-1,8863

Table 21: Confidence intervals for the relative differences in means alternative 2.1

Note that all differences are given in % except for the wait time, these are shown in minutes.

Observations
From Table 21 the following observations can be made:

- Lead time: All differences in lead time are negative and significant. There is no significant difference between the differences of the setups.
- Queue time total: None of the differences for this measure is significant.
- Wait time: Obviously all wait time differences are significant. The setups, in which the parallel tasks share a resource class, (ABC-DEF and AD-BC-EF) have significantly lower waiting times.
- 'Percentage 0 resources available': none of the differences in alternative 1 are significant.
- WIP: All differences are significant for this measure. However no significant differences are found between the setups.

5.4.2 Alternative 2.2

The confidence intervals for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in Table 22. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-26,4431	-17,8058	-24,6754	-15,4923	-28,0205	-16,7975
Q time total	7,5456	76,3803	53,5470	130,2570	0,9578	60,4971
Wait time	62,7393	65,3863	59,9502	60,9149	66,8829	75,1943
% 0 res avail	-3,4044	14,3112	9,7840	25,3757	-9,9523	3,8412
WIP	-27,3653	-16,7332	-26,5007	-14,6703	-29,6675	-16,3329

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-29,1132	-14,8124	-28,3273	-17,5243	-31,9757	-20,2630
Q time total	15,1323	78,7897	11,2455	68,3111	-8,0849	43,6580
Wait time	66,3824	71,6834	66,4672	72,6188	65,5539	70,4206
% 0 res avail	-0,5128	15,3970	3,6417	15,9963	-7,3991	5,7066
WIP	-30,4492	-13,3435	-29,0904	-16,1889	-33,7981	-20,0930

Table 22: Confidence intervals for the relative differences in means alternative 2.2

Note that all differences are given in % except for the wait time, these are shown in minutes.

Observations
From Table 22 the following observations can be made:

- Lead time: All differences in lead time are negative and significant. None of the differences between the setups are significant.
- Queue time total: AC-BD-EF is the only setup with an insignificant difference in queue time. All other setups have significant differences. The differences between the 2 class setups as well as the differences between the 3 class models do not differ significantly.
- Wait time: All setups have significantly increasing wait times. The wait time of AEF-BCD is significantly higher than that of ABC-DEF. The differences between the 3 class setups are not significant.

- 'Percentage 0 resources available': For this measure only AEF-BCD and AB-CD-EF show significant differences. There are no significant differences between the separate setups.
- WIP: All WIP differences are negative and significant. There is no significant difference between the setups for this measure.

5.4.3 Conclusions model variant 2

In this model variant, putting two tasks in parallel only has a significant effect on the lead time, wait time and the WIP. The lead time and the WIP decrease for every setup and the wait time increases. No significant differences can be found between the setups for lead time and WIP. It is suggested to investigate what the impact of the parallel heuristic is on a model with parallel tasks that have slightly differing service times. This will be analyzed later.

In alternative 2, putting three tasks in parallel has a significant positive effect on the lead time and the WIP, as these measures decrease for all setups. The wait time increases significantly for all setups. The redesign has a significant negative effect on '% 0 resources available' for AEF-BCD and AB-CD-EF, because the values for this measure increase.

5.5 Analysis model variant 3 (Exp (14) 40-40)

This sub-section describes the output analysis for model variant 3. The first step was the hypothesis testing. The results of the hypothesis test are listed in the tables of Appendix C. The significantly changed performance measures are depicted in Table 23.

Measures with significant differences model variant 3		
Lead time	Queue time total	Queue length C
Queue time A	Wait time	Queue length D
Queue time B	Percentage 0 resources available	WIP
Queue time C	Queue length A	Lab flex WF
Queue time D	Queue length B	

Table 23: Significantly changed performance measures model variant 3

5.5.1 Alternative 3.1

The confidence intervals for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 24 . The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	**UB (%)**	**LB (%)**	**UB (%)**	**LB (%)**	**UB (%)**	**LB (%)**	**UB (%)**
Lead time	-9,6458	-8,0621	-9,1517	-7,5340	-8,7928	-7,3049	-9,2747	-7,6103
Q time total	20,5443	422,0613	-55,2783	98,3823	-4,0191	111,0845	39,6042	183,1509
Wait time	39,4881	40,8440	39,5850	41,1104	39,5022	40,7854	39,5776	40,8101
% 0 res avail	41,9569	161,8643	-23,7053	55,5374	-0,2289	37,4480	26,4940	72,0540
WIP	-11,2706	-7,0063	-11,6465	-6,8080	-9,4857	-3,8512	-11,1137	-6,8522
Lab flex WF	-3,7216	1,5170	-9,1517	-7,5340	-4,9377	1,1712	-3,9487	0,8584

Table 24: Confidence intervals for the relative differences in means alternative 3.1

From Table 24 the following observations can be made:

- Lead time: All differences in lead time are significant and negative. No significant differences can be found between the different setups.
- Queue time total: Only ABC-DEF and AD-BC-EF change significantly. There are no significant differences between the different setups.

- Wait time: All differences are significant and positive. This is obvious since no wait time occurs in the original situation. No significant differences exist between the different setups.
- 'Percentage 0 resources available': Only the differences of ABC-DEF and AD-BC-EF are significant. These are both setups where B and C share a resource class. Both differences are positive, which means worse. The difference of ABC-DEF is significantly higher than that of AB-CE-DF.
- WIP: For WIP, all differences between the original situation and the parallel situation are significant and negative. No significant differences exist between the setups.
- Labour flexibility WF: Here only the difference of ACE-BDF is significant and negative. The labour flexibility of this setup decreases significantly more than that of the other setups.

5.5.2 Alternative 3.2

The confidence intervals of the relative difference for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in Table 25. The fields that are marked red contain a difference that is not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	**UB (%)**	**LB (%)**	**UB (%)**	**LB (%)**	**UB (%)**
Lead time	-21,0334791	-19,5233	-21,1628	-19,5731	-20,9073	-19,2397
Q time total	130,3255422	476,769	579,9475	1052,318	-13,8736	153,6487
Wait time	59,51983134	61,01711	59,14045	60,23057	59,04217	60,53582
% 0 res avail	66,56464927	196,0597	274,9787	424,6054	-19,2631	35,91606
WIP	-22,5300537	-18,1256	-23,0625	-18,1792	-22,7131	-17,7871
Lab flex WF	-3,58269006	2,120501	-6,39563	-0,9459	-2,0526	3,512327

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	**UB (%)**	**LB (%)**	**UB (%)**	**LB (%)**	**UB (%)**
Lead time	-21,1325	-19,4409	-20,587	-19,2624	-20,8256	-19,0947
Q time total	44,96851	247,3624	73,31597	203,3892	64,4754	197,1077
Wait time	59,01351	60,50477	59,39696	60,92847	59,28168	60,85621
% 0 res avail	24,02369	75,24399	35,38921	87,94342	26,85032	81,41971
WIP	-22,6112	-18,8567	-21,2882	-16,9156	-22,9858	-17,2781
Lab flex WF	-3,78209	1,015428	-4,96051	0,671545	-5,82504	0,738328

Table 25: Confidence intervals for the relative differences in means alternative 3.2

Observations

From Table 25 the following observations can be made:

- Lead time: The lead time of all 6 setups changes significantly and all differences are negative. No significant differences can be found between the differences of the different setups.
- Queue time total: The queue time total of all setups, except AB-CE-DF, increases significantly. The difference in queue time total of AEF-BCD is significantly higher compared to ABC-DEF. The differences of the 3 class setups do not differ significantly from each other.
- Wait time: Also for this alternative, all differences in wait time are positive and significant. There are no differences between the different setups.
- 'Percentage 0 resources available': The differences of all setups, except AB-CE-DF are significant and positive. The difference of the setup AEF-BCD is higher and differs significantly from the other 2 class setup (ABC-DEF).
- WIP: All differences in WIP are significant and negative. None of the differences between the setups is significant.

- Labour flexibility WF: For this measure, only the difference of AEF-BCD is significant. None of the setups has a significant difference, compared to the other setups.

5.5.3 Conclusions model variant 3

For alternative 1, the redesign effort has a positive effect on the lead time and the WIP level of all setups, as both measures decrease for all setups. It also has a negative effect on the wait time for all setups and on the measure '% 0 resources available' for both setups, in which parallel tasks share a resource class. Labour flexibility WF only decreases significantly for ACE-BDF.

For alternative 2, putting three tasks in parallel has a significant positive effect on the lead time and WIP of all setups, with no significant differences between the setups. The wait time increases for all setups and the '% 0 resources available' also increase for almost all setups.

5.6 Analysis model variant 4 (Exp (7) 78-2)

The output analysis of model variant 4 also started with the hypothesis tests to find out what performance measures change significantly. The results of the hypothesis tests for this model variant can be found in the tables of Appendix D. The significantly changed performance measures can be found in Table 26.

