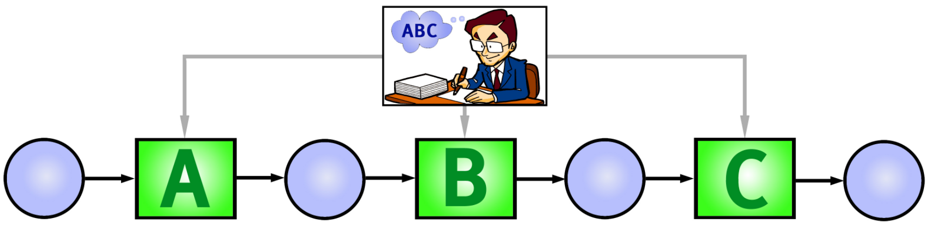
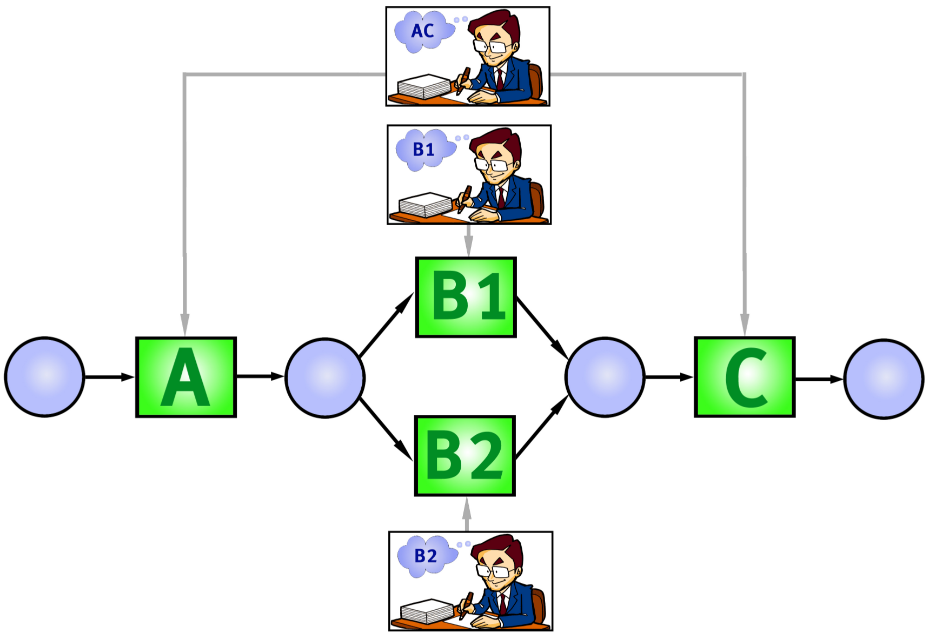
# Triage heuristic : quantification of the implementation

# Triage heuristic

## Quantification of the implementation





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# 1. Introduction

This report has been written as a result of a simulation study in which the impact of the implementation of a particular redesign heuristic has been quantified. The heuristic investigated in this study is the triage 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 triage 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 triage 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
    - Choose variations
    - Specify model variants
    - 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

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 | Chapter 4 & 5 & Appendix A |
| 6. Production runs and results | Appendix B & C |
| 7. Output analysis | Chapter 6 & 7 |
| 8. Conclusions | Chapter 8 |

**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 triage redesign heuristic".*

A set of sub-objectives has been drawn up in order to comply with the main objective of this study:

- Determine for every model variant what the impact of the triage heuristic is.
- Determine what the impact of the triage heuristic is with different arrival rates.
- Determine what the impact of the triage heuristic is with equal and different triage service times.
- Determine what the impact of the triage heuristic is with different arrival ratios.

**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. As eventually two models will be compared, all unused extra details will become redundant and be called off in the comparison.

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

| Performance measures | | | |
|---|---|---|---|
| **Time** | **Cost** | **External Quality** | **Flexibility** |
| Lead time | Total utilization | Nr of specialists used | Labour flexibility WF |
| Queue time per task | Utilization per resource | | Routing flexibility |
| Total queue time | Work in progress | | Volume flexibility |
| TPT per task | Labour cost | | |

**Table 2: Used performance measures**

In order to measure the external quality of a case, it is chosen to use one different performance measure, which is not included in Loosschilder (2006):

- Degree of specialism: This measure indicates the degree of specialism of the resources that worked on one case. The number of executable tasks of the resources that execute the tasks of one case are added up. So, the lower the value of this measure, the higher the expected external quality.

This measure does not directly reflect the external quality dimension. However, the outcomes of this measure can be used to estimate the expected effect of the triage heuristic on the external quality.

A new cost measures has also been introduced:

- Work in progress: This measure depicts the number of cases that is in the complete system. The work in progress can be an indicator of the inventory costs.

An extra analysis measure has been introduced:

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

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

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

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

# 2. Original situation

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

## 2.1 Original model

The process of the original situation consists of four sequential tasks and can be seen in Figure 1.

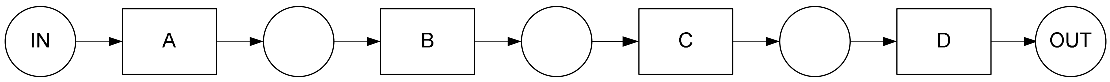


**Figure 1: Model of the original situation**

Two types of cases go through the model of this situation:

- Easy cases
- Hard cases

All four tasks are able to handle both types of cases. Tasks A, C and D are modelled as identical tasks, with an exponentially distributed service time with a mean of 40 (for generalists) or 32 (for specialists) minutes, for easy as well as hard cases. Task B is a different task. In some model variants, there is a difference in the mean value of the service time between easy and hard cases. Both times still have an exponential distribution. This variation in service times is described in Chapter 4. Setup time is left out of consideration in this simulation study.

Another variation, that will be described later, is a variation of resource setups. Different setups with different resource classes have been simulated. These different setups resulted in a difference between specialists and generalists. A generalist is defined as “a resource that can execute more than one task”. A specialist is “a resource that can execute only one task”. “A specialist builds up routine more quickly and may have a more profound knowledge than a generalist” (Reijers, 2003). Therefore specialists can work faster than generalists and deliver higher quality. However, a generalist adds more flexibility to the workflow. In this model, specialists perform tasks 8 minutes faster than generalists, in any model variant and setup. The different service times of the model variants and the difference in service times between specialists and generalists is described in Chapter 4. As a specialist executes a task faster and with a higher quality, its’ salary is 50% higher than that of a generalist. In the simulation models, a generalist earns € 10 per worked hour and a specialist € 15 per worked hour.

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.

As a basis for the comparison with the redesigned situation, a coloured Petri net has been created in CPN Tools. Details and an explanation of the model can be found in the report “Explanation of the simulation model”. The settings of the model, the results of the simulation and the comparison with the redesigned situation are discussed in Chapter 4 and Chapter 5.

## 2.2 Classification of the model

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

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

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

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

## 2.3 Validation of the original model

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

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

- The network has $N$ single-station queues
- The $i$-th station has $s_i$ servers
- There is an unlimited waiting room at each station
- Customers arrive at station $i$ from outside the network according to PP($\lambda_i$). All arrival processes are independent of each other
- Service times of customers at station $i$ are iid Exp($\mu_i$) 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 4 M/M/s queues with the following parameters:

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

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

**Table 4: Theoretical values validation model**

The theoretical value for the lead time is the sum of all system times in Table 4:
$\sum W = W_A + W_B + W_C + W_D = 218.9517$

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 |
| ρ | (0.6599;0.6733) | (0.8880;0.9061) | (0.3311;0.3383) | (0.6626;0.6760) |
| $L_q$ | (0.9875;1.0922) | (6.3518;9.3863) | (0.0786;0.0922) | (1.0787;1.2390) |
| $W_q$ | (14.7404;16.1735) | (94.8511;137.8938) | (1.1774;1.3712) | (16.1917;18.3922) |
| W | (218.3617;263.1088) | | | |

**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 triage redesign heuristic to the model of the original situation. Exiting literature on the triage heuristic has been used as a guideline.

## 3.1 The triage redesign heuristic

According to Reijers (2003), triage can be seen as "the division of a general task into two or more alternative tasks". Seidmann and Sundararajan (1997) define triage as "the separation of customers or work based on a particular distinguishing criterion". There are two situation in which triage can be useful (Van der Aalst and Van Hee, 2002):

- When the allocation of specialized resources reduces the average processing time
- When small clients no longer have to wait for large ones to be processed

Both situation have been simulated and described in Chapter 4 and 5. Hammer and Champy (1993), Klein (1995) and Berg and Pottjewijd (1997) also mention the triage heuristic in their work. Zapf and Heinzl (2000) describe the implementation and the effects of the triage heuristic in a call centre setting.

The alternative and opposite definition of the triage heuristic is: "The integration of two or more alternative tasks into one general task". Since this application of the triage heuristic is less popular and used less often it has been chosen only to use the first definition in this research project.

## 3.2 The redesigned situation

A model of the redesigned situation has been created based on the definitions and formulations of the previous section. The created model represents the situation after the application of the triage heuristic to the model of the original situation, described in Section 2.1. The resulting model of the redesigned situation can be seen in Figure 2.

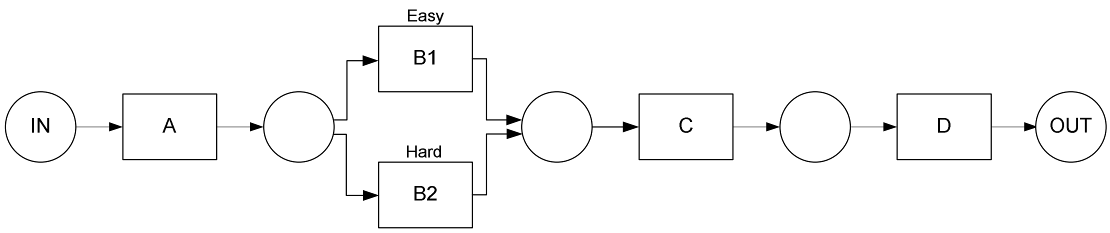


**Figure 2: Model of the redesigned situation**

As can be seen in Figure 2, task B has been divided into two alternative tasks B1 and B2. B1 is a task that is specialized for easy cases and B2 for hard cases. A variation in service times for easy and hard cases as well as a variation in the ratio easy – hard cases has been introduced and simulated. The results are described later in this report. The chosen variations and the resulting model variants are described in the next chapter.

Different setups and variations have been chosen in order to comply with the objectives of this simulation study, described in Section 1.3.

# 4 Experiments

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

## 4.1 Variations triage heuristic

This section describes the setup of the experiments and the chosen variations. In order to quantify the impact of the implementation of the triage heuristic, it has been chosen to introduce four types of variations. Variations in:

- Arrival rate
- Service times
- Arrival ratio easy/hard
- Resources and resource class setups

**Variations in arrival rate**

The first introduced variation is diversity in arrival rate. This variation has been chosen, because changing the arrival rate has a direct effect on the queue times of cases. As arrival rate is also strongly related to the utilization it has been decided to use three different arrival rates which result in a low, a medium and a high utilization. This utilization has been measured in a system with only one resource class containing only generalists. Table 6 gives an overview of different arrival rates and the related, approximate utilizations.

| Arrival rate [$h^{-1}$] | Utilization | Arrival rate [$h^{-1}$] | Utilization |
|---|---|---|---|
| 15 | 50% | 26 | 87% |
| 18 | 60% | 27 | 90% |
| 21 | 70% | 28 | 93% |
| 24 | 80% | 29 | 97% |
| 25 | 83% | 30 | 100+% |

**Table 6: Arrival rate – utilization combinations**

The following arrival processes have been chosen:

- Poisson process with an arrival rate of 28 cases/h. This value has been chosen in order to investigate the system and the differences after redesign at a high utilization rate of the resources. With this arrival rate, the utilization of the resources is approximately 93% (high).
- Poisson process with an arrival rate of 24 cases/h. This arrival rate has been chosen in order to analyze the system with a utilization of approximately 80% (medium).
- Poisson process with an arrival rate of 15 cases/h. This process has been chosen in order to investigate the impact on a system with a utilization of approximately 50% (low)

**Variations in service times**

The second variation is a variation in service times. This variation is chosen in order to investigate what the impact of the triage heuristic is on systems with different service times for easy and hard cases. Three variations in service times for easy and hard cases have been chosen. As explained earlier, a specialist will always execute a task faster than a generalist. The difference between these two types of resources and the chosen variations can be seen in Table 7.

| | Service times generalists | | Service times specialists | |
|---|---|---|---|---|
| | Easy | Hard | Easy | Hard |
| Equal | 40 | 40 | 32 | 32 |
| Different | 32 | 48 | 24 | 40 |
| Completely different | 24 | 56 | 16 | 48 |

**Table 7: Variations in service times**

From Table 7 it can be seen that three variations in service times have been chosen. In the first variant, easy and hard cases have equal service times. In the second variant, the service times of easy cases are shorter than those of hard cases. In the third variant, hard cases have a considerably higher service time than easy cases.

