Bachelor Degree Project

UNIVERSITY OF SKÖVDE

BUFFER OPTIMISATION OF A PACKAGING LINE USING VOLVO GTO'S FLOW SIMULATION METHODOLOGY

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Certificate of Authenticity

Submitted by Mattias Johansson and Peter Wolak to the University of Skövde as a Bachelor degree thesis at the School of Engineering Science. We certify that all material in this thesis project which is not our own work has been identified.

Skövde 2019-01-13
Place and date

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We would like to start by thanking Volvo GTO for the opportunity to write this thesis work. The thesis has been in line with the student's interest and has been very rewarding. It is our humble hope that this thesis leads to the development of flow simulation as a tool within the Lean-toolbox at Volvo GTO.

We would also like to aim special thanks to our supervisors at Volvo Sebastian Eklind and Josefin Bertilsson, our examiner Amos Ng, the simulation network and all other personnel at Volvo GTO who always were available for guidance and help.

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Abstract

With the rapid development of computers and their proven usability in manufacturing environments, simulation-based optimisation has become a recognised tool for proposing near-optimal results related to manufacturing system design and improvement. As a world-leading manufacturer within their field, Volvo GTO in Skövde, Sweden is constantly seeking internal development and has in recent years discovered the possibilities provided by flow simulation. The main aim of this thesis is to provide an optimal buffer size of a new post-assembly and packaging line (Konpack) yet to be constructed. A by-product of the flow simulation optimisation project in form of a flow simulation process evaluation was also requested.

The simulation project started with a pre-study including the development of the frame of reference and an analysis of the literature focused on merging Lean philosophy with simulation-based optimisation. The simulation model was built based on both historical and estimated data. The optimisation results showed different buffer size alternatives depending on the throughput to be achieved, these are discussed, and near-optimal solutions presented for decision-making. Additionally, four experiments were carried out, both contributing to the model's credibility as well as providing new and valuable insight to the stakeholders. The conclusions drawn from the optimisation and experiments indicate that Konpack will be able to meet the established throughput goals, provided that the suggested near-optimal solutions are considered. The experiments also unanimously point to the fact that Konpack has a built-in overcapacity, utilizable by optimising certain suggested input parameters.

Additionally, an evaluation of the completeness of the standard simulation process employed by Volvo GTO is provided, concluding that no major changes are needed. Nevertheless, there is always room for improvement. Hence, future work regarding the flow simulation process at Volvo GTO is proposed.

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1. INTRODUCTION

This chapter includes the thesis background and problem description, the aims and objectives as well as the focus and delimitations for the thesis work. The introduction ends with a brief report structure.

1.1 Background

The Volvo Group is one of the world's leading manufacturers of trucks, buses, construction equipment, and marine as well as industrial engines. The organisation has facilities all over the world. At the powertrain plant in Skövde, most of the engines are produced for the Volvo Group. The production in Skövde is divided into three areas: machining, assembly and casting. With more than 4000 employees and over 100 000 produced engines per year, the plant in Skövde is one of the most important employers in the region.

In recent years, simulation has become a staple tool for the production engineer. Simulation allows virtual representations of production lines which can be experimented on without impacting the real production. If the evaluation of the result is satisfactory, the changes may be implemented saving both time and money but also aiding sustainable development. Therefore, the Volvo division in Skövde envisions simulation as a tool to be used to support strategic and operative decisions at the manufacturing plant.

1.2 Problem description

During the fall of 2018 until late summer of 2019 Volvo GTO will rebuild the post-assembly and packaging-line area known as Konpack at their assembly plant in Skövde. The main purpose of the renewal is to achieve a more streamlined and effective production flow. However, due to a large number of variants and complex production flows, buffer levels in this area have not yet been determined. In order to aid the decision makers, Volvo GTO wants a flow simulation model of Konpack. The goal of the flow simulation is to find buffer levels which grant the desired throughput. In addition to the buffer optimisation, Volvo also requires an evaluation of their current flow simulation methodology.