Measures with significant differences model variant 4		
Lead time	Utilization all resources	Queue length C
Queue time B	Utilization resource A	Queue length D
Queue time C	Utilization resource B	WIP
Queue time D	Utilization resource C	Lab flex WF
Queue time total	Percentage 0 resources available	Volume flexibility
Wait time	Queue length B	

Table 26: Significantly changed performance measures model variant 4

5.6.1 Alternative 4.1

The confidence intervals for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 27. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-46,7560	-0,0801	-38,4215	14,1357	-31,8516	7,2149	-45,0362	-0,2052
Q time total	-29,5456	53,9484	-39,1077	29,2485	-14,3292	52,9280	-15,7455	53,1119
Wait time	74,9487	77,1748	194,0192	319,9311	190,1036	326,8405	74,8203	76,4363
Utilization	-0,3793	1,2284	-1,4410	0,5716	-0,1380	0,9994	0,4779	2,3016
% 0 res avail	-0,7823	6,2561	-5,7124	-1,4427	0,1803	4,6213	2,7536	8,9170
WIP	-47,9882	0,4407	-40,1412	13,9017	-32,5106	7,3260	-42,7826	4,4132
Lab flex WF	-35,1193	16,3235	-7,5944	31,4306	-23,3297	9,1827	-49,8949	-1,9268
Volume flex	-36,8040	11,3658	-11,7345	20,9280	-22,3928	3,0930	-47,0646	-9,7734

Table 27: Confidence intervals for the relative differences in means alternative 4.1

Observations

From Table 27 the following observations can be made:

- Lead time: The differences in lead time are only significant for setups ABC-DEF and AD-BC-EF. There are no significant differences between the setups.
- Queue time total: All differences in queue time total are insignificant.

- Wait time: All wait time difference are significant and positive. The differences in wait times of the setups ABC-DEF and AD-BC-EF are significantly lower compared to the others.
- Utilization all resources: The difference of AD-BC-EF is the only significant difference. The difference is not high enough to differ significantly from the other setups.
- 'Percentage 0 resource available': All setups, except ABC-DEF have significant differences for this measure. ACE-BDF changes significantly more than ABC-DEF.
- WIP: None of the differences in WIP is significant.
- Lab flex WF: only the difference of AD-BC-EF is significant. No significant differences between the setups can be found.
- Volume flexibility: Again, only AD-BC-EF has a significant difference. As with the former flexibility measure, none of the differences between the setups is significant.

5.6.2 Alternative 4.2

The confidence intervals for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in Table 28. The fields that are marked red contain a difference that is not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-54,4020	-1,6239	-62,6906	-0,9423	-23,3404	25,0857
Q time total	-11,0016	102,3266	-8,7656	91,3283	54,3220	169,4219
Wait time	101,7787	178,8347	88,7385	89,9220	294,1370	486,2389
Utilization	-0,0586	1,9284	0,2505	1,8845	-0,2035	0,8656
% 0 res avail	3,2801	12,6508	7,9691	15,3459	0,2519	4,5189
WIP	-55,2637	-0,8818	-65,3604	-1,0710	-23,6057	25,8980
Lab flex WF	-53,1072	6,9348	-63,4501	-11,9522	-15,3997	14,4469
Volume flex	-57,7782	1,7565	-53,6946	-7,1388	-19,3930	4,5611

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-72,3447	-27,9973	-33,9103	12,3195	-49,8733	-10,8105
Q time total	-48,9153	17,3500	20,4713	130,6567	-11,2518	65,6321
Wait time	135,9562	221,4054	203,0564	374,9750	332,8578	649,8585
Utilization	0,3648	2,3249	-0,1721	1,4862	-0,1113	1,3414
% 0 res avail	0,5242	7,0101	6,2656	12,6149	-3,0205	2,1551
WIP	-73,5485	-27,7809	-35,0104	12,6203	-50,3055	-10,4341
Lab flex WF	-40,1734	5,5431	-42,6069	-5,2769	-20,7514	18,0000
Volume flex	-47,5438	-7,4592	-33,7898	3,9150	-31,2389	2,5901

Table 28: Confidence intervals for the relative differences in means alternative 4.2

Observations

From Table 28 the following observations can be made:

- Lead time: For lead time, the setups ABC-DEF, AEF-BCD, AD-BC-EF and AC-BD-EF have significant differences. AD-BC-EF has a significant lower difference in lead time than AB-CE-DF.
- Queue time total: Only the differences in queue time of AB-CE-DF and AB-CD-EF increase significantly. These are also both significantly higher than the difference of AD-BC-EF.
- Wait time: All differences in wait time are significant. The differences in wait time of AEF-BCD and AD-BC-EF are significantly lower.
- Utilization all resources: The differences of setups AEF-BCD and AD-BC-EF have significant positive differences in utilization. None of the differences between the setups is significant.

- 'Percentage o resources available': The differences of all setups except AC-BD-EF are significant. The difference of AB-CD-EF is significantly higher than that of AB-CE-DF and AC-BD-EF.
- WIP: Only the differences of the same setups as for lead time are significant. The difference of AD-BC-EF is significantly lower than that of AB-CE-DF.
- Labour flexibility WF: Only the difference of setup AEF-BCD and AB-CD-EF are significant. None of the setups differ significantly on this measure.
- Volume flexibility: For this measure only AEF-BCD and AD-BC-EF change significantly; it decreases for both setups. They do not significantly differ from the other setups.

5.6.3 Conclusions model variant 4

For alternative 1, putting two tasks in parallel only has a positive effect on the lead time for setups ABC-DEF and AD-BC-EF. These are both setups with parallel tasks that share a resource class. The redesign only has a significant effect on utilization, labour flexibility and volume flexibility for AD-BC-EF. The measure 'percentage o resource available' has a significant difference for three of the setups.

Putting three tasks in parallel with completely differing service times only has a positive impact on lead time and WIP for setups where task B shares a resource class with C and/or D. To verify this it is suggested to simulate an additional setup for alternative 2 in which B is not sharing a resource class with neither C nor D: ABE-CDF. Setups AEF-BCD and AD-BC-EF have significantly lower wait times and higher utilizations. This redesign has a significant impact on 5 of the 6 setups, concerning '% o resources available'. Both flexibility measures have significant, negative differences in only two setups.

5.7 Analysis model variant 5 (Exp (8) 78-2)

This sub-section describes the output analysis for model variant 5. The first step was the hypothesis testing. The results of the hypothesis test are listed in the tables of Appendix E. The significantly changed performance measures are depicted in Table 29.

Measures with significant differences model variant 5		
Lead time	Queue time F	Queue length C
Queue time A	Queue time total	Queue length D
Queue time B	Wait time	Queue length E
Queue time C	Percentage o resources available	Queue length F
Queue time D	Queue length A	WIP
Queue time E	Queue length B	

Table 29: Significantly changed performance measures model variant 5

5.7.1 Alternative 5.1

The confidence intervals for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 30. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-17,6961	-2,6561	-10,5082	0,7263	-6,5706	8,3339	-21,6525	-8,1086
Q time total	-35,6542	31,4409	-18,9956	37,4169	8,6620	89,0254	-39,6374	1,5277
Wait time	74,9153	76,5320	79,3044	85,1075	78,3072	90,4858	74,1894	76,0675
% o res avail	-6,7174	9,4490	-11,1258	5,1056	-4,2046	10,2491	-6,3171	5,0525
WIP	-17,9052	-0,9958	-12,1644	1,4352	-6,7939	10,7451	-22,8435	-7,1041

Table 30: Confidence intervals for the relative differences in means alternative 5.1

Observations
From Table 30 the following observations can be made:

- Lead time: The differences of ABC-DEF and AD-BC-EF are significant. The decrease of AD-BC-EF is significantly higher than that of AB-CE-DF.
- Queue time total: Only the queue time of AB-CE-DF increases significantly. It increases significantly more than that of AD-BC-EF.
- Wait time: All differences in wait time are significant and positive. The differences in wait times of the setups ABC-DEF and AD-BC-EF are significantly lower than those of the other setups.
- 'Percentage 0 resources available': For this measure, none of the differences in this alternative is significant.
- WIP: Again, only the differences of setups ABC-DEF and AD-BC-EF are significant. Also for WIP, the difference of AD-BC-EF is significantly higher than that of AB-CE-DF.

5.7.2 Alternative 5.2

The confidence intervals for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in Table 31. The fields that are marked red contain a difference that is not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-30,0739	-14,6549	-23,6007	-13,0578	-18,6534	-7,4364
Q time total	-33,8654	42,6356	11,7177	84,4323	30,9298	102,5295
Wait time	91,7954	96,5620	88,6788	90,5564	98,3493	105,9521
% 0 res avail	-7,3016	10,3013	4,9313	20,4207	-2,8861	9,7982
WIP	-30,2090	-13,3752	-24,3664	-11,5073	-18,6264	-5,7640

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-35,4714	-21,6578	-25,1044	-10,7098	-28,5023	-10,7547
Q time total	-52,1783	-9,5558	7,1487	67,4374	0,6522	70,2133
Wait time	94,8563	99,9271	94,0023	99,8025	105,1018	121,7810
% 0 res avail	-10,6050	1,7720	-0,3203	12,8692	-6,9691	5,7204
WIP	-37,1141	-21,1931	-26,7352	-10,1548	-29,7866	-9,6465

Table 31: Confidence intervals for the relative differences in means alternative 5.2

Observations
From Table 31 the following observations can be made:

- Lead time: All differences in lead time are significant. The difference of AD-BC-EF is significantly different from that of AB-CE-DF.
- Queue time total: Only the difference in queue time of ABC-DEF is not significant. The setup AD-BC-EF is the only setup with a decrease in queue time. It is significantly different from the other 3 class setups.
- Wait time: All differences in wait time are positive and significant. The difference of AEF-BCD is lower than that of ABC-DEF.
- 'Percentage 0 resources available': For this measure, only the difference of AEF-BCD is significant. No significant differences between the setups can be found.
- WIP: The differences in WIP are all significant. The difference of AD-BC-EF is significantly more negative than that of AB-CE-DF.