**Variations in ratio easy/hard cases**

The third variation is a varying easy/hard cases ratio. With this variation it can be investigated whether the impact of the triage heuristic differs on a system with a changing arrival ratio. Again three variations have been chosen to investigate. Table 8 sums up the variations in arrival ratio:

| | % Easy | % Hard |
|---|---|---|
| Equal | 50 | 50 |
| Different | 60 | 40 |
| Completely different | 75 | 25 |

**Table 8: Variations in arrival ratio easy/hard cases**

**Variations in resources and resource class setups**

The last type of variation is diversity in resources and resource class setups. This variation has been implemented in order to test what the impact of the triage heuristic is on models with varying resource setups. Therefore different resource classes have been defined and a varying number of resource classes have been introduced. The categorization into the different resource classes is shown in Table 9.

| Original model | | | Redesigned model | | |
|---|---|---|---|---|---|
| Nr | Setup | Type of resources | Nr | Setup | Type of resources |
| **1** | **A-B-C-D** | **SPEC** | 9 | A-B1B2-C-D | SPEC |
| 2 | A-B-C-D | GEN | 10 | A-B1-B2-C-D | SPEC |
| **3** | **ABCD** | **GEN** | 11 | AB1B2CD | GEN |
| 4 | ABCD | COMBI | 12 | AB1B2CD | COMBI |
| **5** | **AB-CD** | **GEN** | 13 | AB1B2-CD | GEN |
| 6 | AB-CD | COMBI | 14 | AB1B2-CD | COMBI |
| **7** | **ACD-B** | **GEN** | 15 | ACD-B1-B2 | GEN |
| 8 | ACD-B | COMBI | 16 | ACD-B1-B2 | COMBI |
| | | | 17 | ACD-B1B2 | GEN |
| | | | 18 | ACD-B1B2 | COMBI |

**Table 9: Resource classes triage heuristic**

In Table 9 three types of resource classes are discerned:

- SPEC: this is a setup with only specialists
- GEN: this is a setup with only generalists
- COMBI: this a setup with a combination of generalists (25%) and specialists (75%)

According to Netjes et al. (2005) a distinctive ratio of specialists and generalists is a ratio with mainly specialists and a few generalists. Therefore it has been chosen to use a combination with 25% generalists and 75% specialists.

Four setups of the original situation (setup 1, 3, 5, 7, indicated in yellow) have been chosen as possible starting points for the analysis. For all model variants (described in the next section) these four setups and their possible redesigns have been simulated and assessed. This results in the following comparisons:

- Setups 1, 2, 9, 10 are compared
- Setups 3, 4, 11, 12 are compared
- Setups 5, 6, 13, 14 are compared
- Setups 7, 8, 15, 16, 17, 18 are compared

## 4.2 Model variants triage heuristic

A combination of all variations leads nine to model variants with each three arrival rates. The model variants are shown in Table 10:

| Model variants triage heuristic | | | | |
|---|---|---|---|---|
| | **Arr rate** | **Service time** | **Ratio** | **Resource setups** |
| Model variant 1 | 15/24/28 | 40-40/32-32 | 50-50 | All |
| Model variant 2 | 15/24/28 | 32-48/24-40 | 50-50 | All |
| Model variant 3 | 15/24/28 | 24-56/16-48 | 50-50 | All |
| Model variant 4 | 15/24/28 | 40-40/32-32 | 60-40 | All |
| Model variant 5 | 15/24/28 | 32-48/24-40 | 60-40 | All |
| Model variant 6 | 15/24/28 | 24-56/16-48 | 60-40 | All |
| Model variant 7 | 15/24/28 | 40-40/32-32 | 75-25 | All |
| Model variant 8 | 15/24/28 | 32-48/24-40 | 75-25 | All |
| Model variant 9 | 15/24/28 | 24-56/16-48 | 75-25 | All |

**Table 10: Model variants triage heuristic**

This resulted in 486 simulation runs. What model variants have been compared for what purpose is described in Section 5.1. The different resource classes and the number of resources per resource classes for every model variant can be found in Appendix A. The next sections describe the setup of the simulations.

## 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 3. 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).

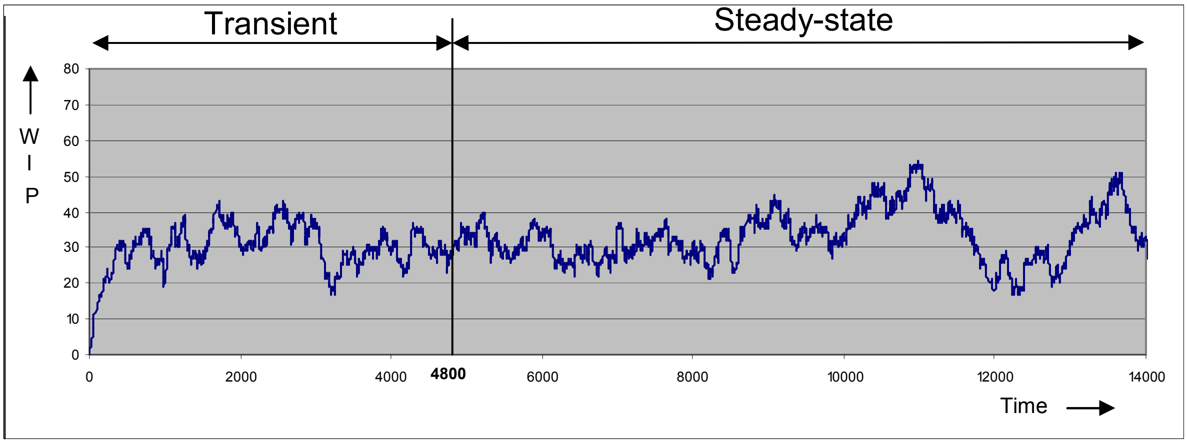


**Figure 3: Example of the warm-up period for one of the replications**

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 4.

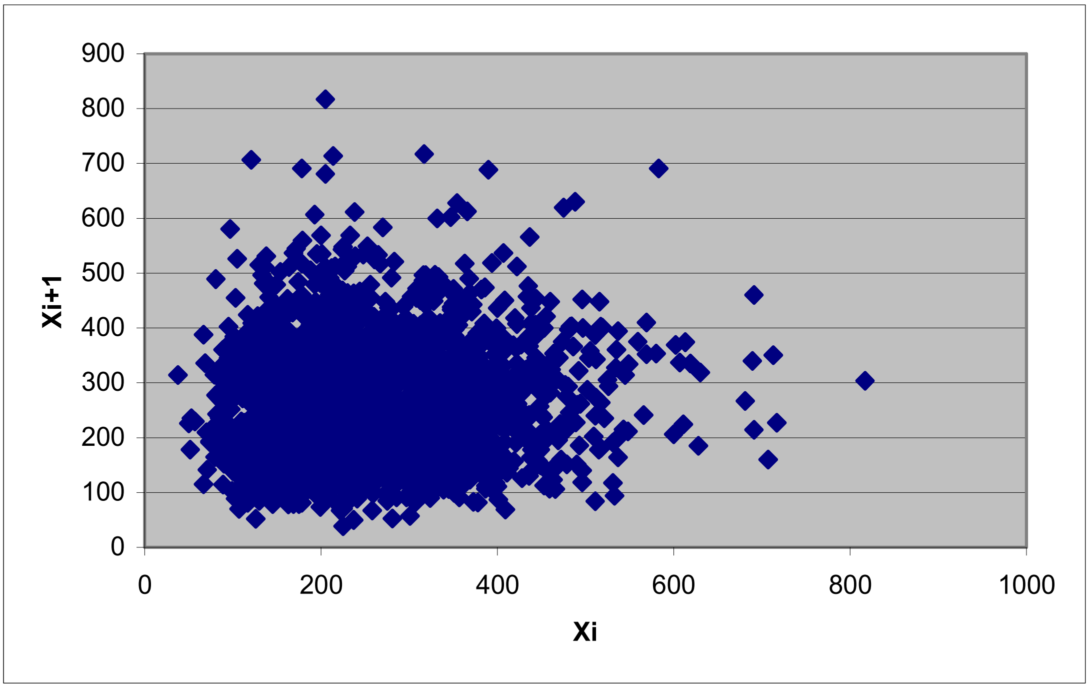


**Figure 4: Scatter plot for lead time, run length = 10 weeks**

From Figure 4 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 modeller should always perform at least three to five replications per simulation.
Law and Kelton (2000) provide a method with which the number of replications can be calculated based on a pre-specified precision of the collected data. The method consists of 3 steps:

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

**Step 1:**
It has been decided to use 4 replications in the pilot run and to test the variable "lead time of the cases". The model of the original situation with only generalists as resources has been simulated, with an arrival rate of 28 cases/h. The following data resulted from the pilot run:

| Results pilot run | |
|---|---|
| $X_{av}$ | 176.104253 |
| S | 7.650084 |

**Table 11: Results pilot run**

**Step 2:**
The absolute error that will be used is 3,5 minutes, which is about 2% of the average value. This seemed to be a reasonable error margin. Other percentages and absolute errors can be chosen, depending on the process, the process owner and the cost and importance of an error.

The absolute error β in the next step is 3,5 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:
$t_{i-1,\alpha/2} = t_{20;0,025} = 2.086$
$n = 4$
$\beta = 3.5$

So, 21 replications will be used in the simulations.

# 5 Setup of the output analysis

This chapter describes the setup of the analysis of the output data. The comparisons and the procedure for the calculations are described in this chapter. The actual output analysis is explained in the next two chapters. Chapter 8 gives the conclusions.

## 5.1 Comparisons

Different models have been compared in order to comply with the objectives of this simulation project, stated in Section 1.3. This Section describes what model variants and setups have been compared to quantify the impact of the triage heuristic and to satisfy the sub-objectives of this simulation project.

**Determine for every model variant what the impact of the triage heuristic is**

The first sub-objective is to determine what the impact of this heuristic is on the model of every model variant. All four original models and their redesigns, shown in Table 9, have been simulated and compared, for every model variant. With these comparisons it is possible to quantify the impact of the triage heuristic for every single model variant, so it can be decided in what situations it is advisable to implement the heuristic.

**Determine what the impact of the triage heuristic is with different arrival rates**

All models in every model variant have been simulated under three different arrival rates in order to test the difference in impact under a different arrival rate. The three models with the different arrival rates within a model variant are compared, to test the difference in impact.

**Determine what the impact of the triage heuristic is with equal and different triage service times**

The third sub-objective is to determine whether there is a difference in impact on the performance of a workflow between models with equal service times for easy and hard cases and models with different service times for the different types of cases. The following comparisons have been made:

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

**Determine what the impact of the triage heuristic is with different arrival ratios**

The fourth sub-objective is to determine whether there is a difference in impact between models with different arrival ratios (ratio easy/hard cases). Models with the same service time variants but differing arrival ratios have been compared. The following comparisons have been made:

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

## 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 triage heuristic and to compare the differences of the different setups under which the heuristic has been implemented:

1. Determine for every measure whether the difference between the original situation and the redesigned situation for the first setup is significant.
2. Calculate the confidence intervals of the relative differences for all measures.
3. Repeat step 1 and 2 for all other setups.
4. Compare the different setups by comparing the confidence intervals.

5. Draw conclusions for all setups in the current model variant.
6. Repeat for all model variants
7. Compare the measures of the different model variants.
8. Draw conclusions for all model variants.

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

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

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

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

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

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

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

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

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

The following test statistic is used:

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

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

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

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

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

In the analysis of this project, the differences of 4 setups have been compared. Therefore, the α of the separate comparisons is 0.05 / 4 = 0.0125.

**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" (Law and Kelton, 2000) are calculated with the following formula:

$$\overline{X_1} - \overline{X_2} \pm t_{f,\alpha/2} \cdot \sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \qquad \text{with} \qquad f = \frac{\left(\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}\right)^2}{\frac{\left(S_1^2/n_1\right)^2}{n_1 - 1} + \frac{\left(S_2^2/n_2\right)^2}{n_2 - 1}}$$

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 5. From this picture it can be seen that the difference between setup

A-B-C-D Gen and A-B1B2-C-D Spec for this measure is not significant, as the confidence intervals overlap. The differences between all other setups are significant.

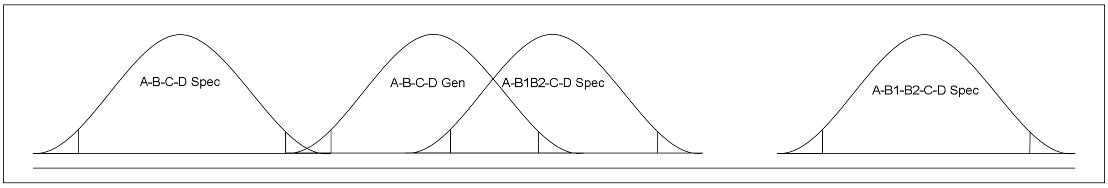


**Figure 5: Example of s setup comparison**

As confidence levels of 98.75% 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 6 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.

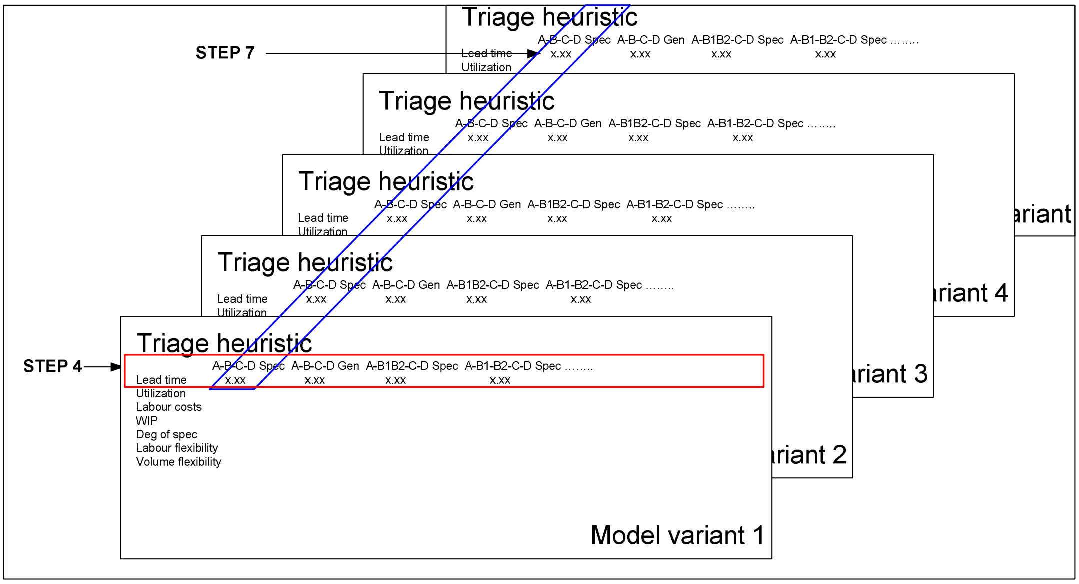


**Figure 6: Comparisons in and between model variants**

The above described procedure is used in the analysis explained in the next two chapters.