1.3 Aim and objectives

The main aim of the thesis is to find an optimal buffer size for Konpack in order to ensure the desired throughput is achieved. The specific objectives to achieve are the following:

- Deliver a verified and validated simulation model of the new post-assembly and packaging-line.
- Propose an optimal buffer size for Konpack that allows desired throughput levels to be achieved. The proposition should be based on results obtained via simulation-based optimisation.
- Determine whether the workstation ExtraEM is necessary. Furthermore, present an optimal sequence position configuration while taking physical limitations into consideration.
- Additionally, propose an improved flow simulation process based on the identified advantages and disadvantages of Volvo GTO´s current simulation methodology.

1.4 Focus and delimitation

This thesis has some limitations, which are described in the following paragraphs:

- The product of this thesis work is focused on providing an optimal buffer size. It is not a model to be used as a tool for other simulation projects with different purposes.
- The simulation model only covers the necessary parts of the plant in order to achieve a valid buffer optimisation for Konpack.
- Data should be made available and supplied by Volvo GTO. It is Volvo GTO's responsibility that the provided data are correct.
- The evaluation of Volvo GTO's current simulation process is, as requested by the company, strictly limited to the steps involved in the process.
- Additional requests made by Volvo Powertrain after the project specification have been considered as optional requirements.

1.5 Report structure

The thesis is divided into different chapters. Chapter 1 includes the introduction to the thesis. Chapter 2 consists of a frame of reference which describes different theories and concepts related to this thesis such as simulation, optimisation and Lean-production. Chapter 3 consists of a literature review and examines previous studies regarding how to work with simulation in a standardized way and using simulation models for buffer optimisation in a manufacturing system. Chapter 4 explains the methodology followed while conducting the thesis work and thus, Chapter 5 describes how the methodology was applied. The results of the buffer optimisation, the conducted experiments and flow simulation process evaluation are given in chapter 6. This is followed by a discussion of the results, thesis conclusions and future work recommendations by the students.

1.6 Introduction summary

This chapter has introduced the thesis background and the main stakeholder, the Volvo Group. The problem to be addressed has been described, as well as the aims and objectives to achieve by the thesis. Finally, the project focus and delimitations and a report structure have been presented. The next chapter, the frame of reference, aims to provide a brief description of the methods used during the project.

2. FRAME OF REFERENCE

The purpose of this chapter is to, with the aid of literature, describe different theories and concepts related to this project such as simulation, optimisation and manufacturing engineering concepts.

2.1 Manufacturing concepts

This chapter introduces the key concepts of modern production philosophy with the basis in Toyota Production System (TPS), popularly known as "Lean". Although this thesis report focuses mainly on simulation and optimisation, the real-life system reproduced by the simulation model is built according to the teachings of Lean. It would be hard to discuss the matter at hand without using the appropriate terminology. Consequently, the reader must be introduced to at least the most fundamental aspects of Lean, e.g. standardized work, cycle time, takt time, work in process (WIP), lead time and bottleneck.

2.1.1 Lean characteristics

During the 20th century, Toyota developed a manufacturing philosophy named Toyota Production System. By strongly contributing to position Toyota as one of the world's leading automotive companies, TPS has proven its usability to improve manufacturing systems (Liker, 2009).

As mentioned earlier, TPS is also known as Lean and Bicheno, Holweg, Anhede and Hillberg (2013) summarizes the main characteristics of Lean philosophy being:

- The Customer – Always try to maximize customer value. Always try to understand what the customer really needs.
- Simplicity – Always strive for the least complex solutions that meet the requirements.
- Waste – Waste will always occur. It may be in the form of, e.g., overproduction, wait, unnecessary movement, scrap, rework or in not utilizing human intellect. Learn to identify waste and eliminate it.
- Flow – Always strive after a continuous flow where the product is moving at the same pace (takt) as the demand. If possible, use single piece flow so that you can deliver just in time.
- Consistency (Heijunka) – Always link production planning, sales and purchase. Be consistent in these areas in order to achieve a consistent production without sudden spikes or droughts. This is key to achieving flows and quality.
- Pull – Always strive after a production rate that matches the demand of the end customer by having a pull-logic based demand chain. This eliminates overproduction.
- Be preventive – Plan your work so that it is preventive rather than reactive.
- Time – Always strive after having the shortest possible lead time. If lead time reduction is prioritized waste, flow and pull will be properly taken care of.
- Continuous improvements (Kaizen) – Make sure that both big and small improvements are being made on a continuous basis throughout the organization. This includes not only waste and deviation reduction but also innovation.