5.7.3 Conclusions model variant 5

For alternative 1, putting two tasks in parallel only has a positive effect on the lead time and the WIP level, when the parallel tasks require resources from the same resource class (setups ABC-DEF and AD-BC-EF). AD-BC-EF even scores significantly better on both measures than AB-CE-DF. For wait time, the above mentioned setups also score significantly better than the others. The measure '% 0 resources available' does not change significantly.

For alternative 2, AD-BC-EF (resources from the same class) scores significantly better on lead time and WIP, compared to AB-CE-DF (resources from different classes). It is also the only setup with an increase in queue time. For the measures wait time and '% 0 resources available' there are no big differences between the setups. As the service times of the 3 parallel tasks are 78-2-40 it is suggested to simulate a model, only for alternative 2, in which the service times of the parallel tasks are more varying (78-2-2). This will be analyzed later.

5.8 *Analysis model variant 6 (Exp (14) 78-2)*

This sub-section describes the output analysis for model variant 6. The first step was the hypothesis testing. The results of the hypothesis test are listed in the tables of Appendix F. The significantly changed performance measures are depicted in Table 32.

Measures with significant differences model variant 6		
Lead time	Queue time total	Queue length C
Queue time B	Wait time	Queue length D
Queue time C	Percentage 0 resources available	WIP
Queue time D	Queue length B	

Table 32: Significantly changed performance measures model variant 6

5.8.1 Alternative 6.1

The confidence intervals for all setups in the comparison between the original model and alternative 1 (2 tasks parallel) can be seen in Table 33. The fields that are marked red are differences that are not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-2,5168	-0,5680	-2,4910	-0,6486	-3,0354	-1,0794	-2,9518	-0,8515
Q time total	-47,0632	135,3960	-43,3820	89,3581	-33,4940	29,3061	-14,1301	81,7330
Wait time	75,0790	77,4308	75,4136	77,6655	74,6783	77,4183	74,5304	76,6834
% 0 res avail	0,5726	78,1641	-38,0483	24,6023	-18,1397	16,6529	-8,4275	32,8113
WIP	-3,4642	0,3967	-5,7678	-1,2256	-4,2867	0,1224	-4,7636	0,8829

Table 33: Confidence intervals for the relative differences in means alternative 6.1

Observations

From Table 33 the following observations can be made:

- Lead time: The differences of ABC-DEF and AD-BC-EF are significant. The difference of AD-BC-EF is significantly lower than that of AB-CE-DF.
- Queue time total: Only the queue time of AB-CE-DF increases significantly. It increases significantly more than that of AD-BC-EF.
- Wait time: All differences in wait time are significant and positive. The differences in wait times of the setups ABC-DEF and AD-BC-EF are significantly lower than those of the other setups.
- 'Percentage 0 resources available': For this measure, none of the differences in this alternative is significant.

- WIP: Again, only the differences of setups ABC-DEF and AD-BC-EF are significant. Also for WIP, the difference of AD-BC-EF is significantly higher than that of AB-CE-DF.

5.8.2 Alternative 6.2

The confidence intervals for all setups in the comparison between the original model and alternative 2 (3 tasks parallel) can be seen in . The fields that are marked red contain a difference that is not significant. This can be seen from the confidence intervals, as these intervals include 0.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-13,6441	-11,5716	-14,4835	-12,3966	-14,0864	-12,3909
Q time total	-50,1345	346,8334	262,9660	746,4232	-34,5073	39,6333
Wait time	88,8615	91,1985	88,0766	90,9063	88,2285	90,7962
% 0 res avail	-14,1908	94,1752	125,1201	229,3774	-18,9871	13,5560
WIP	-14,6007	-10,7219	-16,9450	-12,5763	-15,5693	-11,7910

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-13,7781	-11,5813	-13,6676	-11,5402	-13,9919	-12,1094
Q time total	-5,6819	94,2347	72,3813	192,2472	42,1252	150,6290
Wait time	89,6340	91,7492	88,6265	90,2591	88,3371	91,1905
% 0 res avail	-1,6970	39,5415	35,1632	72,4518	3,7812	38,6879
WIP	-15,6056	-10,1572	-15,3664	-9,8322	-15,4746	-11,2403

Table 34: Confidence intervals for the relative differences in means alternative 6.2

Observations

From Table 34 the following observations can be made:

- Lead time: All differences in lead time are significant and approximately equal. Therefore no significant difference can be found between the setups.
- Queue time total: the differences in queue time of 3 of the 6 setups are significant. The difference in queue time of AB-CE-DF is significantly better than that of AB-CD-EF and AC-BD-EF.
- Wait time: All differences in wait time are significantly positive. No significant difference exists between the differences of the setups.
- 'Percentage 0 resources available': The same setups as for queue time total have significant differences for this measure, with AEF-BCD having a significant higher difference than ABC-DEF and AB-CE-DF scoring significantly better than AB-CD-EF.
- WIP: All differences in WIP level are significant and negative. No significant difference exists between the setups.

5.8.3 Conclusions model variant 6

Putting two tasks in parallel has a slightly positive, but significant impact on the lead time of all setups. When comparing all measures, all setups score approximately equal and there is no significant difference between the setups for any measure.

For alternative 2, all differences in lead time, wait time and WIP are significant and approximately equal for all setups. The setups with resources from different resource classes score slightly better on queue time and 'percentage 0 resources available'.

5.9 Comparisons between model variants

The output of the different model variants has also been compared to each other in order to investigate the different statements, mentioned earlier in Section 5.1. For both alternatives, the model variants with equal service times have been compared to the model variants with completely differing service times in order to test statement 2. The model variants with a certain arrival rate have been compared to model variants with a different arrival rate to test the influence of varying arrival rates. The results of the comparison are described in the next subsections.

5.9.1 Comparison model variants alternative 1

First, statement 2 and 3 have been tested for models with two parallel tasks (alternative 1).

Statement 2 (1 vs 4, 2 vs 5, 3 vs 6)
For alternative 1 (2 tasks parallel), three comparisons have been executed in order to test statement 2 of Section 5.1: "The flow times of the parallel sub-processes must be of the same order of magnitude". Model variants with parallel tasks that have completely different service times have been compared to model variants containing parallel tasks with equal service times, for three different arrival rates. First model variant 1 (Exp (7), 40-40) has been compared to model variant 4 (Exp (7), 78-2), next model variant 2 (Exp (8), 40-40) has been compared to model variant 5 (Exp (8), 78-2) and finally the comparison between model variant 3 (Exp (14), 40-40) and model variant 6 (Exp (14), 78-2) has been made.

Observations statement 2:

- Lead time: There exists no significant difference for any setup between model variant 1 and 4 and between model variant 2 and 5. However, the differences for all setups between the model variants with a low arrival rate are significant. The differences of model variant 3 are significantly different from the differences of model variant 6.
- Queue time total: None of the comparisons resulted in a significant difference between model variants with parallel tasks with equal service times and model variants with parallel tasks with considerably differing service times.
- Wait time: For all setups, the wait times of the model variants with considerably differing service times (4, 5, 6) Are significantly higher than those of the other model variants.
- '% 0 resources available': There are no significant differences between the model variants.
- WIP: For the model variants with higher arrival rates, there are no significant differences between the model variants. For the model variants with a low arrival rate, model variant 3 is in three of the four setups, significantly more negative than model variant 6. Only AB-CE-DF has no significant difference.
- Utilization: There are no significant differences between the model variants.
- Labour flexibility workflow: Only for setup ACE-BDF, there is a significant difference between model variant 3 and 6. All other setups and arrival rates resulted in no significant differences.
- Volume flexibility: None of the comparisons resulted in a significant difference.

Conclusions statement 2:
Only for models with a low arrival rate, there is a significant difference in the decrease of lead time and WIP between models with parallel tasks with completely differing service times and models with parallel tasks with equal service times. The wait times of model variants with considerably differing service times are significantly higher than those of model variants with equal service times. For the other measures there is no significant difference between the different model variants.

Statement 3 (1 vs 2 vs 3, 4 vs 5 vs 6)
For alternative 1 (2 tasks parallel), also statement 3 of Section 5.1: "varying arrival rate leads to different results", has been tested with the comparisons between model variants. To test this statement, the results of model variants with the same service times and setups, but differing arrival rates have been compared. For model variants that contain parallel tasks that have equal service times, a comparison has been made between model variant 1 (Exp (7), 40-40), model variant 2 (Exp (8), 40-40) and model variant 3 (Exp (14), 40-40). For model variants that have parallel tasks with completely different service times, the results of model variant 4 (Exp (7), 78-2), model variant 5 (Exp (8), 78-2) and model variant 6 (Exp (14), 78-2) have been compared.

Observations statement 3:

- Lead time: When looking at lead time, it can be seen that none of the setups of model variant 1, 2 and 3 differs significantly from the same setup in another model variant. For model variant 4, 5 and 6 the setups ABC-DEF and AD-BC-EF of model variant 5 are significantly different from the same setups of model variant 6.
- Queue time total: For this measure, the differences between the model variants do not differ significantly from one another.
- Wait time: For the setups with parallel tasks that do not share a resource class (ACE-BDF and AB-CE-DF) the differences in wait time increase when the arrival rate increases. For the setups where the parallel tasks are sharing a resource class, the differences between the model variants do not differ significantly.
- '% 0 Resources available': For this measure, model variant 3 differs significantly (is higher) from 1 and 2 for the setups where B and C are in the same resource class. All other differences between the model variants are not significant.
- WIP: For WIP, only the difference between model variant 5 and 6 is significant for setup AD-BC-EF (difference of model variant 5 is more negative). All other differences are not significant.
- Utilization: There are no significant differences between the model variants.
- Labour flexibility workflow: Only the difference between model variant 1 and 2 is significant for setup ACE-BDF. All other differences are not significant.
- Volume flexibility: Of all differences, only the difference of setup AD-BC-EF between model variant 4 and 6 is significant.