# 6 Output analysis intended comparisons

This sixth chapter describes the output analysis of the intended comparisons, as has been defined in the previous chapter. From the output data that has been gathered with the simulations, it can be concluded that the intended comparisons and setups, which have been defined before the simulation and described in Chapter 4 and 5, are not suitable for the quantification of the triage heuristic. The results and analysis of alternative comparisons and setups are described in the next chapter. Why the resulting data is not suitable to comply with the objectives of this simulation study is explained in Section 6.1. Next, Section 6.2 gives the setup of the alternative comparisons, which have been made with the gathered data.

## *6.1 Why are the chosen comparisons not suitable?*

This section gives an explanation of the found reasons why the intended comparisons and setups appeared to be unsuitable.

Figure 7 is showing the confidence intervals of the lead times of all resource setups in model variant 1. After a quick scan of the gathered data of all other model variants, it can be seen that the graphs of all 9 model variants under an arrival rate of 15 cases per hour have the same pattern as the graph of model variant 1 (Figure 7). The same is true for the graphs of Figure 8 (arrival rate 24) and Figure 9 (arrival rate 28). Therefore Figure 7, Figure 8 and Figure 9 represent all model variants.

**Error! Objects cannot be created from editing field codes.**
**Figure 7: Confidence intervals of the lead times of all resource setups, arrival rate 15**

**Error! Objects cannot be created from editing field codes.**
**Figure 8: Confidence intervals of the lead times of all resource setups, arrival rate 24**

**Error! Objects cannot be created from editing field codes.**
**Figure 9: Confidence intervals of the lead times of all resource setups, arrival rate 28**

From the three above depicted graphs, it can be seen that the triage redesigns do not have a significantly lower lead time than the original models, with which they have been compared. The differences in lead time that exist between the different resource setups, are brought about by the difference in types of resources that have executed the tasks (Generalists-specialists heuristic) and not by the implementation of the triage heuristic. Faster working specialists have executed the tasks of the first resource setup (A-B-C-D Spec). This results in a lower lead time compared to the lead time of a setup with only generalists (ABCD Gen). According to Reijers (2003) and Reijers and Limam Mansar (2004), implementation of the triage heuristic should have time advantages. The comparisons in the above shown graph between the original models and the redesigns, do not lead to any positive impact on the time dimension. Why does the triage heuristic have an insignificant impact on the time dimension in the intended comparisons?

After an assessment of the comparisons between the models, it has been concluded that the earlier chosen comparisons are not suitable. The intended redesigns do not change anything in the workflow compared to the models of the original situations. What seems to be a triage redesign is actually a model of the same situation that looks a bit different. When in the original situation task B is executed by generalists, also in the intended redesign, tasks B1 and B2 are executed by generalists. The same holds true for specialists. The wrongly chosen, intended redesigns do not incorporate the advantage of specialists carrying out the tasks in the redesigns. This is the reason why the differences between the original models and the redesigns are insignificant. Other models should have been chosen as the triage redesigns of the original models.

The unsuitability of almost all gathered data in this simulation study emphasizes the importance of the iteratively execution of step 6 and 7 of the project plan of Section 1.2. All data of this simulation project has been gathered first and at once, due to the limited availability of the necessary, indispensable computer power. The gathered data has only been analyzed after the completion of all simulations. The unsuitability of the comparisons would have been uncovered earlier in the analysis process, when an iterative execution of step 6 and 7 was used in which the gathered data was analyzed directly after completion of a part of the simulations. The deficiency of the comparisons would have been found after the simulations and the analysis of model variant 1, arrival rate 15.

However, a part of the gathered data can still be used in different comparisons, in order to quantify the impact of the triage heuristic on two original models. The setup of the alternative comparisons is shown in the next section.

## 6.2 Setup alternative comparisons

After a thorough examination of the output data and a reconsideration of all possible redesigns and the literature on the triage heuristic, it has been concluded that two comparisons between original models and their triage redesigns can be made with the data that resulted from simulating the unsuitable comparisons. The following original model, depicted in Figure 10, has been used as a starting point for the comparison with the redesigns.

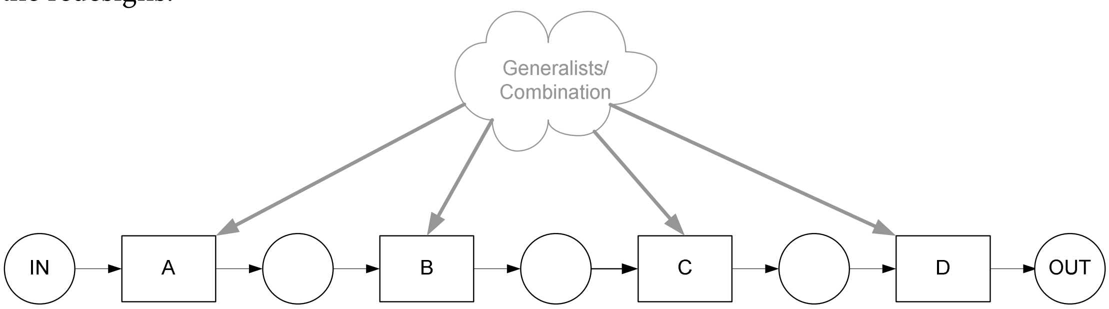


**Figure 10: Original model for the alternative analysis**

The model contains one resource pool that consists of only generalists in the first original model (ABCD Gen) and of a combination of generalists and specialists (as described earlier in Section 4.1) in the second original model (ABCD Combi). Both original models have each been compared to one triage redesign. The model of the redesigns can be seen in Figure 11.

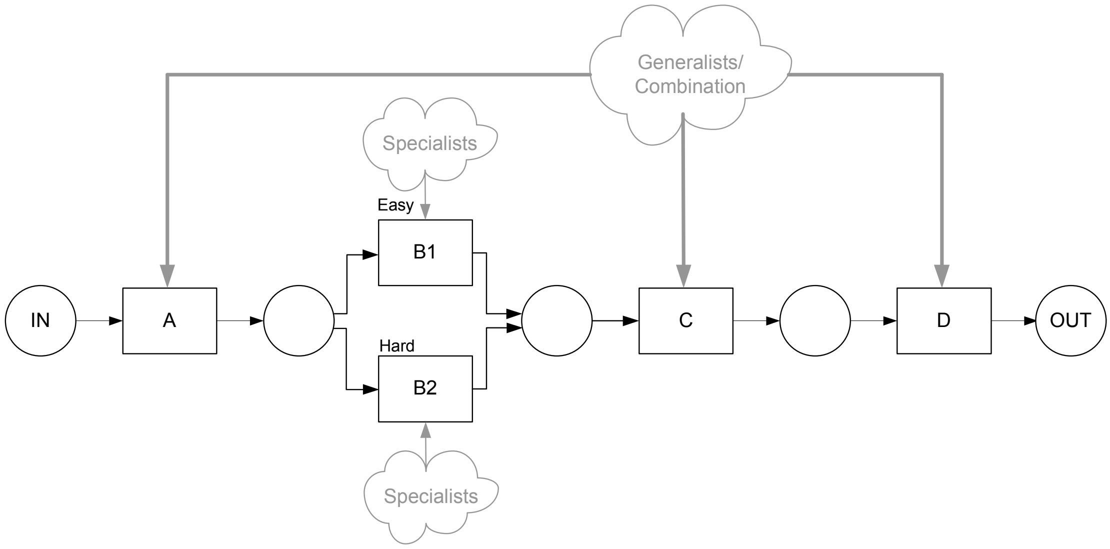


**Figure 11: Model of the triage redesigns for the alternative analysis**

Tasks A, C and D of the redesigned models are again executed by generalists in the first redesign (ACD-B1-B2 Gen) and by a combination of generalists and specialists in the second redesign (ACD-B1-B2 Combi). However, task B has been split up in two alternative tasks B1 and B2, which are both executed by different specialists. Task B1 only handles easy cases, while B2 takes care of the hard cases. The generalists of the original model need to be trained in order to become specialists in the redesign, which induces training cost.

This results in the following comparisons between original models and redesigns:

| Original model | Redesigned model |
|---|---|
| ABCD Gen | ACD-B1-B2 Gen |
| ABCD Combi | ACD-B1-B2 Combi |

**Table 12: Alternative comparisons**

The two discerned resource types in Table 12 are:

- GEN: this is a setup with only generalists
- COMBI: this a setup with a combination of generalists (25%) and specialists (75%)

For example, in setup 'ACD-B1-B2 Gen' tasks A, C and D are executed by generalists from the same resource class and B1 and B2 are both executed by specialists from two separate resource classes.

Other redesigns like AB1CD-B2, in which only task B2 is executed by specialists, are also possible. However, the proposed alternative comparisons are the only possible comparisons with the available data.

All other variations in arrival rate, service times and ratio easy/hard cases, stated in Chapter 4, remained the same in the alternative model variants. An adapted overview of the used model variants of the alternative analysis, based on the overview of Table 10, is shown in Table 13.

| Alternative model variants triage heuristic |
|---|

| | Arrival rate | Service time | Ratio |
|---|---|---|---|
| Model variant 1 | 15/24/28 | 40-40/32-32 | 50-50 |
| Model variant 2 | 15/24/28 | 32-48/24-40 | 50-50 |
| Model variant 3 | 15/24/28 | 24-56/16-48 | 50-50 |
| Model variant 4 | 15/24/28 | 40-40/32-32 | 60-40 |
| Model variant 5 | 15/24/28 | 32-48/24-40 | 60-40 |
| Model variant 6 | 15/24/28 | 24-56/16-48 | 60-40 |
| Model variant 7 | 15/24/28 | 40-40/32-32 | 75-25 |
| Model variant 8 | 15/24/28 | 32-48/24-40 | 75-25 |
| Model variant 9 | 15/24/28 | 24-56/16-48 | 75-25 |

**Table 13: Alternative model variants triage heuristic**

Another deficiency of the executed simulations is that the number of resources of all model variants has been chosen so that the utilizations of the resources are the same for all model variants. This causes small or insignificant differences between the different model variants. A variation that should have been introduced is a variation in number of resources per resource class within one model variant. This would have been a realistic variation. Because of this deficiency, not all comparisons of Section 5.1 have been analyzed.

Some small but necessary adjustments have been made to the calculation procedure of Section 5.2, due to the above described shortcoming. Since there is not much difference between the model variants, it has been decided to omit step 5 and 6, and analyze all model variants at once.

The next chapter describes the alternative analysis and the results. Finally Chapter 8 gives the final conclusions and the recommendations.

# 7 Output analysis alternative comparisons

This chapter describes the output analysis of the alternative comparisons, as described in Section 6.2. As in the alternative comparisons two types of original models (ABCD Gen and ABCD Combi) are compared to their redesigns, both comparisons are analyzed separately. First, Section 7.1 describes the output analysis of the data that resulted from the comparison between the model with only generalists and its' redesign. Next, Section 7.2 describes the analysis of the output data of the models with the resource classes consisting of a combination of generalists and specialists. Finally, Section 7.3 gives a summary of the results. All graphs in this chapter show confidence intervals of the relative differences between the original situation and the triage redesign, for one specific measure

## *7.1 Analysis MV1 – MV9 Generalists*

This first section is about the analysis of the output data of the comparison between the original model with only generalists and its' redesign. Every measure is analyzed separately for all model variants, because the number of resources has been chosen so that the triage heuristic has comparable impacts on most model variants, as explained earlier in Section 6.2. The output data of this alternative comparison can be found in Table 18 – Table 26 in Appendix B. These tables depict the confidence intervals of the differences between the original model and the redesign for all measures and model variants. The following subsections each describe the observations that can be made from the resulting data for one specific measure of performance.

### 7.1.1 Lead time

When looking at the confidence intervals of the differences in lead time of all nine model variants it can be seen that there are two types of graphs. Model variants 1, 2, 3, 4 and 7 all have the same graph of their lead times. The graph of the relative differences in lead time of model variant 1, with three arrival rates is shown in Figure 12.

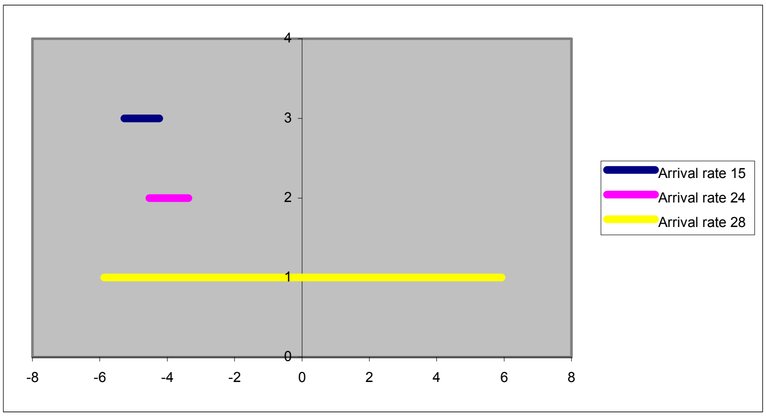


**Figure 12: Confidence intervals of the differences in lead time of MV1, generalists**

Models variants 5, 6, 8 and 9 also have comparable graphs, but do not have the same graph as Figure 12. Figure 13, showing the graph of model variant 8, has the same pattern as the graphs of model variants 5, 6 and 9.

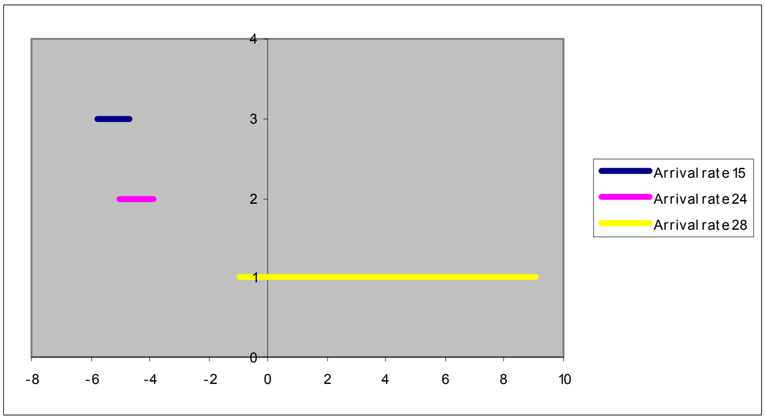


**Figure 13: Confidence intervals of the differences in lead time of MV8, generalists**

From these two graphs it can be seen that there is no difference between the models with an arrival rate of 15 and 24 of Figure 12 and the models with the same arrival rate in Figure 13. In contrast, the models with the highest arrival rate differ considerably. What causes these equalities and differences in the graphs of the different model variants?