- Gemba – Be where the work is done and seek the data yourself. The best leadership is often the kind of leadership that is practiced in the proximity of subordinates.

- Variation – This is often the worst enemy of Lean. Variation in time and/or quantity is always present in every process. One should seek it out, determine the cause of variation and eliminate it.

- Standardized work – By documenting the current best method a platform for continuous improvement is created. When a better method is discovered it should be adopted as the new standard and thus raising the platform to a new level. This is the most crucial aspect of Lean when fighting, i.e., variation and inconsistency.

A more graphical understanding of the above-mentioned characteristics is also given by Bicheno et al. (2013) and can be seen in figure 1.

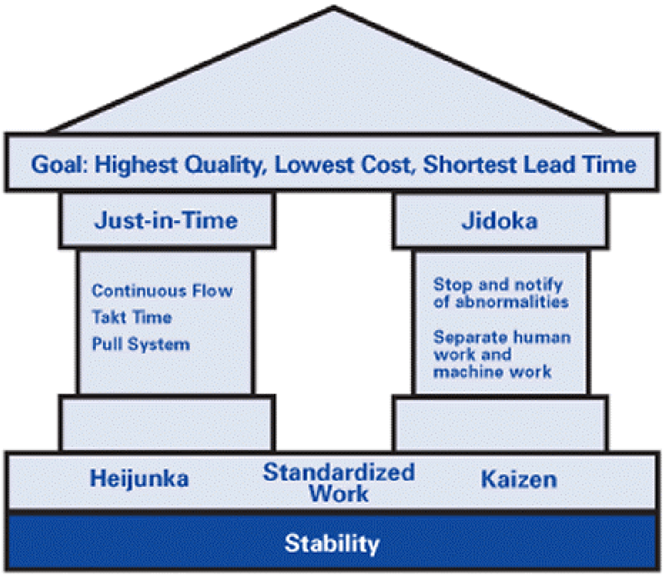

Figure 1. The Lean-house

2.1.2 Cycle- and takt time

One common definition of takt time is perhaps the one given by Bicheno et al. (2013). They state that takt time is the available production time divided by the demand for the same time period. To understand what sort of measurement this is one must first understand what is meant by available production time and demand. Demand is described as the average sale-rate and anticipated scrap work for the product produced. Available production time, on the other hand, is defined by the authors as the actual time available for production with regard to scheduled interruptions such as maintenance, team meetings and breaks for the same time period as the demand. Hence the takt time is a measurement of how many units need to be produced per time unit so that the demand is met.

Niebel and Freivalds (2014) define cycle time as the time from start to finish of a process, i.e., from the moment that work begins on a work object until the exact moment that work has finished, and the work object moves on. When putting takt time and cycle time in relation to each other, it becomes apparent that the correlation between them is that the takt dictates the maximum allowed cycle time. If the cycle time of one operation in the production line exceeds the takt, customer demand will not be met and therefore not satisfied.

2.1.3 Lead-time

It is essential for manufacturing companies to be aware of the time it takes for their organization to satisfy a demand. According to Jonsson and Mattson (2012), this time period is defined by the calendar time it takes from when a demand is registered until the demand has been satisfied. Lead-time can be applied on many levels in an organization; on a factory level, it would be the time from a received customer order until the customer receives the product ordered. On the shop-floor level, it could be the time taken for one department to process and deliver a product to the next department for further processing. Consequently, lead time measures effective process time, but in contrast to cycle time, it also accounts for transportation and waiting times.