Conclusions statement 3:
For lead time, only when the service times of the parallel tasks differ considerably and when the parallel tasks share a resource class, a significant difference can be found between the model variant with a low arrival rate (Exp (14)) and the model variant with a higher arrival rate (Exp (8)). Also for wait time, some significant differences between the model variants exist. For the setups with parallel tasks that do not share a resource class (ACE-BDF and AC-BD-EF) the differences in wait time increase when the arrival rate increases. For the other measures, increasing the arrival rate does not have a significant impact.

5.9.2 Comparisons model variants alternative 2

Also for models with three tasks in parallel (alternative 2) statement 2 and 3 have been tested with comparisons between model variants.

Statement 2 (1 vs 4, 2 vs 5, 3 vs 6)
Statement 2 described in Section 5.1: "The flow times of the parallel sub-processes must be of the same order of magnitude" has also been tested for alternative 2 (3 tasks parallel) by comparing the results of the different model variants. Model variants with the same arrival rate but different service times have been compared. First model variant 1 (Exp (7), 40-40) has been compared to model variant 4 (Exp (7), 78-2), next model variant 2 (Exp

(8), 40-40) has been compared to model variant 5 (Exp (8), 78-2) and finally the comparison between model variant 3 (Exp (14), 40-40) and model variant 6 (Exp (14), 78-2) has been made.

Observations statement 2:

- Lead time: Only in model variants with a low arrival rate, for all setups the impact of the parallel heuristic is significantly higher on the lead time of model variants with equal service times compared to model variants with considerably different service times. None of the differences of model variants with higher arrival rates are significant.
- Queue time total: The difference between model variant 2 and 5 (Exp (8)) is only significant for setup AD-BC-EF. In model variant 5 the queue time even decreases. All other comparisons resulted in no significant results.
- Wait time: Not all differences between the model variants with a high arrival rate are significant (the differences of ABC-DEF, AD-BC-EF and AB-CD-EF are not significant). For the other model variants, with lower arrival rates, the wait times of the models with equal service times are significantly lower than those of the model variants with completely differing service times, for all setups.
- '% 0 Resources available': Only the difference of the setup where all three parallel tasks share a resource class is significant for low arrival rate model variants. All other differences are not significant.
- WIP: The differences of all setups between model variants with a low arrival rate are significant. All other differences are not significant.
- Utilization: None of the differences in utilization between the model variants is significant.
- Labour flexibility workflow: None of the differences appears to be significant.
- Volume flexibility: Also for this flexibility measure, the difference of none of the setups is significant.

Conclusions statement 2:

For models with a low arrival rate, putting three tasks in parallel has significantly more impact on lead time and WIP when the parallel tasks have equal service times compared to models in which the parallel tasks have considerably differing service times. For higher arrival rates, the differences between the model variants are not significant. The impact on the wait times of model variants with differing service times is higher than on those of model variants with equal service times. Putting three tasks in parallel has no significantly different impact on the other measures.

Statement 3 (1 vs 2 vs 3, 4 vs 5 vs 6)

To test statement 3 of Section 5.1: "varying arrival rate leads to different results" for alternative 2 (3 tasks parallel), two comparisons have been made. The results of model variants with the same service times but different arrival rates have been compared. For model variants that contain parallel tasks that have equal service times, a comparison has been made between model variant 1 (Exp (7), 40-40), model variant 2 (Exp (8), 40-40) and model variant 3 (Exp (14), 40-40). For model variants that have parallel tasks with completely different service times, the results of model variant 4 (Exp (7), 78-2), model variant 5 (Exp (8), 78-2) and model variant 6 (Exp (14), 78-2) have been compared.

Observations statement 3:

- Lead time: All differences between model variants with equal service times are insignificant. In 3 of the 6 setups (ABC-DEF, AD-BC-EF and AC-BD-EF) of the model variants with differing service times, the parallel heuristic has lesser impact on model variant 6 than on model variant 4 and/or 5.

- Queue time total: For all setups, except for setup AD-CE-DF, The model variants with Exp (8) arrival rate have a lower increase in queue time than the model variants with a low arrival rate (Exp (14)). In setup AEF-BCD, the differences of model variants 3 and 6 are significantly higher than the differences of the other model variants.
- Wait time: for all setups, except AEF-BCD, leads increasing arrival rates to increasing differences in wait times.
- '% 0 Resources available': For this measure, all setups (except AB-CE-DF) in models with a low arrival rate and equal service times have significantly higher differences than the model variants with higher arrival rates. For the model variants with differing service times, only the differences in setup AEF-BCD and AB-CD-EF of model variant 6 are higher than those of model variants 4 and 5.
- WIP: Only in 3 resource class setups AD-BC-EF and AC-BD-EF, the impact on model variant 6 is significantly smaller than on model variant 4 and/or 5. All other differences are not significant.
- Utilization: None of the differences in utilization between the model variants is significant.
- Labour flexibility workflow: For this measure none of the setups has a significant difference between the model variants 1, 2 and 3. For the setups AEF-BCD and AB-CD-EF, the impact on model variant 4 is bigger than the impact on model variant 6.
- Volume flexibility: For this measure none of the setups has a significant difference between the model variants 1, 2 and 3. For the setups AEF-BCD and AD-BC-EF, the impact on model variant 4 is bigger than the impact on model variant 6.

Conclusions statement 3:
For alternative 2, increasing the arrival rate does not lead to a significant difference in lead time, WIP, Labour flexibility and volume flexibility, between model variants with equal service times (1, 2 and 3). The measures WIP and lead time show a significant difference between model variant 4, 5 and/or 6 for the setups AD-BC-EF and AC-BD-EF. For both flexibility measures, there are two setups that have a significant difference between model variants 4 and 6. In most setups, model variants with a low arrival rate have higher increases in queue times compared to model variants with higher arrival rates. For wait time the opposite is true, the higher the arrival rate, the higher the increase in wait time. Increasing the arrival rate has a positive impact on the measure '% 0 resources available' for model variants with equal service times, since in five of the six setups the difference in this measure decreases with an increasing arrival rate.

5.9.3 Additional measurements

Throughout the analyses of the separate model variants it has been suggested to perform a number of additional measurements in order to gain stronger evidence to support or reject the statements. First in Section 5.4.3, it has been suggested to investigate a model with slightly differing service times for the parallel tasks instead of exactly equal service times. Then in Section 5.6.3, the second additional measurement has been suggested. Here an extra setup ABE-CDF has been suggested for alternative 2 (3 tasks parallel), as in this setup task B is not sharing a resource class with neither C nor D. Finally the third additional measurement has been suggested in Section 5.7.3. Here it has been suggested to simulate model variants in which task B has a service time of 78 minutes and tasks C and D a service time of 2 minutes. With this service time variant, it can be investigated what impact the parallel heuristic has when putting three tasks in parallel with a considerable difference in service times between all three parallel tasks.

The setup, the analysis and the results of the additional measurement are described in the next chapter. Based on the gathered data, conclusions about the additional measurement are drawn at the end of the chapter.

6 Additional measurements

In order to gather stronger evidence to support or reject a statement, additional simulation runs with differing setups or service time have been made. In Chapter 5, three extra measurements have been suggested. This chapter first describes the setups of the additional measurements. Next, the results are analyzed and finally a conclusion is drawn.

6.1 Setup of the additional measurements

In Chapter 5, three suggestions have been proposed.

Suggestion 1: use slightly differing service times
In Section 5.4.3, it is suggested to use slightly differing service times for the parallel tasks, instead of equal service times and considerably differing service times. The following service times have been chosen to investigate in a model variant with an Exp (8) arrival process: 40-47-33-40-40-40, to find out whether there are differences between the setups for this arrival rate.. To keep a constant utilization for all resources, the number of resources has been adapted accordingly. Table 35 and Table 36 show the used setups and the number of resources per resource class.

Alternative 1: 2 Tasks parallel			
# Classes	**Class 1**	**Class 2**	**Class 3**
2 Resource classes	ABC (18)	DEF (18)	
	ACE (17)	BDF (19)	
3 Resource classes	AB (13)	CE (11)	DF (12)
	AD (12)	BC (12)	EF (12)

Table 35: Resource classes for suggestion 1.1

Alternative 2: 3 Tasks parallel			
# Classes	**Class 1**	**Class 2**	**Class 3**
2 Resource classes	AEF (18)	BCD (18)	
	ABC (18)	DEF (18)	
3 Resource classes	AB (13)	CE (11)	DF (12)
	AD (12)	BC (12)	EF (12)
	AB (13)	CD (11)	EF (12)
	AC (11)	BD (13)	EF (12)

Table 36: Resource classes for suggestion 1.2

Suggestion 2: try setup ABE-CDF for alternative 2
At the end of Section 5.6.3 it is proposed to investigate the impact of the implementation of the parallel heuristic for setup ABE-CDF. It is expected that the difference with the original model in model variant 4 is insignificant, because task B is neither sharing a resource class with task C nor D. The setup is also executed in model variants 1, 2 and 5.