Table 14 is a combination of Table 7 and Table 8 of Section 4.1. This table depicts the expected service times of tasks B per type of resource in the original model and of B1 and B2 in the redesigned model in minutes.

| MV | Generalist | | | Specialist | | | Difference |
|---|---|---|---|---|---|---|---|
| | B1 | B2 | B | B1 | B2 | B | |
| MV1 | 20 | 20 | 40 | 16 | 16 | 32 | 8 |
| MV2 | 16 | 24 | 40 | 12 | 20 | 32 | 8 |
| MV3 | 12 | 28 | 40 | 8 | 24 | 32 | 8 |
| MV4 | 24 | 16 | 40 | 19.2 | 12.8 | 32 | 8 |
| MV5 | 19.2 | 19.2 | 38.4 | 14.4 | 16 | 30.4 | 8 |
| MV6 | 14.4 | 22.4 | 36.8 | 9.6 | 19.2 | 28.8 | 8 |
| MV7 | 30 | 10 | 40 | 24 | 8 | 32 | 8 |
| MV8 | 24 | 12 | 36 | 18 | 40 | 28 | 8 |
| MV9 | 18 | 14 | 32 | 12 | 12 | 24 | 8 |

**Table 14: Expected service times tasks B1, B2 and B in minutes**

It can be seen that task B of model variants 1, 2, 3, 4 and 7 has an expected service time of 40 minutes in the original model. However, task B of model variants 5, 6, 8 and 9 has a smaller expected service time, due to the chosen variations. This reduces the queue times of all tasks in the original model (with only one resource pool), as the resources that were executing task B can now be allocated earlier to other tasks. This advantage is lost when a triage redesign is created, because the resources of task B cannot be allocated to other tasks any more. The lead times of the original situation are therefore lower in models in which the arrival rates are high enough to cause queue times. The models with an arrival rate of 15 and 24 cases/h do not have queue times, which are high enough to cause a difference. That is why the graphs of all model variants show the same graph for these arrival rates. The lead times of the original models of model variants 5, 6, 8 and 9 with an arrival rate of 28 are so low (because of lower queue times) that the lead time of the triage redesign is equal or even higher. This causes the significantly less positive impact on models with an arrival rate of 28 in model variants 5, 6, 8 and 9.

An insignificant difference or even an increase in lead time can also be expected when the number of resources of tasks B1 and B2 are chosen so that the utilization of one of the classes is high and the other one is low. The resource class with a high utilization will cause a queue for its' task while resources from the other resource class are waiting without the possibility of being allocated to the other task.

**Analysis:**
From Figure 12 and Figure 13 it can be seen that implementation of the triage redesign leads in all model variants to a 4 – 5% lower lead time in models with a low arrival rate of 15 cases/h and to a 3 – 4% decrease in models with a medium arrival rate of 24 cases/h. This decrease in lead time is brought about by the faster working specialists that execute tasks B1 and B2 in the redesigned situation.

The lead times of models with a high arrival rate of 28 cases/h do not change significantly after the redesigning effort. The reduction of time resulting from the faster execution of tasks B1 and B2 are annulled by the higher queue times of tasks A, C and D in the redesign. As explained earlier, this is due to the loss of flexibility in models with higher queue times.

The queue times increase when the arrival rate increases. When the queue times increase, the reduction of lead time decreases as the loss of time caused by the higher queue times outweighs the gain in time that resulted from the faster working specialists.

### 7.1.2 Utilization

The graphs, showing the confidence intervals of the differences in utilizations, are comparable for all model variants, unlike the graphs of the lead times. The graph of Figure 14, showing the confidence intervals of the relative differences in utilization of model variant 1, and the analysis of the differences in utilization can therefore be generalized onto the other model variants. This equality in differences is caused by the equal gain in service times for all model variants (8 minutes, see Table 14)

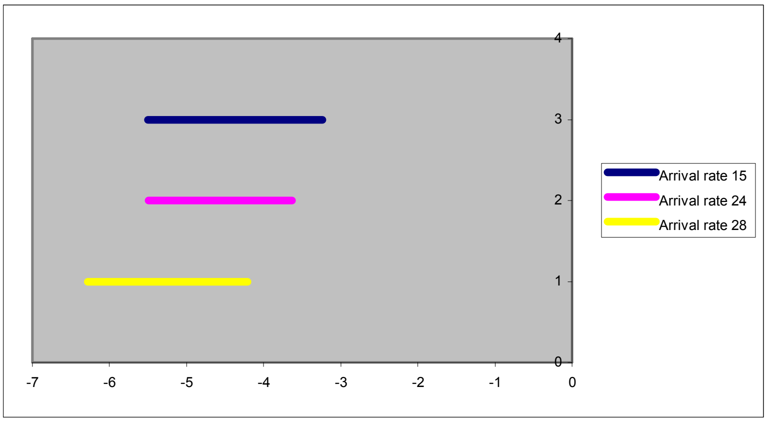


**Figure 14: Confidence intervals of the differences in utilization of MV1, generalists**

From Figure 14, it can be seen that creating two alternative tasks B1 and B2 results in a 5% lower utilization for all model variants. These lower utilizations are caused by the lower service times of tasks that are executed by specialists in the redesign. The difference in utilization is not significantly different for models with another arrival rate. This is because the arrival rate does not affect the service times of the tasks. From Table 14 it can be seen that the gain in service time is on average 8 minutes for all model variants. The arrival rate only affects the queue times and the lead times.

### 7.1.3 Labour cost

As already mentioned in Section 2.1, specialists are more expensive than generalists. In this study it has been assumed that a specialist earns 50% more per worked hour (€15) than a generalist (€10). This assumption is based on the characteristics of a specialist: a specialist works quicker and delivers higher quality (Reijers, 2003). This difference in salary causes a difference in labour cost between the original situation and the redesign. The difference between the labour cost of the original model and that of the redesign is the result of additional salary costs of more expensive specialists minus the gain in costs caused by the decrease in the amount of worked hours, which is the result of faster working specialists. In this situation, 20 generalists are turned into specialists (which cost €5 more per worked hour) and 8 minutes are worked less per case. This causes an increase in labour cost. The labour cost will decrease when the difference in salary decreases and/or the gain in service time increases.

The differences are comparable for all model variants, as the number of specialists, the difference in salary and the difference in worked hours are constant for all model variants. Figure 15 shows the confidence intervals of the relative differences in labour costs for model variant 1. The differences are comparable for all model variants.

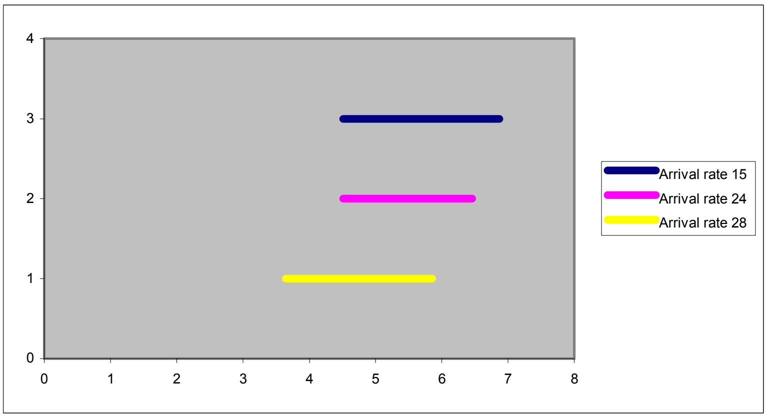


**Figure 15: Confidence intervals of the differences in labour cost of MV1, generalists**

Implementation of the triage heuristic in models comparable to these models leads to an average increase in labour cost of 4 – 6%. This increase is caused by the more expensive specialists.

The increase and the degree in increase are specific for the chosen settings (€5 difference in salary and 8 minutes difference in service time). Different settings lead to different increases or even to decreases. Different combinations and settings have been simulated in order to investigate the increase and decrease in labour costs in this redesigned model. Table 15 shows a sensitivity analysis for the relative difference in labour cost with different combinations of salary differences and service time differences.

| Service time differences | Salary differences | | | | |
|---|---|---|---|---|---|
| | €3 | €4 | €5 | €6 | €7 |
| 4 | 4,1% | 6,3% | 8,5% | 10,8% | 13,0% |
| 6 | 3,0% | 5,2% | 7,3% | 9,5% | 11,6% |
| 8 | 0,5% | 2,5% | 4,5% | 6,5% | 8,5% |
| 10 | -2,4% | -0,5% | 1,4% | 3,2% | 5,1% |
| 12 | -3,1% | -1,2% | 0,6% | 2,4% | 4,3% |

**Table 15: Relative difference in labour cost with different combinations, generalists**

From the results of the sensitivity analyses in Table 15 it can be seen that when specialist still work 8 minutes faster than generalists, the difference in salary must be lower than €3 per worked hour for the labour cost to decrease. When the difference in salary is €5, the service time of a specialist must be at least 13 minutes shorter than that of a generalist.

### 7.1.4 WIP level

The WIP level measure is strongly related to the lead time and is affected the same way by the implementation of the triage heuristic. For the same reasons as for lead time, the graphs of the WIP level of model variants 1, 2, 3, 4 and 7 show an equal pattern. The graphs of model variants 5, 6, 8 and 9 also have a comparable pattern, which is different from the patterns of the other model variants. Again the graphs of model variants 1 and 8, shown in Figure 16 and Figure 17 have been used as an example for the other related model variants.

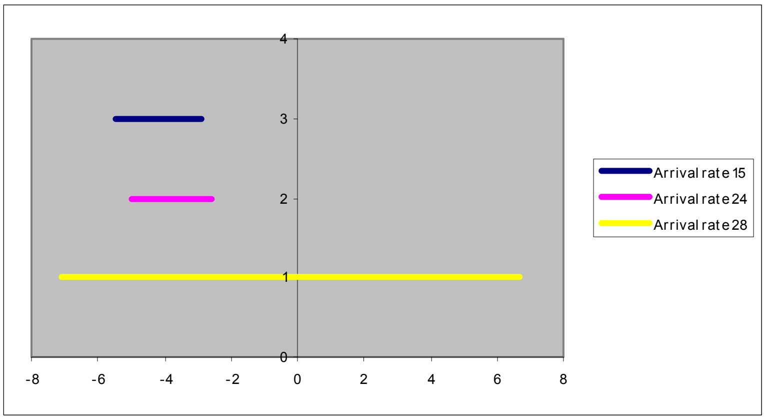


**Figure 16: Confidence intervals of the differences in WIP level of MV1, generalists**

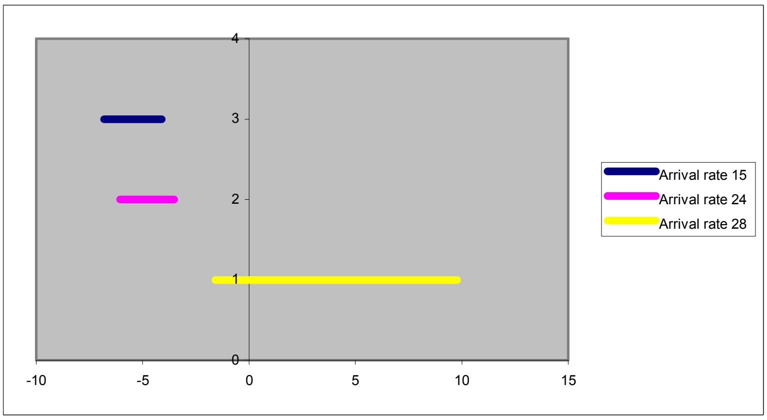


**Figure 17: Confidence intervals of the differences in WIP level of MV8, generalists**

Also for WIP level it can be seen that models with a low arrival rate of 15 cases/h, have a 4 – 6% decrease in the redesign. Models with a medium arrival rate of 24 cases/h have a 3 – 4% decrease in all model variants. The WIP levels of model variants 1, 2, 3, 4 and 7 with a high arrival rate do not change significantly and the differences are not significantly different from those of the models with the lower arrival rates. This is in contrast to the differences of the models with a high arrival rate of model variants 5, 6, 8 and 9, which are significantly lower compared to the models with a lower arrival rate. The impact on the WIP level is less positive on these models. This observation is in accordance with the observations of the lead time.

### 7.1.5 Degree of specialism

This measure has been added to the set of performance measures that resulted from the preceding literature review, as discussed earlier in Section 1.3. Its' outcome does not directly reflect the impact of the triage heuristic on the quality dimension, but it only gives an indication of the effect of the triage heuristic on the quality dimension.

The value of the degree of specialism measure of the original model is higher compared to that of the redesign. The value is 20 for the original situation. All resources of the original situation can perform five tasks: A-B1-B2-C-D. Although B1 and B2 are not discerned in the original situation, they are counted in the degree of specialism, in order to make a fair comparison with the same measure in the redesign. All four tasks are executed by a resource that can execute five tasks. This makes the degree of specialism 20. The value for the redesigned situation is 10. The resources from one resource class, executing three of the four tasks for one case (A-C-D) can execute three tasks (A-C-D). Both tasks B1 and B2 are executed by a resource, which can only execute one task. This brings the value to 10.

As explained earlier in Section 1.3, the lower the value of this measure the higher the expected impact on the external quality. It can therefore be expected that the delivered external quality of the redesigned situation is higher than that of the original situation. That the value of the original situation is two times the value of the redesigned situation does not mean that the impact on the external quality is twice as high in the redesign. It is important to consider that it is just an indicator.