2.1.4 Work-in-Process

Products that are being processed or are between processing operations are called Work-in-Process (WIP). Thus, according to Groover (2015), WIP is a measurement of the quantity of product currently at the factory. The author further explains that WIP embodies an investment made by the manufacturer and is ideally kept as low as possible but without a negative impact on the production. This investment cannot be turned into revenue until all processing has been completed. Countless manufacturing companies sustain unnecessary costs because work remains in-process in the factory for too long. One way of preventing these unnecessary costs from occurring is via pro-active buffer optimisation (see chapter 3.3). This can severely reduce mean lead-time and consequently reduce WIP.

2.1.5 Bottleneck Analysis

According to the Theory of Constraints first presented by Eliiyahy M. Goldratt in 1984, there are some machines that negatively impact the overall system performance more than others (Goldratt, 2014). These machines are the weak link in the chain and called bottlenecks. As such they are also the ones setting the possible takt for the system they are a part of. Consequently, if the goal is to improve, for instance, throughput or buffer levels, the bottleneck needs to be dealt with. Goldratt (2014) recommends this being done in five steps:

- Identification of the bottleneck.
- Utilize the bottleneck as much as possible.
- Subordinate other processes to the bottleneck.
- Make investments if previous steps didn’t help enough.
- Repeat the process since a new machine is likley to take on the role of bottleneck, limiting the system.

2.2 Simulation

Real-world facilities or processes are often called a *system* and Law (2015) claims that to study a system scientifically, it’s often required to make assumptions about how it works. The assumptions often take the form of different logical or mathematical relationships, which together becomes a model of the real-world system. Law (2015) also claims that since most real-world systems are very complex, the usage of traditional analytical methods (such as algebra or calculus) to study them becomes difficult. But with the support of computers and simulation software, large and complex systems can be better studied.

Banks, Carsson, Nelson and Nicol (2010) define simulation as an imitation of the operation of a real-world system over time. Once the model is developed, verified and validated it can be used to predict the effect of changes in the real-world system. The authors also defend that simulation could be used as a design tool when a new system is designed in order to predict its performance under various circumstances. For this reason, Banks et al. (2010) claim that simulation has become a popular tool for problem-solving and have had numerous applications in different areas including manufacturing, business processing, construction, military, healthcare and logistics.

Law (2015) means that a careful simulation study can provide answers such as if a change in a manufacturing plant is cost-effective. The focus should be on finding the sought answer, not to perfectly mimic the real system. He thinks it’s unfortunate that many people have the impression of simulation studies being an exercise in computer programming rather than finding the sought answer and drawing the right conclusions.

Discrete-event simulation (DES) is a type of simulation that uses different variables which only change in a discrete set of points in time (Banks et al. 2010). For DES to work, a simulation clock which keeps track of these discrete set of points is required. The simulation clock has no relationship with the time it takes to run the simulation on the computer (Law, 2015). DES is according to Negahban and Smith (2014), one of the most regularly used tools when analysing and understanding manufacturing systems. Thanks to its flexibility, it can analyse different system configurations aiding decision makers managing and developing manufacturing systems.

2.3 Simulation Process Steps

Achieving a verified and valid simulation model is not a simple task and should not be taken lightly. One of the most popular approaches to conduct simulation studies is the one presented by Banks et al. (2010). As seen in figure 2 it consists of twelve steps with iterations between a few of them. Its purpose is to aid the model builder to accomplish a systematic and comprehensive simulation study.