Suggestion 3: use 78-2-2 as service times for the parallel tasks of alternative 2
To test whether the impact of the implementation of the parallel heuristic is indeed insignificant in a model where the service times of two of the three parallel tasks are considerably lower than the service time of the other task, a model with the following service times has been simulated; 78-78-2-2-40-40. For all setups the original model has been compared to alternative 2, as suggested in Section 5.7.3. The number of resources has been adapted as well to keep a constant utilization for all resources. The number of resources per resource class can be seen in Table 37.

Alternative 2: 3 Tasks parallel			
# Classes	**Class 1**	**Class 2**	**Class 3**
2 Resource classes	AEF (23)	BCD (13)	
	ABC (23)	DEF (13)	
3 Resource classes	AB (22)	CE (7)	DF (7)
	AD (12)	BC (12)	EF (12)
	AB (22)	CD (2)	EF (12)
	AC (12)	BD (12)	EF (12)

Table 37: Resource classes for suggestion 3

The setups have been simulated with an exponentially distributed inter-arrival time with a mean of 7 minutes, 8 minutes and 14 minutes, so the results can be compared with the other model variants.

6.2 *Output analysis additional measurements*

This section describes the output analysis for the additional measurements.

6.2.1 Output analysis suggestion 1

The setups of suggestion 1 have been simulated in order to investigate what the impact of the implementation of the parallel redesign heuristic is on tasks with slightly differing service times. The results for alternative 1 (2 tasks parallel) can be seen in Table 38:

	ABC-DEF		ACE-BDF		AB-CE-DF		AD-BC-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-16,5055	-5,7336	-14,0728	-3,5932	-13,9922	-6,5080	-19,9580	-8,3819
Q time total	-33,9580	31,2899	-16,8403	58,4178	-4,2028	31,0659	-16,9238	31,4065
Wait time	40,9873	41,9390	43,6710	45,8761	45,6371	49,6873	41,3788	42,1693
% 0 res avail	-3,6916	11,8511	-10,7343	5,0856	-5,6066	4,8758	-4,1007	7,0981
WIP	-17,9136	-4,9239	-14,7796	-2,4976	-15,4029	-5,9728	-21,2347	-8,0414

Table 38: Results suggestion 1.1

Observations

- For lead time, Wait time and WIP, all setups have significant differences. The other two measures have insignificant differences for all setups.
- For lead time and WIP there is no significant difference between the differences of the setups.
- The differences in wait time of the setups ABC-DEF and AD-BC-EF are significantly lower than for the other setups.

The results for alternative 2 are shown in Table 39:

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-26,2165	-14,8278	-21,8681	-14,1756	-25,9408	-17,3355
Q time total	15,9476	102,7603	72,2005	148,6249	8,1759	62,3053
Wait time	64,0456	67,5151	60,6953	61,7106	68,0558	74,0309
% 0 res avail	3,0864	21,3066	19,1405	35,8323	-4,8207	6,7516
WIP	-26,8709	-12,9762	-22,1238	-12,1630	-26,9212	-16,7910

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-33,0466	-21,2652	-31,3468	-18,6335	-28,7734	-15,0375
Q time total	-13,7149	47,2842	0,4723	59,7286	8,8210	86,1118
Wait time	66,7259	72,1953	65,9167	71,2928	67,0815	74,0962
% 0 res avail	-8,9299	4,9778	-0,0744	13,9608	-5,4064	10,0019
WIP	-34,0876	-20,6901	-32,8187	-18,5599	-29,9225	-13,4942

Table 39: Results suggestion 1.2

Observations

- For lead time, wait time and WIP, all setups have significant differences. '% 0 resources available' only has significant differences in the 3 resource class setups and Queue time total is only insignificant for AD-BC-EF.
- The increase in wait time of AEF-BCD is significantly lower compared to ABC-DEF. All other differences in the comparison of the setups are insignificant.

Statement 1: "Resources from different classes should execute the tasks".
The results of this suggestion are comparable to the results of model variant 2. The same measures have significant differences. For this suggestion, as for model variant 2, there is no significant difference between the setups for lead time and WIP. The results of comparing the wait time differences of the setups are also the same as for model variant 2. No strong evidence has been found here to reject or support statement 1, as there is no significant difference between the setups.

Statement 2: "The flow times of the parallel sub-processes must be of the same order of magnitude".
When comparing the results of this suggestion to the data of model variant 2 and 5, it can be seen that almost all differences in this suggestion are not significantly different from the differences of model variant 2 and 5. This rejects statement 2 for models with this arrival rate.

6.2.2 Output analysis suggestion 2

For suggestion 2, simulation runs with an extra setup have been executed. The new setup ABE-CDF is simulated for the original situation and for alternative 2. This setup has been introduced in four model variants. The same analysis as described in Chapter 5 has been performed on the resulting output data. The confidence intervals of the relative differences in means for the four model variants are shown in Table 40:

	Exp (7) 40-40		Exp (8) 40-40		Exp (7) 78-2		Exp (8) 78-2	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-19,1339	35,3610	-24,3668	-15,5526	-14,4844	39,0946	-18,1722	-3,1736
Q time total	64,3107	183,3427	19,1524	86,4486	65,7686	169,9991	18,2369	166,9090
Wait time	117,4747	208,5546	63,5052	67,3923	205,2775	312,7177	90,0304	99,7631
WIP	-19,4124	36,9932	-24,6921	-14,2432	-14,8325	39,6748	-19,0095	-1,3072
% 0 res avail	6,5723	13,6707	-1,13728	14,28521	5,5563	10,1263	1,6853	22,3473
Utilization	-42,9988	13,64676	-15,6584	10,4172	-40,8140	-8,9088	-23,5066	7,328608
Lab flex WF	-44,7333	2,273889	-8,06204	13,4443	-28,0320	-1,1298	-15,8284	8,802091
Volume flex	-0,07969	1,568163	-1,8584	1,1144	0,0404	1,0027	-1,33602	2,402383

Table 40: Output analysis suggestion 3

Observations

- Both Exp (7) model variants have insignificant differences for lead time and WIP. All other differences in these model variants are significant.
- Both Exp (8) model variants have insignificant differences for utilization and flexibility measures.

Statement 1: "Resources from different classes should execute the tasks".
For model variant 1 and 4, where the queue times are high, the differences in lead time and WIP are insignificant. This is due to task B not sharing a resource class with task C and/or D. When this is the case, the gain in queue times of C and D (which are lower than when they share a resource class with B) is not high enough to make up for the increase in queue times when putting three tasks in parallel. All this is according to the conclusion of Section 5.6.3.

For model variant 2 and 5, differences in both flexibility measures are insignificant, like all the other setups of model variant 2 and 5. The differences on the other measures are significant, as expected.

Statement 2: "The flow times of the parallel sub-processes must be of the same order of magnitude".
For this setup, no significant difference can be found when comparing the differences of model variant 1 with 4 and model variant 2 with 5.

6.2.3 Output analysis suggestion 3

In order to assess the impact of making the service time of task D considerably small compared to task B, the service times of all setups have been adapted to 78-78-2-2-40-40. The results of all three variants (Exp (7), Exp (8) and Exp (14)) are shown in Table 41, Table 42 and Table 43:

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-39,3484	23,5111	-49,2354	-3,0432	-27,6226	25,8904
Q time total	49,5689	186,8253	-15,2428	60,8129	39,8596	155,0231
Wait time	290,5016	503,6903	76,7296	78,4811	353,5358	594,7002
WIP	-39,2496	24,6259	-49,8945	-2,5361	-27,8026	27,5588
% 0 res avail	5,3060	11,5455	6,8438	12,7230	-1,4340	3,8379
Lab flex WF	-39,5957	-6,3397	-44,6079	-7,1754	-12,9144	11,6395
Volume flex	-36,8453	-7,3912	-38,6371	-5,1932	-15,3308	8,6208
Utilization	0,3410	1,7001	0,2127	1,5822	-0,5064	0,9005

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-52,8486	-9,1077	-24,4422	31,5688	-53,4015	-5,0245
Q time total	-7,7722	69,4151	33,7768	161,6521	-13,5397	81,5792
Wait time	239,3541	365,9328	343,0791	641,8906	196,6650	423,0881
WIP	-54,2068	-9,9640	-25,2064	34,2295	-54,0517	-5,2132
% 0 res avail	-0,8269	3,4498	8,6481	14,5519	-2,7958	2,8802
Lab flex WF	-26,2468	15,9642	-29,0435	-3,8011	-36,4560	10,1993
Volume flex	-28,0399	4,2377	-17,1282	10,4397	-41,5948	-1,2912
Utilization	-0,1877	1,2419	-0,6141	1,0076	0,0602	1,9405

Table 41: Results suggestion 3, Exp (7)

Observations
From Table 41 the following observations can be made:

- Looking at lead time and WIP, the difference is only significant when task B shares a resource class with task C and/or D and does NOT share a resource class with task A!
- The same classes as for lead time have insignificant differences in queue time.
- For the measure 'percentage 0 resources available', both 2 resource class setups and AB-CD-EF have significant increases compared to the other setups.
- On the other three measures, no significant difference can be found between the setups.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-15,0942	1,0771	-21,2697	-7,1097	-13,9359	0,6954
Q time total	1,3023	125,5390	-16,4916	52,7619	9,2817	90,4433
Wait time	84,9684	99,2256	77,3600	78,8306	92,1915	106,5735
WIP	-16,1209	3,0077	-22,4802	-6,1234	-16,2130	0,4883
% 0 res avail	-2,9176	19,9008	1,8055	17,2466	-5,4054	9,2757
Lab flex WF	-22,9805	6,5292	-16,9657	5,4759	-11,7094	15,8189
Volume flex	-16,6613	7,7096	-13,8228	4,4319	-11,8885	10,3122
Utilization	-1,2055	2,6052	-0,7033	2,1937	-1,5968	1,8410