### 7.1.6 Labour flexibility

Again, as for lead time and WIP level, two types of graphs showing the confidence levels can be found. The first type is the graph of model variants 1, 2, 3, 4 and 7. It looks like the graph of Figure 18, which shows the relative confidence intervals of the differences in labour flexibility of model variant 1. The second type of graph is the graph of model variants 5, 6, 8 and 9, which shows the same differences for arrival rates 15 and 24, but a more negative difference for models with an arrival rate of 28. This more negative impact on the labour flexibility is caused by the higher labour flexibility of the original models of model variants 5, 6, 8 and 9, compared to the constant labour flexibility of the redesigns of all model variants. However, none of the model variants has a significant difference in impact between the different arrival rates.

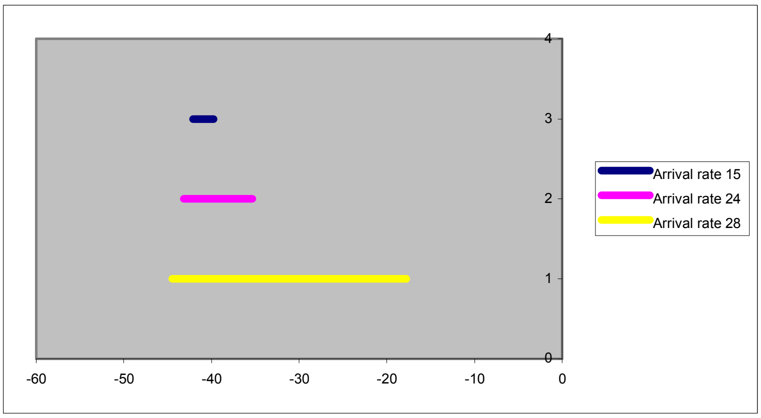


**Figure 18: Confidence intervals of the differences in labour flex. of MV1, generalists**

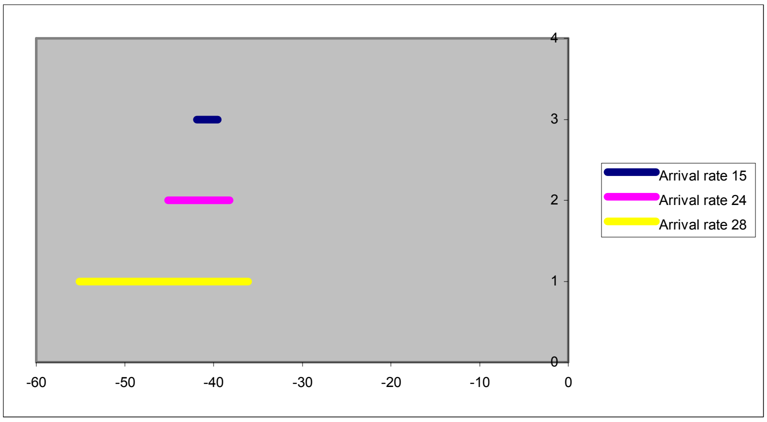


**Figure 19: Confidence intervals of the differences in labour flex. of MV8, generalists**

Turning generalists into specialists with the implementation of the triage heuristic has a negative impact on the labour flexibility of a workflow, since generalists can be allocated to more tasks than specialists. The labour flexibility is on average reduced with 40%.

### 7.1.7 Volume flexibility

Although, the difference between the graphs is smaller here compared to the previous measures, two types of graph can also be discerned for volume flexibility. The triage heuristic has an equal impact on the volume flexibility of model variants 1, 2, 3, 4 and 7. The graph of Figure 20 represents the pattern for the volume flexibility of all these model variants. Model variants 5, 6, 8 and 9 have divergent graphs. An example of the pattern of the volume flexibility of these model variants can be seen in Figure 21. The impact on models with a low (15) and medium (24) arrival rate is equal for all model variants. However, the impact on models with a high arrival rate is higher for model variants 1, 2, 3, 4 and 7 compared to model variants 5, 6, 8 and 9. The reason for this difference is the same as before; the volume flexibility of the original model is higher in model variants 5, 6, 8 and 9. The relative difference with the redesign is therefore smaller.

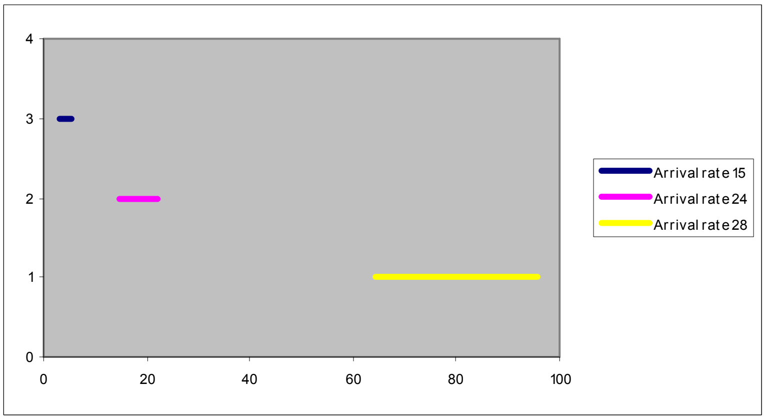


**Figure 20: Confidence intervals of the differences in volume flex. of MV1, generalists**

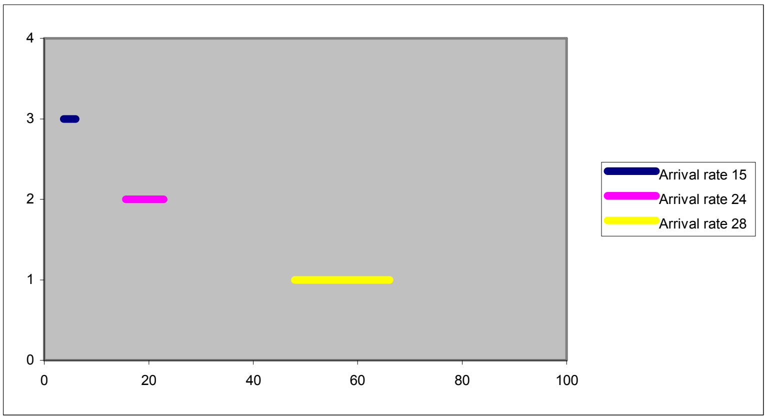


**Figure 21: Confidence intervals of the differences in volume flex. of MV8, generalists**

Implementation of the triage heuristic increases the volume flexibility of all model variants under all arrival rates. This increase is due to the lower service times of the tasks, which are performed by specialists in the redesign. The relative increase is higher on models with a high arrival rate. The increases in volume flexibility under the different arrival rates are respectively 5%, 20% and 60 – 80%.

## 7.2 Analysis MV1 – MV9 Combination

This section describes the analysis of the output data of the comparison between the original model with a combination of generalists and specialists and its' redesign. As in the previous section, every measure is analyzed separately for all model variants. The output data of this second alternative comparison can be found in Table 27 – Table 35 in Appendix C. These tables show the confidence intervals of the relative differences between the original model and the redesign for all measures. The following subsections each describe the observations that can be made from the resulting data for one specific measure of performance.

### 7.2.1 Lead time

Also for the differences in lead times of this situation, two types of graphs can be distinguished:

- The graphs of model variants 1, 2, 3, 4, 5 and 7 in which models with an arrival rate of 15 have the highest decrease, models with an arrival rate of 24 only have a small or no significant decrease and models with a high arrival rate have an increase in lead time. The graph of model variant 1, which represents this group of model variants, is shown in Figure 22.
- The graphs of model variants 6, 8 and 9. These model variants also have comparable graphs. The graph of the differences in lead times of model variant 8 is an example of this type of graph and can be seen in Figure 23.

The cause of the difference between the types of graph is similar to that of the situation in Section 7.1. Only model variant 5 is now in the group with the first type of graph. The decrease in expected service time of task B, which can be seen in Table 14, is apparently not big enough (38,4) to cause a significant difference in this situation.

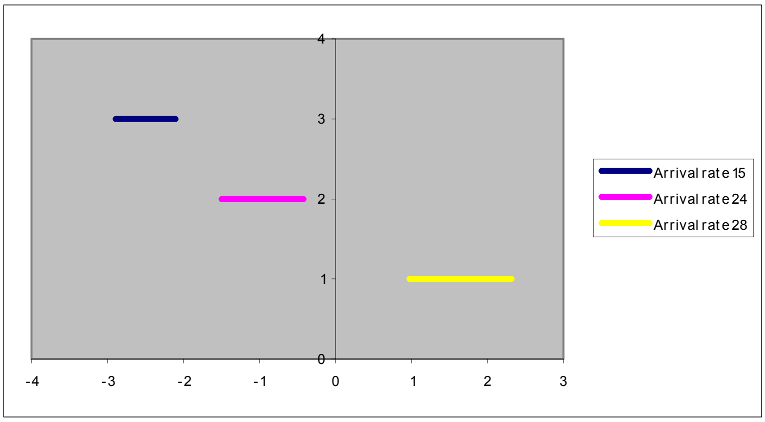


**Figure 22: Confidence intervals of the differences in lead time of MV1, combi**

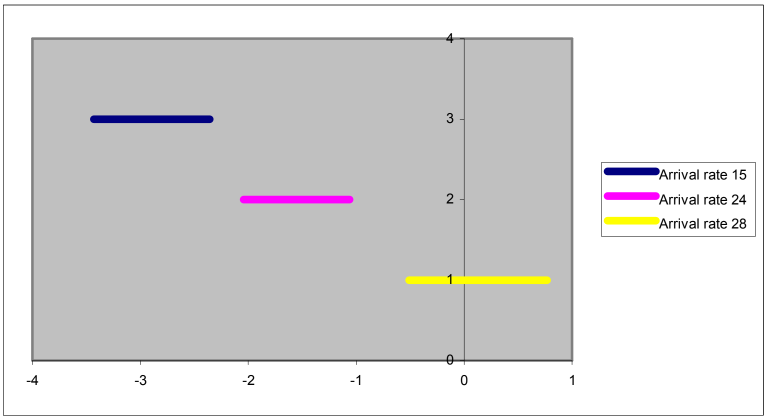


**Figure 23: Confidence intervals of the differences in lead time of MV8, combi**

### Arrival rate 15

The lead time of the redesigned models with a low (15) arrival rate are on average 2 – 3% lower compared to the original models, in all model variants. This is lower than the decrease in lead time in the situation with only generalists (4 – 5%), described in Section 7.1. This is because in this situation, task B of the original model is not only executed by generalist, but also by specialists. This causes a lower lead time in the original situation. The decrease in lead time by adding a few more specialists is therefore lower. The gain in service times in all model variants was 8 minutes per case in the previous situation (40-32=8); in this situation the gain in service time is only 2 minutes (34-32=2).

### Arrival rate 24

Implementation of the triage heuristic also leads to lower lead times for models with a medium arrival rate of 24 cases/h. However, the gains are only small (and even insignificant in model variants 2 and 3); on average 0 – 2%. The small gain in lead time is again caused by faster working specialists that execute tasks B1 and B2, instead of a combination of generalists and specialists. The gain in lead time is smaller compared to models with an arrival rate of 15 cases/h. This is different from the observation of the situation with only generalists, where the difference in impact between models with a low and medium arrival rate was insignificant. The reason for the lower impact in this situation is a lower lead time of the original model with a medium arrival rate compared to original models with a low arrival rate. This is because under a higher arrival rate, fewer tasks are executed by generalists (due to the high utilizations of the generalists) and more tasks by specialists. This causes a smaller relative difference between the original situation and the redesign.

**Arrival rate 28**
Models with an arrival rate of 28 cases/h even have an increase in lead time in model variants 1, 2, 3, 4, 5, and 7. The lead times of the other model variants do not change significantly or decrease slightly (MV9). The differences in impact between the type of graphs are again caused by the lower expected service times of task B. Under this high arrival rate, the queue times high. The lower flexibility of the resources in the redesign causes queue times, which outweighs the gain in lead time that results from the faster working specialists.

From these observations it can be seen that the impact of the triage heuristic on this situation is comparable to the impact on the situation with only generalists. The implementation of the heuristic has a positive impact on the lead time when the arrival rate is not high enough to cause queue times.

### 7.2.2 Utilization

The differences in utilizations are comparable for all model variants and all arrival rates, in accordance with the differences in utilization of the previous situation. Again the same explanation can be given for the equality in differences. The gain in service time is equal for all models variants and all arrival rates: 2 minutes. Resources have to work fewer hours, because of these lower service times. Figure 24 is showing the confidence intervals of the relative differences in utilization for model variant 1. This graph is comparable to the graphs of the other model variants.

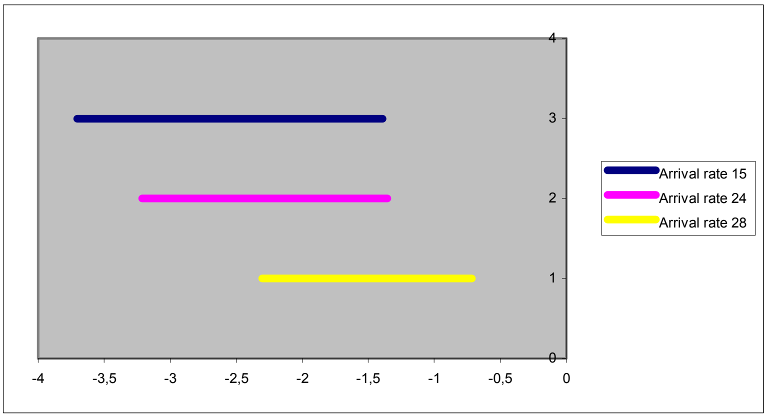


**Figure 24: Confidence intervals of the differences in utilization of MV1, combi**

The utilization of the redesigned model is 1 – 4% lower compared to the utilization of the original model. No significant difference exists between the differences of the arrival rates, since arrival rate does not affect the service times and the difference in working hours.

The differences are lower compared to the differences of the previous situation, due to the lower gain in service times.