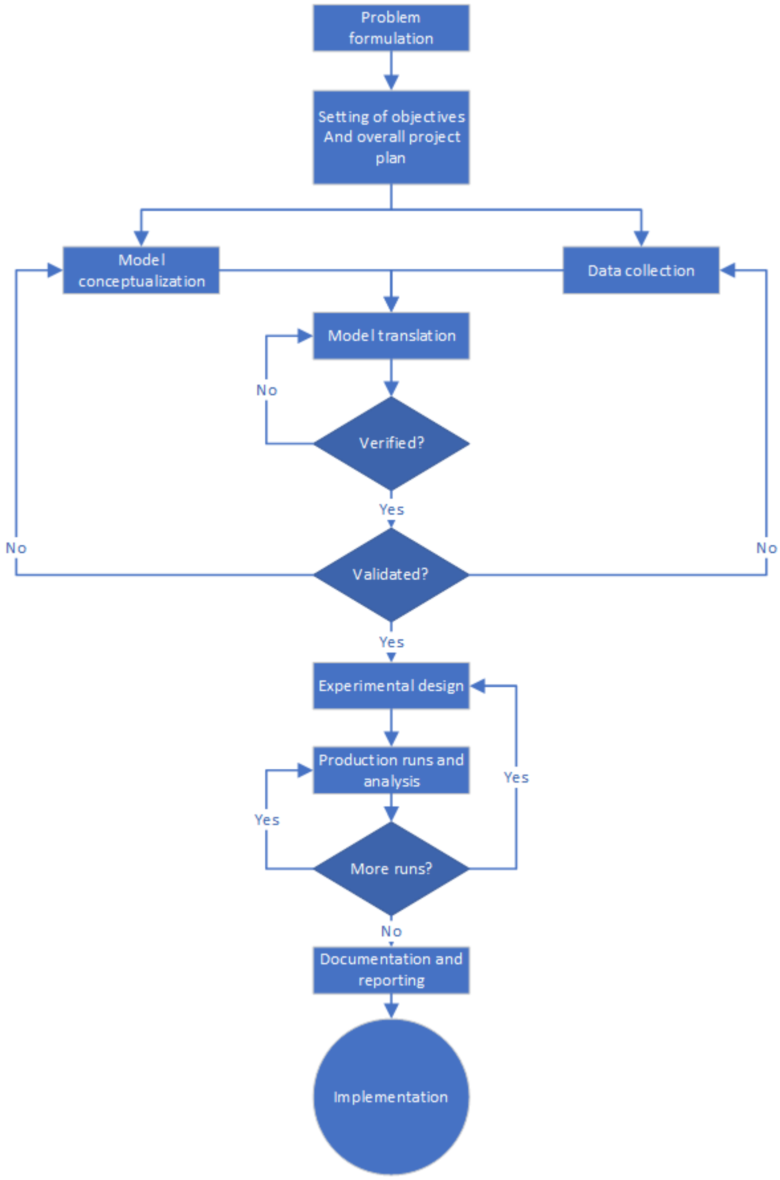

Figure 2. Steps in a simulation study as presented by Banks et al. (2010).

In the following paragraphs, a brief description of each of the different steps seen in figure 2 is given.

Step 1. Problem formulation

The first step of a simulation study is to formulate the problem at hand. The problem formulation should be understood by those formulating it and also by those who own the problem or will work with the model.

Step 2. Setting of objectives and overall project plan.

The objectives define which questions will be answered by the study. At this point, it is also fitting to question simulation as the appropriate tool for reaching the objectives and solving the problem. Banks and Gibson (1997) give an example of when it's not appropriate to use simulation:

- When the system behaviour is too complex to simulate.
- When the problem can be solved by common sense.
- When the problem can be solved analytically.
- When simulation is more expensive than direct experimentation.
- When the resources for a proper simulation study are not available.
- When there is no available or estimated data.
- When verification and validation of the model are not possible due to lack of time or personnel.
- When the decision makers have unreasonable expectations.

Step 3. Model conceptualization

The fundamental features of the problem to be simulated need to be formalized and visualized. This creates a common ground for the model builder and the decision makers, which is useful since the two parties often have a different perspective and understanding of the problem and how simulation works. A typical conceptual model is a flowchart.

Step 4. Data collection

Just like the objectives define which questions will be answered they also dictate, in a large way, what kind of data needs to be gathered. A large portion of a simulation study’s total time often consists of data collection. Therefore it is recommended to begin this process as early as possible. However, as the complexity of the model changes, the required data also changes, meaning that data collection is not a one-time activity but an on-going process throughout a large portion of a simulation study.