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-21,6731	-6,2336	-9,2613	1,0727	-44,7079	-8,4052
Q time total	7,0436	69,0306	19,0705	82,3688	-54,6682	33,9840
Wait time	96,4378	109,4790	90,5025	99,5858	93,2969	106,8985
WIP	-23,1561	-5,4682	-10,2670	1,6027	-47,2259	-7,6227
% 0 res avail	-6,5860	4,7330	5,7621	17,7709	-16,5830	0,8650
Lab flex WF	-8,3277	14,5366	-12,6107	10,1012	-9,6414	25,2081
Volume flex	-6,7537	9,4439	-9,4442	13,3790	-10,0538	20,2425
Utilization	-1,4786	1,0573	-2,0569	1,4521	-3,0676	1,5236

Table 42: Results suggestion 3, Exp (8)

Observations

From Table 42 the following observations can be made:

- Looking at lead time and WIP, the difference is only significant when task B shares a resource class with task C and/or D and does NOT share a resource class with task A!
- The increase in wait time of AEF-BCD is significantly lower compared to the other setups.
- The only setups with a significant increase in 'percentage 0 resources available' are AEF-BCD and AB-CD-EF.
- All differences in flexibility measures and utilization are insignificant.

	ABC-DEF		AEF-BCD		AB-CE-DF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-4,7483	-2,5355	-4,3636	-2,4302	-3,7909	-1,4552
Q time total	-35,0636	189,8329	46,8681	299,9988	24,9959	128,6962
Wait time	76,9247	79,3843	76,3080	79,2634	76,3861	79,2202
WIP	-7,4253	-1,4439	-6,6957	-2,2193	-5,3671	1,1343
% 0 res avail	-36,6598	43,8166	143,1696	216,3980	-3,8589	27,8109
Lab flex WF	-3,1733	3,6574	-5,5653	-1,0888	-4,1066	2,5715
Volume flex	-1,3539	4,5846	-0,8643	2,6712	-3,3294	1,7156
Utilization	-4,4279	1,4560	-2,6781	1,4740	-2,2792	3,6514

	AD-BC-EF		AB-CD-EF		AC-BD-EF	
	LB (%)	UB (%)	LB (%)	UB (%)	LB (%)	UB (%)
Lead time	-3,8141	-1,4506	-4,1670	-1,6979	-3,5365	-0,9758
Q time total	3,1141	164,3656	108,8701	162,4636	9,3745	166,0183
Wait time	76,6472	78,9949	75,9253	78,0213	77,3795	80,4391
WIP	-4,5179	1,1601	-4,9406	0,4159	-5,2420	0,1297
% 0 res avail	4,3211	66,0616	60,3041	70,6670	-9,7734	36,3722
Lab flex WF	-6,9372	-0,8489	-5,2897	0,5622	-6,0654	-0,1172
Volume flex	-3,5664	1,2660	-3,3890	1,5554	-2,0577	2,3112
Utilization	-2,3055	4,5174	-1,8332	3,7962	-2,8647	2,4378

Table 43: Results suggestion 3, Exp (14)

Observations

From Table 43 the following observations can be made:

- All differences in lead time and wait time are significant; differences between the setups are not significant.
- For WIP, only the differences of both 2 class setups are significant.
- AEF-BCD has a significantly higher increase in '% 0 resources available'.
- None of the differences in utilization and volume flexibility are significant.
- AEF-BCD, AD-BC-EF and AC-BD-EF have significant differences in labour flexibility WF.

Statement 1: "Resources from different classes should execute the tasks".
For model variants Exp (7) and Exp (8) of suggestion 3, putting three tasks in parallel only has a significant impact on lead time and WIP in the setups where task B shares a resource class with task C and/or D and NOT with A. For the Exp (14) model variant, all differences in lead time appear to be significant. All increases in wait time are significant. AEF-BCD and AB-CD-EF have significant differences in all three model variants on the measure '% 0 resources available'.

Statement 2: "The flow times of the parallel sub-processes must be of the same order of magnitude".
From the comparison of Exp (7) of this suggestion with model variant 1 it can be seen that none of the differences from this comparison is significant. So, for a model with a high arrival rate, putting three tasks in parallel with considerably differing service times (78-2-2) does not have lesser impact on any measure than putting three tasks with equal service times in parallel.

The only measures with a significant difference between Exp (8) of this suggestion and model variant 2 are lead time and WIP. In setups where tasks A and B share a resource class, the decreases in lead times and WIP levels are significantly higher in model variant 2. This is due to the fact that both tasks A and B have very high service times. There are no other significant differences between the measures of model variant 2 and Exp (8) of this suggestion.

When comparing model variant 3 with the Exp (14) values of this suggestion it can be concluded that the impact on lead time and WIP is higher on model variant 3 than on the suggested model variant, since the differences of model variant 3 are significantly more negative for all setups. For 'percentage 0 resources available', there is only a significant difference for the 2 class setups. Here model variant 3 has a higher increase.

Statement 3: "A varying arrival rate leads to different results".
Here the tables of Exp (7), Exp (8) and Exp (14) have been compared. It can be seen that for lead time and WIP the setups of Exp (14) where B shares a resource class with C and/or D and NOT with A have a significantly lower increase than Exp (7) and/or Exp (8). In all setups, except AEF-BCD, is the increase in wait time higher when the arrival rate is higher. The 'percentage 0 resources available' is in three of the six setups higher for model variant Exp (14). The differences in flexibility measures of Exp (14) are only higher than those of Exp (7) in the 2 class setups.

6.3 Conclusions of the additional measures

Suggestion 1:
No strong evidence has been found that supports or rejects statement 1. The same conclusion as drawn in Sections **Error! Reference source not found.** and **Error! Reference source not found.** can be drawn here: There is no significant difference in impact between models with parallel tasks with equal service times compared to models with parallel tasks with considerably differing service times, for model with this arrival rate.

Suggestion 2:
Suggestion 2 fully supports the conclusion drawn in Section 5.6.3, regarding statement 1.

Suggestion 3:
Only for low arrival rates, statement 1 and 2 hold true.

7 Conclusions

Based on the results and the sub-conclusions described in Chapter 5 and 6, conclusions can be drawn. First, Section 7.1 gives the conclusions on the statements. Then, Section 7.2 gives the drawn conclusions on the quantification of the parallel heuristic. Finally, Section 7.3 gives a reflection on the quantification of the parallel heuristic.

When stated; setups with tasks that require resources from the same resource class, in this conclusions chapter the following is intended:
For alternative 1:
- Task B is in the same resource class as task C

For alternative 2:
- Task B is in the same resource class as task C and/or D (for 40-40 and 78-2)
- Task B is in the same resource class as task C and/or D and NOT as A (for 78-2-2)

7.1 Conclusions on the statements

Statement 1: "Resources from different classes should execute the tasks".
- For the Exp (7) model variants, putting tasks in parallel only has a significant impact on lead time and WIP when the parallel tasks require resources from the same resource class. The same setups also have a lower increase in wait time. For '% 0 resources available' no clear difference can be found.
- For the Exp (8) model variants, putting tasks in parallel has a significant positive impact on the lead time and WIP level for all setups, except when the service times are completely different; here setups with parallel tasks sharing a resource class are the only setups with a significant difference. For wait time all setups have significant differences. However, setups in which all parallel tasks share a resource class have significantly lower wait times. The '% 0 resources available' only changes significantly in some setups.
- For the Exp (14) model variants, the parallel heuristic has a significant effect on lead time and wait time for all setups, with no difference between the setups. The differences in WIP are also all significant when the service times of the parallel tasks are not completely differing. For setups with completely different service times, only the two class setups have significant differences in WIP. For '% 0 resources available' setups with parallel tasks sharing a resource class perform worse with a higher increase.

- Other measures do not change significantly.

Final conclusion:
In systems with a high arrival rate, the opposite of statement 1 holds true for lead time, WIP and wait time. For model variants with a medium arrival rate (Exp (8)) again statement 1 is not correct for lead time, WIP and wait time. Here all setups have significant differences with the original situation, when the service times of the parallel tasks are approximately equal. When these are completely different, the opposite of the statement is true, since setups with parallel tasks sharing a resource class, only have significant differences. For model variants with a low arrival rate, all setups have significant differences on the same measures, so again statement 1 is not true. No strong and unambiguous conclusion can be drawn for the '% 0 resources available'.

Statement 2: "The flow times of the parallel sub-processes must be of the same order of magnitude".
For models with a lower arrival rate, statement 2 is true. The decrease in lead time and WIP is lower for models with parallel tasks that have completely differing service times compared to models with parallel tasks with equal service times. The increase in wait times is also higher for models with completely differing parallel service times. For

models with a higher arrival rate, there is no significant difference in lead time, WIP and wait time between the models with equal parallel service times and models with completely differing parallel service times. For these model variants, statement 2 does not hold true.

Final conclusion:
Statement 2 is true for systems with low arrival rates and utilizations. For system with a higher arrival rate, statement 2 is not correct, since the parallel heuristic does not have significantly more impact on models with parallel tasks with equal service times than on models with parallel tasks with considerably differing service times.