### 7.2.3 Labour cost

Also for this situation, the labour cost of the original model has been compared to the labour cost of the redesign, since specialists have higher salaries than generalists. All model variants have the same type of graph. The graph of model variant 1, shown in Figure 25, represents all model variants. None of the model variants shows a significant difference in impact for the different arrival rates. Models with an arrival rate of 24 (model variants 1, 5, 8 and 9) and models with an arrival rate of 28 (4, 7 and 9) have an only just insignificant difference, in some model variants.

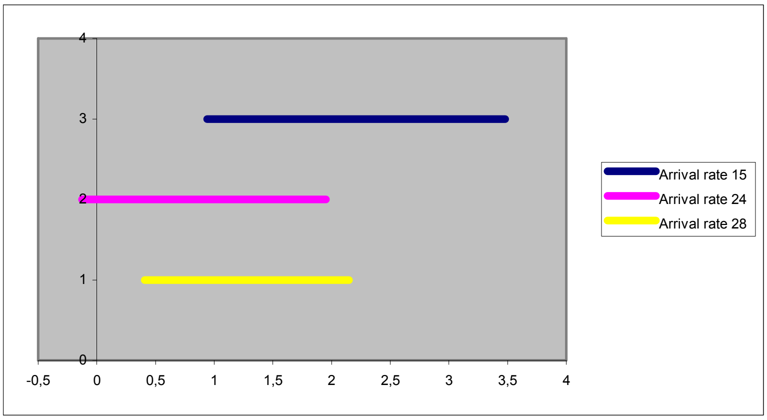


**Figure 25: Confidence intervals of the differences in labour cost of MV1, combi**

The labour cost of this situation mainly increases. In this situation, the increases are on average 1 – 3%. This is lower compared to the increases of the previous situation. As defined before, the difference between the labour cost of the original model and that of the redesign is the result of additional salary costs of more expensive specialists minus the gain in costs caused by the decrease in the amount of worked hours, which is the result of faster working specialists. With the salaries of this situation, the additional costs outweigh the gain in costs of working fewer hours. Here, only five extra specialists are used in the redesign and only 2 minutes are gained per case. The additional salary costs are therefore lower compared to the additional costs (20 extra specialists) of the previous situation. These low numbers result in small or even insignificant differences.

As discussed in the previous situation, the increase and the degree in increase are specific for the chosen settings. In this situation the difference in salary between a generalists and a specialist is €5 and the difference in service time is 2 minutes. Different settings lead to different increases or even to decreases. Different combinations and settings have been simulated in order to investigate the increase and decrease in labour costs in this redesigned model. Table 16 shows a sensitivity analysis for the relative difference in labour cost with different combinations of salary differences and service time differences. The differences in service times are given in minutes. The numbers between brackets are the service times of specialists, which causes the difference in expected service time of a task.

| **Service time differences** | **Salary differences** | | | |
|---|---|---|---|---|
| | **€3** | **€4** | **€5** | **€6** |
| 1 (36) | 1,7% | 2,6% | 3,3% | 4,1% |
| 2 (32) | 1,0% | 1,8% | 2,6% | 3,4% |
| 3 (28) | -2,0% | -1,2% | -0,4% | 0,3% |
| 4 (24) | -2,2% | -1,3% | -0,5% | 0,2% |

**Table 16: Relative difference in labour cost with different combinations, combi**

From the results of the sensitivity analyses in Table 16, it can be seen that when faster working specialists cause a difference in service time of 2 minutes, the difference in salary must be lower than €3 per worked hour for the labour cost to decrease. When the difference in salary is €5, the service time of a specialist must be 12 minutes shorter than that of a generalist (which causes a 3 minute shorter service time of a task). The differences in service times are smaller in this situation, since shorter service times of specialists also lower the service times of complete tasks in the original situation, unlike in the previous situation.

### 7.2.4 WIP level

When looking at the differences in WIP levels of this situation, it can be seen that again there are two types of graphs. In the first type of graph, the difference of models with an arrival rate of 24 is only small or insignificant. The second type of graph has an insignificant difference in WIP level for models with an arrival rate of 28. The models with an arrival rate of 15 have a significant decrease in WIP level for all model variants. Figure 26, showing the relative differences in WIP level of model variant 2, is an example of the first type of graph. Model variants 1, 3 and 7 have comparable graphs. Figure 27 is an example of the second type of graph in which models with an arrival rate of 28 have insignificant differences in WIP levels. Model variants 4, 5, 6, 7 and 9 have comparable graphs. Model variant 7 is a combination of both types, since models with arrival rate of 24 and 28 both have insignificant differences.

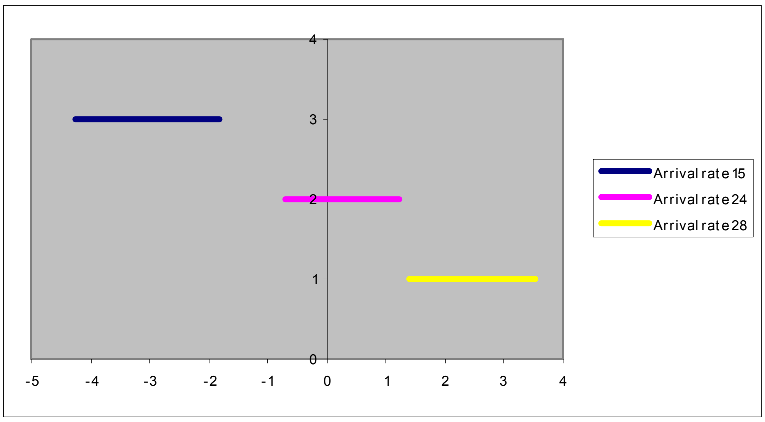


**Figure 26: Confidence intervals of the differences in WIP level of MV2, combi**

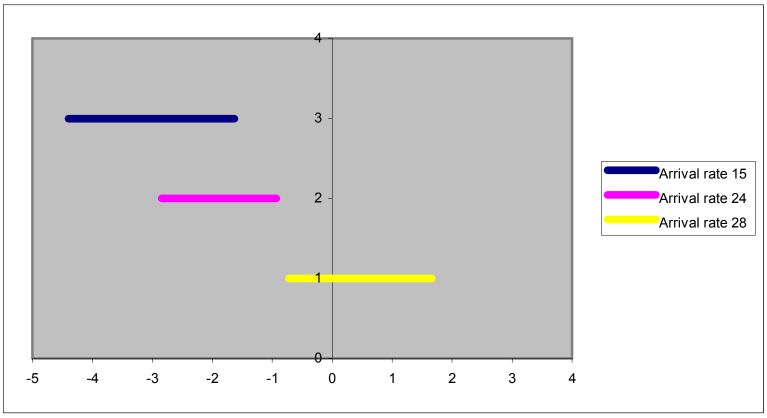


**Figure 27: Confidence intervals of the differences in WIP level of MV8, combi**

**Arrival rate 15**

The WIP levels of all model variants decrease significantly with 2 – 4% under an arrival rate of 15 cases/h. This decrease is caused by the faster working specialists. In the redesign, cases leave the system earlier than in the original model. This causes the decrease in the number of cases in the system: the WIP level. The decrease is again lower compared to the previous situation of Section 7.1. This is because the gain in time is smaller than in the previous situation.

**Arrival rate 24**

As WIP level is closely related to lead time, the same trend in graphs can be found. The differences in WIP level are only small or even insignificant. The difference in this situation is only 0 – 2%. The same explanation as for lead time of models with an arrival rate of 24 can be used to explain this phenomenon. The WIP level of the original situation is low because more specialists execute the tasks under a higher arrival rate instead of generalists. This causes the small differences, compared to models with an arrival rate of 15. The differences of this situation are again smaller compared to those of the previous situation. This is also here the result of the smaller gain in time.

**Arrival rate 28**
The same explanation holds true for models with a high arrival rate. However, the occurrence of queue times can even make the WIP level increase. The increase in WIP level is on average 0 – 2% for all models variants.

### 7.2.5 Degree of specialism

The degree of specialism is also in this situation measured in order to give an indication of the impact of the triage heuristic on the expected quality of the output. The value of this measure has been measured in the same way as that of the same measure in the situation of Section 7.1. Generalists are able to execute five tasks, while specialists of task B perform two tasks and other specialists only one.

From the output data it can be seen that the degree of specialism increases after the redesigning effort as the values of this measure are lower in the redesign. The increase is bigger in models with a low arrival rate, because more tasks are executed by generalists in the original model. The utilizations of the generalists increase, when the arrival rate of the process increases. These utilizations increase so far that these generalists are working all the time, so more specialists execute the tasks in the original model. This increases the degree of specialism of the original models, which lowers the difference with the redesigned models.

These lower values mean an increase in degree of specialism. So, the expected external quality will be higher after the redesigning effort. Again, it must be said that this measure is only an indicator of the impact on the external quality and not a reflector.

### 7.2.6 Labour flexibility

This first flexibility measure, determines the difference in labour flexibility between the original and the redesigned situation. The graphs of all model variants show a comparable graph with a decrease in labour flexibility for all three arrival rates. The decreases in labour flexibility of model variant 1 are shown in Figure 28.

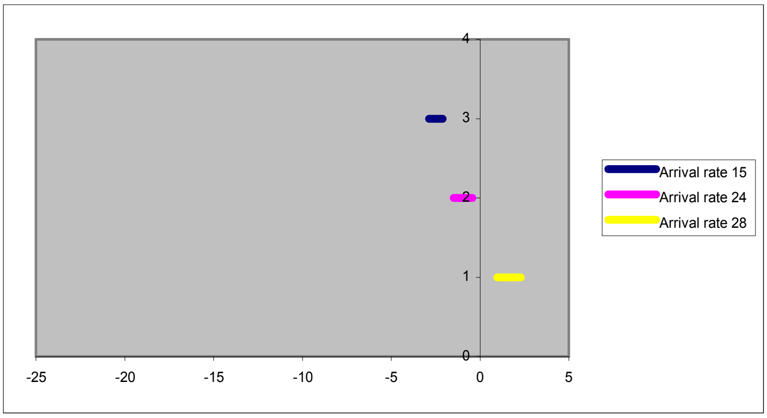


**Figure 28: Confidence intervals of the differences in labour flexibility of MV1, combi**

The labour flexibility of all models is lower in the redesign. This is according the expectation since specialists are less flexible than generalists. It can also be seen that the difference is higher in models with a low arrival rate. This is because the labour flexibility of the original situation is lower in models with a higher arrival rate, as fewer generalists execute the tasks. This lower labour flexibility results in a smaller difference with the redesign. The decrease of models with a low arrival rate is on average 16 – 18% while the decrease of the models with a medium and high arrival rate is approximately 10 – 15%. These percentages are lower than the decreases of the previous situation (40%). This is because in this situation fewer generalists are trained to become a specialist.

### 7.2.7 Volume flexibility

The last monitored performance measure is volume flexibility. Again all model variants have a comparable pattern in their graphs. The models of all model variants show an increase in volume flexibility for all three arrival rates. Figure 29 shows an example of the differences in volume flexibility.

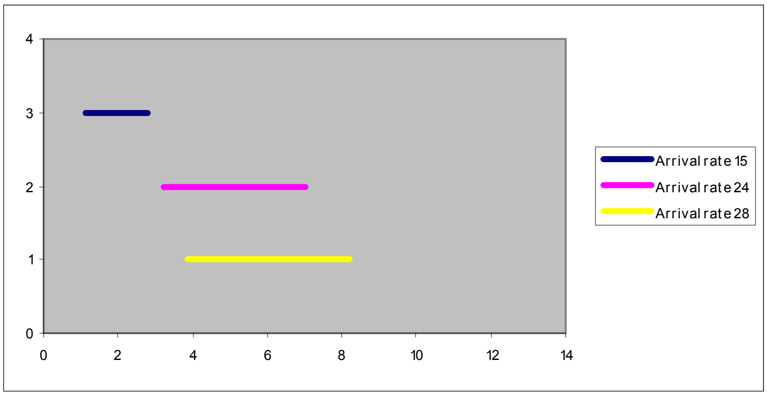


**Figure 29: Confidence intervals of the differences in volume flexibility of MV5, combi**

It can be seen that the increase of models with a low arrival rates are only small: 2%. The models with an arrival rate of 24 cases/h have a slightly higher increase of 5%. The models with a high arrival rate have an average increase of 6%. This increase is the result of the gain in available time of the more specialized resources. The increases are lower compared to those of the previous situation. This is because the gain in lead time is smaller in this situation and fewer generalists are turned into faster working specialists.

## *7.3 Summary of the results of the analysis*

This concluding section gives an overview and a summary of the results. The results of the analysis of both situations are summarized. Table 17 gives an overview of the impact of the triage redesign heuristic on the performance of the workflows of both situations. The relative differences between the original situations and the redesigns are depicted in this table. These relative differences are differences between the average values of the original model and the redesign and can be used to discover a trend in the differences.

| | Generalists | | | Combination | | |
|---|---|---|---|---|---|---|
| **Arrival rate** | **15** | **24** | **28** | **15** | **24** | **28** |
| Lead time | -4,5% | -3,5% | 0% | -2,5% | -1% | 0% |
| Utilization | -5% | -5% | -5% | -2,5% | -2,5% | -2,5% |
| Labour cost | 5% | 5% | 5% | 1,5% | 1,5% | 1,5% |
| WIP level | -5% | -3,5% | 0% | -3% | -1% | 1% |
| Labour flexibility | -40% | -40% | -40% | -17% | -12,5% | -12,5% |
| Volume flexibility | 5% | 20% | 70% | 2% | 5% | 6% |

**Table 17: Summary of the impact of the triage redesign heuristic**

The following observation can be made from the overview of Table 17:

- **Lead time**: Creating two alternative tasks for task B lowers the lead times of the cases in models in which the arrival rate is not high enough to cause queue times. This decrease in lead time is the result of faster working specialists that execute alternative tasks B1 and B2. However, the difference in lead time is insignificant or it can even increase in models with higher arrival rates. The queue times of the redesigned model are higher due to the reduced flexibility of the more specialistic resources.
- **Utilization**: The utilizations of the redesigned models are lower than the utilizations of the resources classes in the original models. This decrease in utilization is the result of the lower service times of the tasks that are executed by specialists in the redesigns. The difference in utilization is constant for all arrival rates, since arrival rate does not affect the service times.
- **Labour cost**: The labour cost of the redesigned models is higher compared to the original model, due to the extra specialists, which are paid more per worked hour. Although the specialists work faster, with fewer working hours as a result, the additional salary costs cause the labour cost to increase. The difference in labour cost can be insignificant or the cost can even decrease when the difference in salary becomes smaller and/or the gain in service time increases. The differences in labour cost are constant for all arrival rates.
- **WIP level**: The differences in WIP level are related to the differences in lead time. Implementation of the triage heuristic leads to a decrease in WIP level in models with an arrival rate that is not high enough to cause queue times. These lower WIP levels are the result of the lower service times of tasks B1 and B2. With higher arrival rates, the lower flexibility of the resources causes higher queue times in the redesigned model. As the gain in service times cannot compensate for the loss in time caused by the higher queue times, the difference in WIP level becomes insignificant or the WIP level even increases.
- **Labour flexibility**: The labour flexibility of the workflow decreases after the redesigning effort under all arrival rates. These decreases are induced by the lower number of tasks that a specialist can execute, compared to a generalist. This makes a generalist more flexible in the allocation.
- **Volume flexibility**: Implementation of the triage heuristic increases the volume flexibility of the workflow. The specialists in the redesign have lower service times than the generalists in the original model. This causes the volume flexibility to increase. The increase of the volume flexibility is higher in models with a higher arrival rate.
- **Degree of specialism**: The values of this measure decrease in the redesign, which means that the expected external quality is higher in the redesign. This is obvious, because more specialists work on a case. The allocation of more specialists is an indication of higher quality of the output (external quality).