Statement 3: "A varying arrival rate leads to different results".
When the arrival rate of the system is increasing the following can be concluded:

- There is only a difference in decrease of lead time for model variants with parallel tasks that have differing service times. For these model variants the parallel heuristic has more impact on model with a higher arrival rate.
- Most of the increases in wait time increase significantly when the arrival rate is increasing.
- For WIP most of the comparisons lead to insignificant results.
- In most cases, there is no significant difference in '% 0 resources available' when increasing the arrival rate. In some cases this measure decreases when the arrival rate increases, which is positive.
- When looking at labour flexibility it can be seen that the differences between the model variants with the different arrival rates of this measure are only small.
- For volume flexibility, the impact on a model with a high arrival rate and different parallel service times is higher compared to the same model with a low arrival rate for setups AD-BC-EF and AEF-BCD.

Final conclusion:
An increase in the arrival rate eventually leads to insignificant differences in lead time and WIP in systems with parallel tasks that require resources from different resource classes. The differences of systems with different parallel service times become insignificant under lower arrival rates compared to systems with equal parallel service times.

7.2 Conclusions on the quantification

- Putting sequential tasks in parallel, which require resources from the same resource class, results in a decrease in lead time and WIP level under all arrival rates. The '% 0 resources available' remains the same or even increases. The wait time always increases. The flexibility measures are not affected. In these situations it is advisable to implement the parallel heuristic.
- In systems with parallel tasks that require resources from different resource classes, putting tasks in parallel only leads to lower lead times and WIP levels under low arrival rates. The differences become smaller or even insignificant when the arrival rate increases. The flexibility measures are still unaffected. Putting tasks in parallel is only advisable when the arrival rate is low.
- Putting tasks in parallel in systems with a low arrival rate and equal parallel service times leads to a higher impact on the lead time and WIP compared to systems with completely different parallel service times. In both situations implementation of the parallel heuristic leads to a decrease in lead time and WIP and is therefore advisable. However, the differences in impact between the two service time variants decreases or even becomes insignificant when the arrival rate increases. Whether it is still advisable to implement the parallel heuristic depends on the resource classes, as explained in the two previous conclusions.

- Putting more than two tasks in parallel leads to lower lead times and WIP levels. However, the wait times and the '% 0 resources available' increase. The flexibility measures still remain the same.

7.3 Reflection parallel heuristic

In this section, conclusions about the impact on all measures of the implementation of the parallel heuristic will be drawn.

- The difference in lead time is sometimes insignificant (in systems with a high arrival rate, when the difference in service times of the parallel tasks is significantly high and the parallel tasks are not sharing a resource class), but in most cases the implementation of the parallel heuristic leads to a decrease in lead time.
- The WIP level is strongly related to the lead time. Therefore the implementation of the heuristic mostly leads to a decrease in WIP level.
- The wait time always increases when two or more tasks are put in parallel. This is straightforward, because the wait time in the original model is always 0.
- The measure % '0 resources available' decreases only a few times. Mostly it does not change significantly or increases.
- Volume flexibility and labour flexibility WF almost always do not change significantly. When they change, they decrease.
- Routing flexibility always increases when putting tasks in parallel.

To what extent the parallel heuristic effects the performance of a business process is heavily dependable on the arrival rate, the setups, the number of parallel tasks and other parameters. Therefore it has been chosen not to assign one general value to the impact of the parallel heuristic on a certain measure.

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

- Time: +4
- Cost: -2
- Quality: -2
- Flexibility: -1.5

According to Reijers and Limam Mansar (2004), the positive impact on the time dimension is caused by the decrease of lead time. The impact on the cost dimension is only negative when the tasks that are put in parallel incorporate possibilities of knockouts. The negative impacts on the quality and the flexibility dimensions are caused by an increasing complexity level.

Since the tasks in this simulation study do not incorporate possibilities of knockouts and the complexity of the system cannot be measured, it is hard to compare the quantitative results of this study with qualitative results of Reijers and Limam Mansar (2004).

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Appendix A

Significance tables model variant 1

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Lead time	Y	N	N	Y	N	N	Y	Y	N	N
Queue time A	N	N	N	N	N	N	N	N	N	N
Queue time B	N	N	N	N	N	N	N	N	N	N
Queue time C	N	N	N	N	Y	N	N	N	N	N
Queue time D	N	N	N	N	N	N	N	N	N	N
Queue time E	N	N	N	N	Y	N	N	N	N	N
Queue time F	N	N	N	N	N	N	N	N	N	N
Queue time total	N	N	N	Y	N	N	N	N	Y	Y
Service time A	N	N	N	Y	N	N	N	N	N	N
Service time B	N	N	N	N	N	N	N	N	N	N
Service time C	N	N	N	N	N	N	N	N	N	N
Service time D	N	N	N	N	N	N	N	N	N	N
Service time E	N	N	N	N	N	N	N	N	N	N
Service time F	N	N	N	N	N	N	N	N	N	N
Setup time A	N	N	N	N	N	N	N	N	N	N
Setup time B	N	N	N	N	N	N	N	N	N	N
Setup time C	N	N	N	N	N	N	N	N	N	N
Setup time D	N	N	N	N	N	N	N	N	N	N
Setup time E	N	N	N	N	N	N	N	N	N	N
Setup time F	N	N	N	N	N	N	N	N	N	N
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Utilization all res	N	N	N	N	N	N	N	N	N	N
Utilization res 1	N	N	N	N	N	N	N	N	N	N
Utilization res 2	N	Y	N	N	Y	Y	N	N	N	N
Utilization res 3	-	-	-	-	N	Y	N	Y	N	Y
Utilization res 4	-	-	-	-	-	-	-	-	-	-
Utilization res 5	-	-	-	-	-	-	-	-	-	-
Utilization res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
% 0 res available	N	Y	N	Y	N	Y	Y	N	Y	N
Queue length A	N	N	N	N	N	N	N	N	N	N
Queue length B	N	N	N	N	N	N	N	N	N	N
Queue length C	N	N	N	N	Y	N	N	N	N	N
Queue length D	N	N	N	N	N	N	N	N	N	N
Queue length E	N	N	N	N	Y	N	N	N	N	N
Queue length F	N	N	N	N	N	N	N	N	N	N
WIP	N	N	N	Y	N	N	Y	Y	N	N
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-
Task identity res 1	-	-	-	-	-	-	-	-	-	-

Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE - BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Lab flex WF	N	N	N	N	N	N	N	N	N	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	N	N	N	N	N	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-

Appendix B

Significance tables model variant 2

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Lead time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Queue time A	N	N	N	N	N	N	N	N	N	N
Queue time B	N	N	N	Y	N	N	Y	N	N	N
Queue time C	N	N	N	Y	N	N	Y	N	Y	N
Queue time D	Y	N	N	Y	N	N	N	N	Y	N
Queue time E	Y	N	N	N	N	N	N	N	N	N
Queue time F	Y	N	N	N	N	N	N	N	N	N
Queue time total	N	Y	N	Y	N	Y	N	Y	Y	N
Service time A	N	N	N	N	N	N	N	N	N	N
Service time B	N	N	N	N	N	N	N	N	N	N
Service time C	N	N	N	N	N	N	N	N	N	N
Service time D	N	N	N	N	N	N	N	N	N	N
Service time E	N	N	N	N	N	N	N	N	N	N
Service time F	N	N	N	N	N	N	N	N	N	N
Setup time A	N	N	N	N	N	N	N	N	N	N
Setup time B	N	N	N	N	N	N	N	N	N	N
Setup time C	N	N	N	N	N	N	N	N	N	N
Setup time D	N	N	N	N	N	N	N	N	N	N
Setup time E	N	N	N	N	N	N	N	N	N	N
Setup time F	N	N	N	N	N	N	N	N	N	N
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Utilization all res	N	N	N	N	N	N	N	N	N	N
Utilization res 1	N	N	N	N	N	N	N	N	N	N
Utilization res 2	N	N	N	N	N	N	N	N	N	N
Utilization res 3	-	-	-	-	N	N	N	N	N	N
Utilization res 4	-	-	-	-	-	-	-	-	-	-
Utilization res 5	-	-	-	-	-	-	-	-	-	-
Utilization res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
% 0 res available	N	N	N	Y	N	N	N	N	Y	N
Queue length A	N	N	N	N	N	N	N	N	N	N
Queue length B	N	N	N	Y	N	N	Y	N	N	N
Queue length C	N	N	N	Y	N	N	Y	N	Y	N
Queue length D	Y	N	N	Y	N	N	N	N	Y	N
Queue length E	Y	N	N	N	N	N	N	N	N	N
Queue length F	Y	N	N	N	N	N	N	N	N	N
WIP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-
Task identity res 1	-	-	-	-	-	-	-	-	-	-

Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lab flex WF	N	N	N	N	N	N	N	N	N	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	N	N	N	N	N	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-