- The impact of the triage heuristic is higher on the original situation with only generalists compared to the original situation with a combination of generalists and specialists. This can be seen from Table 17, where the relative differences of the situation with only generalists are higher.

# 8 Conclusions and recommendations

This final chapter gives the conclusions and recommendations based on the analysis of the resulting output data. First Section 8.1 gives the conclusions that resulted from the analysis. Then Section 8.2 gives a reflection on the triage heuristic. Finally Section 8.3 describes some recommendations for the future use of the approach that has been used in this project.

## 8.1 Conclusions

This section gives the conclusions on the implementation of the triage heuristic, based on the conclusions on the analysis of the intended combinations and the analysis of the alternative combinations. The conclusions of the intended comparisons focus on the process, while the conclusions of the alternative comparisons focus more on the results.

**Intended comparisons:**

- The step with the setup of the simulations and the selection of the variations and variants is a very important step of the project plan, presented in Section 1.2. Well chosen variations and variants are essential for the success of the simulation project.
- The iteratively execution of step 6 and 7 of the project plan is very important. The gathered data must be analyzed immediately after the simulation, before the simulation of the next model variant.
- The availability of the indispensable computer power is of great importance.

**Alternative comparisons:**

- Replacing task B with two alternative tasks B1 and B2, results in all tested situations in lower utilizations, higher labour cost, lower labour flexibility and higher volume flexibility. Lower utilization and higher volume flexibility are positive and higher labour cost and lower labour flexibility is negative.
- Implementation of the triage heuristic leads to a decrease in lead time and WIP level in models with an arrival rate that is low enough to prevent the occurrence of queue times. Both measures can even increase in models with higher arrival rates.
- The expected quality of the output is higher after implementation of the triage heuristic, since more specialists work on a case.
- Using the triage heuristic to redesign a workflow induces one time training cost, as generalists must be trained to become specialists.
- The positive results of enhanced performance, caused by the implementation of the triage heuristic explain the lower popularity of the opposite definition of the triage heuristic (The integration of two or more alternative tasks into one general task). In all situations where the triage heuristic lead to positive results, the opposite of the heuristic leads to negative results.

## 8.2 Reflection triage heuristic

This section gives a reflection on the impact of the triage heuristic on the performance of a workflow. A comparison is made between the generalized results of this simulation study and the qualitative analysis of Reijers and Limam Mansar (2004)

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

- Time: +2
- Cost: +2
- Quality: +3
- Flexibility: -1

The positive impact on the time dimension indicated by Reijers and Limam Mansar (2004) has also been found in this simulation study, but only in models with a low arrival rate. The impact on the cost dimension is different in this simulation project. Lower WIP levels in models with a low arrival rate result in lower inventory costs. In contrast, more expensive specialists result in higher labour cost and the training of generalists to become specialists causes training cost. The conclusion of increased external quality is in accordance with the conclusion of this project. The labour flexibility of this project is reduced considerably, while the volume flexibility increases. The impact on the flexibility dimension is high in this simulation project.

## 8.3 Recommendations

This last section gives recommendations on the use of the project plan, which result from the application of the plan in this simulation project and on the execution of a subsequent simulation project on the triage heuristic

**Recommendations on the use of the project plan**

- Plan and spend enough time on step 5 of the project plan, in which the setup of the simulation takes place. Incorrect chosen variations make the rest of the steps and the resulting output data unusable.
- Use existing literature to choose variations which seem to have impact on the implementation of the chosen heuristic.
- Analyze the data that results from simulating the first part of the first model variant directly after the simulation, to test whether the chosen variations and setups are correct and continue to execute step 6 and 7 iteratively.
- Organize enough available computer power, so the execution of step 6 and 7 of the plan can be iteratively throughout the entire simulation project, as recommended above.

**Recommendations for future research**

- Choose AB1CD-B2 as a redesign of the original situations ABCD Gen and ABCD Combi and investigate the difference in impact, compared to the results of this study.
- Investigate the impact of the triage heuristic on a model with a different resource setup in order to be able to generalize the results.
- Simulate and investigate a system with the application of the opposite definition of the triage heuristic, to verify the expected negative impact.
- Vary the number of resources per resource class, so that the utilizations of all resource classes do not remain the same.

# Literature

Van der Aalst, W.M.P., Van Hee, K.M. (2002): Workflow Management: Models, Methods, and Systems, MIT Press, Cambridge

Berg, A., Pottjewijd, P. (1997): Workflow: Continuous Improvement by Integral Process Management, Academic Service, Schoonhoven (In Dutch)

Bowerman, B.L., O'Connell, R.T. (1997): Applied Statistics: Improving Business Processes, Irwin, London

Cho, Y.H., Kim, J.K., Kim, S.H. (1998): Role-Based Approach to Business Process Simulation Modeling and Analysis, *Computers and Industrial Engineering*, **35**(1-2), 343-346

Goossenaerts, J., Pels, H.J. (2005): Methodology for the simulation of operational processes, Eindhoven University of Technology, Technology Management, IS.

Greasley, A. (2003): Using Business-Process Simulation within a Business-Process reengineering Approach, *Business Process Management Journal*, **9**(4), 408-420

Hammer, M., Champy, J. (1993): Reengineering the Corporation; A Manifesto for Business Revolution. Harper Business, New York

Hays, W.L. (1994): Statistics, Harcourt Brace College, Forth Worth, TX

Van Hee, K.M., Reijers, H.A. (2000): Using Formal Analysis Techniques in Business Process Redesign, in Van der Aalst, W.M.P., Desel, J., Oberweis, A. (Eds.) (2000): Business Process Management: Models, Techniques and Empirical Studies, *Lecture Notes in Computer Science 1806*. Springer-Verlag, Berlin, 142-160

Kirk, R.E. (1982): Experimental Design: Procedures for the Behavioral Sciences, Brooks/Cole Publishing Company, Monterey, California

Klein, M. (1995): 10 Principles of Reengineering. *Executive Excellence*, **12**(2), 20

Kulkarni, V.G. (1999): Modeling, Analysis, Design, and Control of Stochastic Systems, Springer-Verlag, New York

Law, A.M., Kelton, W.D. (2000): Simulation Modeling and Analysis, McGraw-Hill Book Co, Singapore

Loosschilder, M.W.N.C. (2006): Literature Review: Quantification and Operationalization of Performance Dimensions for Workflows, *Report Literature Review*

Mehta, A. (2000): Smart modeling: Basic methodology and advanced tools, *Proceedings of the winter simulation conference*, Joines, J.A., Barton, R.R., Kang, K., Fishwick, A., eds., 241-245

Miller, R.G., Jr. (1981): Simultaneous Statistical Inference, Springer-Verlag, New York

Montgomery, D.C., Runger, G.C. (2003): Applied Statistics and probability for engineers, Wiley, New York

Netjes, M., Van der Aalst, W.M.P., Reijers, H.A. (2005): Analysis of Resource Constrained Processes with Colored Petri Nets, CPN'05

Ott, R.L., Mendenhall, W. (1994): Understanding Statistics, International Thomson Publishing, Belmont, California

Reijers, H.A. (2003): Design and Control of Workflow Processes: Business Process Management for the Service Industry, Springer Verlag, Berlijn

Reijers, H.A., Limam Mansar, S. (2004): Best Practices in Business Process Redesign: an Overview and Qualitative Evaluation of Successful Redesign Heuristics, *Omega, The International Journal of Management Science*, **33**, 283-306

Seidmann, A., Sundararajan, A. (1997): Competing in Information-Intensive Services: Analyzing the Impact of Task Consolidation and Employee Empowerment, *Journal of Management Information Systems*, **14**(2), 33-56

Tumay, K. (1996): Business Process Simulation, *Proceedings of the 1996 Winter Simulation Conference*, Charnes, J.M., Morrice, D.J., Brunner, D.T., Swain, J.J., eds., 93-98

Zapf, M., Heinzl, A. (2000): Evaluation of Generic Process Design Patterns: an Experimental Study, in Van der Aalst, W.M.P., Desel, J., Oberweis, A. (Eds.) (2000): Business Process Management: Models, Techniques and Empirical Studies, *Lecture Notes in Computer Science 1806*. Springer-Verlag, Berlin, 83-98

# Appendix A

Resource setups intended combinations

**Resource setups model variant 1:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 7 | B2 | 8 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 7 | B2 | 8 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 10 | B2 | 10 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 10 | B2 | 10 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 10 | B2 | 10 | | | | | | |

**Resource setups model variant 2:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 6 | B2 | 9 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 6 | B2 | 9 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 7 | B2 | 13 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 7 | B2 | 13 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 7 | B2 | 13 | | | | | | |

**Resource setups model variant 3:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 4 | B2 | 11 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 4 | B2 | 11 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 5 | B2 | 15 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 5 | B2 | 15 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 5 | B2 | 15 | | | | | | |

**Resource setups model variant 4:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 9 | B2 | 6 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 9 | B2 | 6 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 12 | B2 | 8 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 12 | B2 | 8 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 12 | B2 | 8 | | | | | | |

**Resource setups model variant 5:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 7 | B2 | 8 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 7 | B2 | 8 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 9 | B2 | 11 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 9 | B2 | 11 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 9 | B2 | 11 | | | | | | |

**Resource setups model variant 6:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 5 | B2 | 10 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 5 | B2 | 10 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 7 | B2 | 13 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 7 | B2 | 13 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 7 | B2 | 13 | | | | | | |

**Resource setups model variant 7:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 4 | B2 | 11 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 4 | B2 | 11 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 15 | B2 | 5 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 15 | B2 | 5 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 15 | B2 | 5 | | | | | | |

**Resource setups model variant 8:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 9 | B2 | 6 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 9 | B2 | 6 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 13 | B2 | 7 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 13 | B2 | 7 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 13 | B2 | 7 | | | | | | |

**Resource setups model variant 9:**

| | | Class 1 | | Class 2 | | Class 3 | | Class 4 | | Class 5 | | Class 6 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AB1B2CD | COMBI | AB1B2CD | 20 | A | 15 | B1 | 7 | B2 | 8 | C | 15 | D | 15 |
| AB1B2-CD | COMBI | AB1B2 | 10 | A | 15 | B1 | 7 | B2 | 8 | CD | 40 | | |
| AB1B2CD | GEN | AB1B2CD | 80 | | | | | | | | | | |
| AB1B2-CD | GEN | AB1B2 | 20 | CD | 20 | | | | | | | | |
| A-B1B2-C-D | SPEC | A | 20 | B1B2 | 20 | C | 20 | D | 20 | | | | |
| A-B1-B2-C-D | SPEC | A | 20 | B1 | 10 | B2 | 10 | C | 20 | D | 20 | | |
| ABCD | COMBI | ABCD | 20 | A | 15 | B | 15 | C | 15 | D | 15 | | |
| AB-CD | COMBI | AB | 10 | A | 15 | B | 15 | CD | 40 | | | | |
| ABCD | GEN | ABCD | 80 | | | | | | | | | | |
| AB-CD | GEN | AB | 40 | CD | 40 | | | | | | | | |
| A-B-C-D | GEN | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| A-B-C-D | SPEC | A | 20 | B | 20 | C | 20 | D | 20 | | | | |
| ACD-B | COMBI | ACD | 15 | A | 15 | B | 20 | C | 15 | D | 15 | | |
| ACD-B | GEN | ACD | 60 | B | 20 | | | | | | | | |
| ACD-B1B2 | COMBI | ACD | 15 | A | 15 | B1B2 | 20 | C | 15 | D | 15 | | |
| ACD-B1-B2 | COMBI | ACD | 15 | A | 15 | B1 | 10 | B2 | 10 | C | 15 | D | 15 |
| ACD-B1B2 | GEN | ACD | 60 | B1B2 | 20 | | | | | | | | |
| ACD-B1-B2 | GEN | ACD | 60 | B1 | 10 | B2 | 10 | | | | | | |

# Appendix B

Output data alternative comparisons triage heuristic, situation with only generalists:

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,2674 | -4,2324 | -4,5293 | -3,3697 | -5,8721 | 5,9317 |
| Utilisation_all_resources | -5,5016 | -3,2384 | -5,4938 | -3,6292 | -6,2789 | -4,2105 |
| Labour_Cost | 4,5093 | 6,8673 | 4,5121 | 6,4569 | 3,6474 | 5,8552 |
| WIP_data_col | -5,4941 | -2,9017 | -5,0074 | -2,6047 | -7,1272 | 6,6492 |
| Lab_Flex_WF | -42,1090 | -39,7822 | -43,1604 | -35,3317 | -44,4819 | -17,7750 |
| Volume_Flex | 3,2030 | 5,4414 | 14,6642 | 22,1987 | 64,1751 | 95,7007 |

**Table 18: Output data model variant 1, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,2981 | -4,3549 | -4,4081 | -3,1807 | -6,4198 | 3,0782 |
| Utilisation_all_resources | -6,4349 | -4,0646 | -6,3875 | -4,1188 | -5,8344 | -4,3460 |
| Labour_Cost | 3,5174 | 5,9627 | 3,5598 | 5,9259 | 4,1254 | 5,7003 |
| WIP_data_col | -6,3556 | -3,8205 | -5,1849 | -2,7281 | -7,2016 | 3,5353 |
| Lab_Flex_WF | -41,4212 | -39,1892 | -42,1950 | -33,8416 | -40,7651 | -19,4345 |
| Volume_Flex | 4,0590 | 6,4261 | 16,7225 | 25,9341 | 64,7868 | 86,9753 |

**Table 19: Output data model variant 2, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,4341 | -4,2124 | -4,4007 | -3,1900 | -4,3921 | 6,7446 |
| Utilisation_all_resources | -5,7470 | -3,3721 | -5,8820 | -4,3848 | -6,2244 | -4,4709 |
| Labour_Cost | 4,2381 | 6,7279 | 4,0855 | 5,6690 | 3,6537 | 5,5593 |
| WIP_data_col | -5,7362 | -3,2048 | -5,1521 | -3,1087 | -5,2110 | 7,3395 |
| Lab_Flex_WF | -41,7518 | -39,6273 | -40,8998 | -34,4404 | -42,4856 | -20,9371 |
| Volume_Flex | 3,3273 | 5,6704 | 17,8328 | 23,9215 | 67,9501 | 94,5997 |

**Table 20: Output data model variant 3, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,3402 | -4,3138 | -4,6204 | -3,5338 | -6,2985 | 4,9064 |
| Utilisation_all_resources | -5,9572 | -3,6549 | -5,7209 | -3,9460 | -6,3961 | -4,3798 |
| Labour_Cost | 4,0141 | 6,4399 | 4,2882 | 6,1290 | 3,4963 | 5,6603 |
| WIP_data_col | -5,9545 | -3,3927 | -5,0786 | -2,8767 | -7,0720 | 5,7315 |
| Lab_Flex_WF | -41,5875 | -39,3077 | -42,0105 | -34,5562 | -45,1571 | -19,5641 |
| Volume_Flex | 3,6151 | 5,8921 | 15,9445 | 23,1164 | 66,7555 | 97,4867 |

**Table 21: Output data model variant 4, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,4564 | -4,3258 | -4,5300 | -3,5777 | -2,7139 | 3,6393 |
| Utilisation_all_resources | -6,1209 | -3,6325 | -6,1669 | -4,3447 | -5,9986 | -4,3201 |
| Labour_Cost | 3,5107 | 6,0617 | 3,4212 | 5,2854 | 3,5712 | 5,2940 |
| WIP_data_col | -6,2991 | -3,6204 | -5,3873 | -3,1139 | -3,2403 | 3,8773 |
| Lab_Flex_WF | -42,2999 | -39,7753 | -44,5762 | -36,5709 | -50,5154 | -27,4028 |
| Volume_Flex | 3,5688 | 6,0135 | 16,7617 | 23,7917 | 55,9496 | 77,6880 |

**Table 22: Output data model variant 5, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,3839 | -4,3206 | -4,6817 | -3,6934 | -0,1755 | 7,6818 |
| Utilisation_all_resources | -5,6058 | -3,2913 | -5,7458 | -4,2577 | -5,7293 | -4,1969 |
| Labour_Cost | 3,5733 | 6,0295 | 3,4256 | 5,0225 | 3,4605 | 5,0710 |
| WIP_data_col | -5,6472 | -3,2792 | -5,2779 | -3,2890 | -0,2658 | 8,4753 |
| Lab_Flex_WF | -42,9230 | -40,9495 | -46,3014 | -40,3832 | -57,2688 | -39,2850 |
| Volume_Flex | 3,1148 | 5,3052 | 15,5712 | 21,0139 | 46,4680 | 63,4347 |

**Table 23: Output data model variant 6, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,0623 | -4,2003 | -4,3194 | -3,1917 | -4,9723 | 2,2987 |
| Utilisation_all_resources | -5,7449 | -3,6198 | -5,8584 | -4,0396 | -5,9656 | -4,3512 |
| Labour_Cost | 4,2450 | 6,4534 | 4,1186 | 5,9823 | 4,0153 | 5,7011 |
| WIP_data_col | -5,4368 | -3,1507 | -4,8492 | -2,5335 | -5,4299 | 3,0978 |
| Lab_Flex_WF | -40,9426 | -38,7354 | -40,9669 | -33,2092 | -41,8977 | -18,2136 |
| Volume_Flex | 3,5803 | 5,6821 | 16,3225 | 23,6717 | 66,3177 | 90,9253 |

**Table 24: Output data model variant 7, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,7999 | -4,6816 | -4,9987 | -3,8778 | -0,9292 | 9,0761 |
| Utilisation_all_resources | -6,3223 | -3,9208 | -6,3900 | -4,3852 | -6,1693 | -4,4771 |
| Labour_Cost | 2,6367 | 5,1019 | 2,4982 | 4,6420 | 2,7275 | 4,4941 |
| WIP_data_col | -6,8055 | -4,1063 | -6,0476 | -3,5263 | -1,5725 | 9,7768 |
| Lab_Flex_WF | -41,8632 | -39,5283 | -45,1280 | -38,1759 | -55,1353 | -36,0885 |
| Volume_Flex | 3,7453 | 6,0392 | 15,6786 | 22,8461 | 47,9944 | 66,1350 |

**Table 25: Output data model variant 8, generalists**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -5,6347 | -4,6554 | -5,1827 | -4,2970 | -0,5287 | 6,1379 |
| Utilisation_all_resources | -5,6471 | -3,3272 | -6,3631 | -4,5647 | -6,9701 | -5,1587 |
| Labour_Cost | 2,2854 | 4,6828 | 1,4927 | 3,3712 | 0,8262 | 2,7379 |
| WIP_data_col | -5,6210 | -3,0968 | -6,0105 | -3,8149 | -1,4719 | 6,1383 |
| Lab_Flex_WF | -44,2214 | -42,2038 | -49,7320 | -44,1563 | -60,7255 | -46,8650 |
| Volume_Flex | 2,9639 | 5,0303 | 14,5793 | 20,3234 | 45,4885 | 61,4603 |

**Table 26: Output data model variant 9, generalists**

# Appendix C

Output data alternative comparisons triage heuristic, situation with combination of resources:

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -2,8821 | -2,0944 | -1,4899 | -0,4148 | 0,9691 | 2,3054 |
| Utilisation_all_resources | -3,7038 | -1,3924 | -3,2118 | -1,3556 | -2,3016 | -0,7174 |
| Labour_Cost | 0,9386 | 3,4780 | -0,1255 | 1,9497 | 0,4060 | 2,1463 |
| WIP_data_col | -3,8899 | -1,1302 | -2,2109 | -0,1045 | 0,5600 | 3,1118 |
| Lab_Flex_WF | -18,6709 | -15,7269 | -14,9005 | -10,3992 | -15,8220 | -8,0554 |
| Volume_Flex | 1,1069 | 2,9445 | 3,0207 | 7,1564 | 2,8601 | 9,1755 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 27: Output data model variant 1, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,4089 | -2,3702 | -0,6659 | 0,3559 | 1,9623 | 3,2925 |
| Utilisation_all_resources | -4,1686 | -1,9461 | -2,2130 | -0,4265 | -2,3920 | -0,8079 |
| Labour_Cost | 0,4464 | 2,9326 | 1,0004 | 2,9955 | 0,3014 | 2,0436 |
| WIP_data_col | -4,2625 | -1,8098 | -0,6887 | 1,2340 | 1,4030 | 3,5383 |
| Lab_Flex_WF | -17,8841 | -15,3794 | -17,0161 | -12,6618 | -15,2305 | -8,6317 |
| Volume_Flex | 1,5581 | 3,3377 | 0,9320 | 4,8364 | 3,2053 | 9,4899 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 28: Output data model variant 2, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,3065 | -2,3012 | -1,1206 | 0,0140 | 1,4528 | 2,6977 |
| Utilisation_all_resources | -3,8848 | -1,5617 | -2,8842 | -1,2115 | -1,8860 | -0,0676 |
| Labour_Cost | 0,7426 | 3,3545 | 0,2438 | 2,0993 | 0,8666 | 2,8631 |
| WIP_data_col | -3,7173 | -1,5368 | -1,9472 | 0,2985 | 1,2893 | 3,7403 |
| Lab_Flex_WF | -18,0732 | -15,7470 | -15,4573 | -10,7881 | -16,9688 | -9,3129 |
| Volume_Flex | 1,2377 | 3,0786 | 2,6982 | 6,4245 | 0,2633 | 7,3409 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 29: Output data model variant 3, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -2,8614 | -1,8933 | -1,4242 | -0,4051 | 0,4073 | 1,8962 |
| Utilisation_all_resources | -3,0948 | -1,0819 | -3,0754 | -1,3578 | -2,8606 | -0,9657 |
| Labour_Cost | 1,6385 | 3,8481 | 0,0221 | 1,9369 | -0,2073 | 1,8714 |
| WIP_data_col | -3,1022 | -0,4982 | -2,3783 | -0,3522 | -0,4083 | 2,6956 |
| Lab_Flex_WF | -18,6778 | -15,7912 | -14,0401 | -9,6692 | -14,8203 | -5,8416 |
| Volume_Flex | 0,8601 | 2,4603 | 3,0256 | 6,8526 | 3,8495 | 11,4036 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 30: Output data model variant 4, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,2659 | -2,3581 | -1,5391 | -0,6078 | 0,1693 | 1,3039 |
| Utilisation_all_resources | -3,6248 | -1,4343 | -3,2377 | -1,4852 | -2,1916 | -1,0258 |
| Labour_Cost | 1,0170 | 3,4064 | -0,1494 | 1,8015 | 0,5426 | 1,8222 |
| WIP_data_col | -3,6007 | -1,3621 | -2,6207 | -0,4662 | -0,1931 | 1,5475 |
| Lab_Flex_WF | -19,4665 | -16,9714 | -16,3006 | -11,7464 | -16,8429 | -11,5999 |
| Volume_Flex | 1,1068 | 2,7970 | 3,2182 | 7,0157 | 3,8408 | 8,2069 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 31: Output data model variant 5, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,1021 | -1,9172 | -1,9301 | -0,8414 | -0,4878 | 0,6659 |
| Utilisation_all_resources | -3,9921 | -1,4521 | -2,8790 | -1,1080 | -2,3178 | -0,8602 |
| Labour_Cost | 0,4825 | 3,3514 | 0,2854 | 2,2602 | 0,4128 | 2,0194 |
| WIP_data_col | -4,1057 | -1,4762 | -2,0602 | -0,3063 | -0,8870 | 1,1629 |
| Lab_Flex_WF | -20,1873 | -17,6269 | -18,3787 | -14,9341 | -19,6790 | -14,0957 |
| Volume_Flex | 1,1157 | 3,0674 | 2,2882 | 5,9457 | 3,0898 | 8,3251 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 32: Output data model variant 6, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -2,8323 | -2,1219 | -1,3387 | -0,2069 | 0,5481 | 1,9614 |
| Utilisation_all_resources | -3,7516 | -1,6065 | -2,6390 | -0,7322 | -2,8956 | -1,2802 |
| Labour_Cost | 0,8689 | 3,2277 | 0,5084 | 2,6364 | -0,2482 | 1,5246 |
| WIP_data_col | -3,9063 | -1,0875 | -1,3931 | 0,9515 | -0,5049 | 2,0934 |
| Lab_Flex_WF | -15,7246 | -12,6856 | -13,1243 | -8,3833 | -9,8328 | -2,1566 |
| Volume_Flex | 1,2772 | 2,9826 | 1,6316 | 5,8800 | 5,1035 | 11,5430 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 33: Output data model variant 7, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,4306 | -2,3574 | -2,0431 | -1,0621 | -0,5100 | 0,7672 |
| Utilisation_all_resources | -4,0840 | -2,0965 | -3,3175 | -1,6438 | -2,1557 | -0,5623 |
| Labour_Cost | 0,3829 | 2,6575 | -0,2017 | 1,6735 | 0,6067 | 2,3605 |
| WIP_data_col | -4,3934 | -1,6325 | -2,8451 | -0,9290 | -0,7160 | 1,6639 |
| Lab_Flex_WF | -17,6852 | -14,9879 | -15,0265 | -11,1412 | -17,6396 | -11,4077 |
| Volume_Flex | 1,5910 | 3,0994 | 3,3701 | 6,8018 | 1,9565 | 7,5018 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 34: Output data model variant 8, combination**

| | Arrival rate 15 | | Arrival rate 24 | | Arrival rate 28 | |
|---|---|---|---|---|---|---|
| | LB | UB | LB | UB | LB | UB |
| Lead_Time_complete | -3,8844 | -2,6187 | -2,3503 | -1,2980 | -1,4789 | -0,6046 |
| Utilisation_all_resources | -4,3959 | -1,7822 | -3,2924 | -1,5741 | -3,1067 | -1,2900 |
| Labour_Cost | 0,0294 | 2,9632 | -0,1175 | 1,7984 | -0,4014 | 1,6118 |
| WIP_data_col | -4,7244 | -1,8382 | -3,4438 | -1,3957 | -2,0211 | 0,3629 |
| Lab_Flex_WF | -20,7979 | -18,1005 | -19,6090 | -15,6117 | -23,1348 | -17,2827 |
| Volume_Flex | 1,2803 | 3,1582 | 2,9674 | 6,2068 | 3,9951 | 9,6209 |
| Deg_Spec | -43,6151 | -42,8207 | -39,6740 | -38,8560 | -38,1249 | -37,2837 |

**Table 35: Output data model variant 9, combination**