Appendix C

Significance tables model variant 3

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lead time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Queue time A	Y	Y	N	N	N	N	N	N	N	N
Queue time B	Y	Y	N	Y	N	N	Y	Y	N	Y
Queue time C	Y	Y	N	Y	N	N	Y	Y	Y	N
Queue time D	N	N	N	Y	N	N	N	N	Y	Y
Queue time E	N	N	N	N	N	N	N	N	N	N
Queue time F	N	N	N	N	N	N	N	N	N	N
Queue time total	Y	Y	N	Y	N	N	Y	Y	Y	Y
Service time A	N	N	N	N	N	N	N	N	N	N
Service time B	N	N	N	N	N	N	N	N	N	N
Service time C	N	N	N	N	N	N	N	N	N	N
Service time D	N	N	N	N	N	N	N	N	N	N
Service time E	N	N	N	N	N	N	N	N	N	N
Service time F	N	N	N	N	N	N	N	N	N	N
Setup time A	N	N	N	N	N	N	N	N	N	N
Setup time B	N	N	N	N	N	N	N	N	N	N
Setup time C	N	N	N	N	N	N	N	N	N	N
Setup time D	N	N	N	N	N	N	N	N	N	N
Setup time E	N	N	N	N	N	N	N	N	N	N
Setup time F	N	N	N	N	N	N	N	N	N	N
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Utilization all res	N	N	N	N	N	N	N	N	N	N
Utilization res 1	N	N	N	N	N	N	N	N	N	N
Utilization res 2	N	N	N	N	N	N	N	N	N	N
Utilization res 3					N	N	N	N	N	N
Utilization res 4										
Utilization res 5										
Utilization res 6										

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
% 0 res available	Y	Y	N	Y	N	N	Y	Y	Y	Y
Queue length A	N	Y	N	N	N	N	N	N	N	N
Queue length B	Y	Y	N	Y	N	N	Y	Y	N	Y
Queue length C	Y	Y	N	Y	N	N	Y	Y	Y	N
Queue length D	N	N	N	Y	N	N	N	N	Y	Y
Queue length E	N	N	N	N	N	N	N	N	N	N
Queue length F	N	N	N	N	N	N	N	N	N	N
WIP	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-

Task identity res 1	-	-	-	-	-	-	-	-	-	-
Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lab flex WF	N	N	Y	Y	N	N	N	N	N	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	N	N	N	N	N	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-

Appendix D

Significance tables model variant 4

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lead time	Y	Y	N	Y	N	N	Y	Y	N	Y
Queue time A	N	N	N	N	N	N	N	N	N	N
Queue time B	N	N	N	N	N	N	N	Y	N	N
Queue time C	N	N	N	N	N	N	N	Y	Y	N
Queue time D	N	N	N	N	N	N	N	N	Y	N
Queue time E	N	N	N	N	N	N	N	N	N	N
Queue time F	N	N	N	N	N	N	N	N	N	N
Queue time total	N	N	N	N	N	Y	N	N	Y	N
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Utilization all res	N	N	N	Y	N	N	Y	Y	N	N
Utilization res 1	N	N	N	Y	N	N	Y	Y	N	N
Utilization res 2	N	Y	N	N	N	N	N	N	Y	N
Utilization res 3	-	-	-	-	N	N	Y	Y	N	Y
Utilization res 4	-	-	-	-	-	-	-	-	-	-
Utilization res 5	-	-	-	-	-	-	-	-	-	-
Utilization res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
% 0 res available	N	Y	Y	Y	Y	Y	Y	Y	Y	N
Queue length A	N	N	N	N	N	N	N	N	N	N
Queue length B	N	N	N	N	N	N	N	Y	N	N
Queue length C	N	N	N	N	N	N	N	Y	Y	N
Queue length D	N	N	N	N	N	N	N	N	Y	N
Queue length E	N	N	N	N	N	N	N	N	N	N
Queue length F	N	N	N	N	N	N	N	N	N	N
WIP	N	Y	N	Y	N	N	N	Y	N	Y
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-
Task identity res 1	-	-	-	-	-	-	-	-	-	-
Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative / Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lab flex WF	N	N	N	Y	N	N	Y	N	Y	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	Y	N	N	Y	Y	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-

Appendix E

Significance tables model variant 5

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lead time	Y	Y	N	Y	N	Y	Y	Y	Y	Y
Queue time A	N	N	N	N	N	N	N	Y	N	N
Queue time B	N	N	N	Y	N	N	N	N	N	N
Queue time C	N	N	N	Y	Y	Y	N	N	Y	N
Queue time D	Y	Y	N	Y	N	N	Y	Y	Y	N
Queue time E	Y	Y	N	N	Y	Y	Y	Y	N	N
Queue time F	Y	Y	N	Y	N	N	Y	Y	N	N
Queue time total	N	N	N	Y	Y	Y	N	Y	Y	Y
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Utilization all res	N	N	N	N	N	N	N	N	N	N
Utilization res 1	N	N	N	N	N	N	N	N	N	N
Utilization res 2	N	N	N	N	N	N	N	N	N	N
Utilization res 3					N	N	N	N	N	N
Utilization res 4	-	-	-	-	-	-	-	-	-	-
Utilization res 5	-	-	-	-	-	-	-	-	-	-
Utilization res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
% 0 res available	N	N	N	Y	N	N	N	N	N	N
Queue length A	N	N	N	N	N	N	N	Y	N	N
Queue length B	N	N	N	Y	N	N	N	N	N	N
Queue length C	N	N	N	Y	Y	Y	N	N	Y	N
Queue length D	Y	Y	N	Y	N	N	Y	Y	Y	N
Queue length E	Y	Y	N	N	Y	Y	Y	Y	N	N
Queue length F	Y	Y	N	N	N	N	Y	Y	N	N
WIP	Y	Y	N	Y	N	Y	Y	Y	Y	Y
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-
Task identity res 1	-	-	-	-	-	-	-	-	-	-
Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lab flex WF	N	N	N	N	N	N	N	N	N	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	N	N	N	N	N	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-

Appendix F

Significance tables model variant 6

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Lead time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Queue time A	N	N	N	N	N	N	N	N	N	N
Queue time B	N	N	N	Y	N	N	N	N	N	Y
Queue time C	N	N	N	Y	N	N	N	N	Y	N
Queue time D	N	N	N	Y	N	N	N	N	Y	Y
Queue time E	N	N	N	N	N	N	N	N	N	N
Queue time F	N	N	N	N	N	N	N	N	N	N
Queue time total	N	N	N	Y	N	N	N	N	Y	Y
Wait time	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Utilization all res	N	N	N	N	N	N	N	N	N	N
Utilization res 1	N	N	N	N	N	N	N	N	N	N
Utilization res 2	N	N	N	N	N	N	N	N	N	N
Utilization res 3	-	-	-	-	N	N	N	N	N	N
Utilization res 4	-	-	-	-	-	-	-	-	-	-
Utilization res 5	-	-	-	-	-	-	-	-	-	-
Utilization res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative Measure	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
% 0 res available	Y	N	N	Y	N	N	N	N	Y	Y
Queue length A	N	N	N	N	N	N	N	N	N	N
Queue length B	N	N	N	Y	N	N	N	N	N	Y
Queue length C	N	N	N	Y	N	N	N	N	Y	N
Queue length D	N	N	N	Y	N	N	N	N	Y	Y
Queue length E	N	N	N	N	N	N	N	N	N	N
Queue length F	N	N	N	N	N	N	N	N	N	N
WIP	N	Y	Y	Y	N	Y	N	Y	Y	Y
Skill variety res 1	-	-	-	-	-	-	-	-	-	-
Skill variety res 2	-	-	-	-	-	-	-	-	-	-
Skill variety res 3	-	-	-	-	-	-	-	-	-	-
Skill variety res 4	-	-	-	-	-	-	-	-	-	-
Skill variety res 5	-	-	-	-	-	-	-	-	-	-
Skill variety res 6	-	-	-	-	-	-	-	-	-	-
Task identity res 1	-	-	-	-	-	-	-	-	-	-
Task identity res 2	-	-	-	-	-	-	-	-	-	-
Task identity res 3	-	-	-	-	-	-	-	-	-	-
Task identity res 4	-	-	-	-	-	-	-	-	-	-
Task identity res 5	-	-	-	-	-	-	-	-	-	-
Task identity res 6	-	-	-	-	-	-	-	-	-	-

	ABC-DEF		ACE-BDF	AEF-BCD	AB-CE-DF		AD-BC-EF		AB-CD-EF	AC-BD-EF
Alternative	0-1	0-2	0-1	0-2	0-1	0-2	0-1	0-2	0-2	0-2
Measure										
Lab flex WF	N	N	N	N	N	N	N	N	N	N
Routing Flex	-	-	-	-	-	-	-	-	-	-
Volume Flex	N	N	N	N	N	N	N	N	N	N
Labour flex res 1	-	-	-	-	-	-	-	-	-	-
Labour flex res 2	-	-	-	-	-	-	-	-	-	-
Labour flex res 3	-	-	-	-	-	-	-	-	-	-
Labour flex res 4	-	-	-	-	-	-	-	-	-	-
Labour flex res 5	-	-	-	-	-	-	-	-	-	-
Labour flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex res 1	-	-	-	-	-	-	-	-	-	-
Mix Flex res 2	-	-	-	-	-	-	-	-	-	-
Mix Flex res 3	-	-	-	-	-	-	-	-	-	-
Mix Flex res 4	-	-	-	-	-	-	-	-	-	-
Mix Flex res 5	-	-	-	-	-	-	-	-	-	-
Mix Flex res 6	-	-	-	-	-	-	-	-	-	-
Mix Flex task A	-	-	-	-	-	-	-	-	-	-
Mix Flex task B	-	-	-	-	-	-	-	-	-	-
Mix Flex task C	-	-	-	-	-	-	-	-	-	-
Mix Flex task D	-	-	-	-	-	-	-	-	-	-
Mix Flex task E	-	-	-	-	-	-	-	-	-	-
Mix Flex task F	-	-	-	-	-	-	-	-	-	-