Step 5. Model translation

At this stage, the conceptual model and the data collection are merged and translated into a computer format. A decision has to be made whether the model builder shall program the model using a simulation language such as GPSS/H or to use commercial simulation software like Siemens Plant Simulation, Flexsim or Facts Analyzer.

Step 6. Verification

When the computerized representation of the model has been constructed it has to be verified. The main goal of this step is to confirm that the computer program is performing properly. The difficulty of this task is linked to the complexity of the real-world system. The main criteria to verify a model is to ensure that the input parameters and the logical structure are behaving correctly. Verification is usually achieved using common sense.

Step 7. Validation

This is a highly iterative process that can be seen as fine-tuning the model against the actual or expected system behaviour and performance until the model’s accuracy is deemed sufficient.

Step 8. Experimental design

Experiments based on the needs and requests of the user or decision maker are defined. These experiments may also be defined by insights gained during the previous stages of the modelling process.

Step 9. Production runs and analysis

The previously defined experiments are run and an analysis of the results is performed.

Step 10. More runs?

If the experiment results are not satisfactory or more questions arise, the need for more runs is considered.

Step 11. Documentation and reporting

The documentation of a simulation project is recommended to be carried out continuously and in two formats: program- and progress documentation. Program documentation refers to the actual simulation model, how it’s coded and how it operates. Program documentation may also include instructions with the end user in mind, e.g. how to change parameters. The progress documentation covers the work done during a simulation project such as key decisions and accomplishments. Goienetxea Uriarte, Urenda Morris and Ng (2018) recommend frequent updates of the documentation so that misunderstandings are avoided and track keeping of the project is facilitated. After a completed project, a final project report is also recommended. It's useful for decision-makers, for presentational purposes and validation of the results of the simulation project.

Step 12. Implementation

According to Banks et al. (2010), this is the last step of a simulation project. It is the step where the results of the simulation model are implemented in the real system. The success of the implementation depends on how well the preceding eleven steps have been completed. Another proven success factor described both by Banks et al. (2010) and Goienetxea Uriarte, Urenda Morris and Ng (2018) is the end user's involvement in the entire simulation process. An end-user with high involvement rate and a profound understanding of the model and its outputs, drastically improves the chances for a successful implementation.

2.4 Conceptual Modelling

Conceptual modelling is one of the 12 steps in Banks et al. (2010) simulation methodology and is briefly described in the previous chapter. Yet, since conceptual modelling is believed to be an integral part of this thesis work, it has been given its own chapter for a deeper explanation.

Conceptual modelling is the process of extracting a model from a real or proposed system while keeping it as simple as possible without compromising the model’s validity and at the same time achieving predetermined model objectives set by the client and/or the modeller. As described by Robinson (2008) the approach taken by conceptual modelling is that of simplicity, e.g. if it's possible to describe a segment of a production line consisting of multiple machines by grouping them into one object this should be done. The author implies that the benefits of the simplicity that conceptual modelling offers are that the resulting product (the conceptual model) can be developed faster, be more flexible, require less data, run faster and be easier to interpret. However, one should keep in mind that even though simplicity is something to strive for, the aim should always be to achieve the simplest model that still meets the requirements, not simple models per se.

2.4.1 Method and characteristics

Robinson (2008) states that conceptual modelling is sometimes described as an art form rather than an exact science, meaning that there is relatively little said and written about its methodology. Therefore, the author attempts to provide guidelines for activities that need to be included. These are (Robinson 2008):

- Understanding the problem/task.
- Defining modelling and general project objectives.
- Identification of the model’s inputs and outputs.
- Determination of the model content.

Robinson (2008) continues his conceptual modelling methodology description by stating that:

- It is iterative and repetitive, with the model being continually revised throughout a modelling study.
- It is a simplified representation of the real system.
- The conceptual model is independent of the model code or software.
- The perspective of the client and the modeller are both important in conceptual modelling.

Pidd (1999) also discusses modelling and has his own guiding principles. The first principle is to model simple. Do not create a model that is unnecessary complicated but simple enough to still fulfil its purpose. A model created by this principle is often more user-friendly and easier to interpret than its more detailed counterpart. The second, third, fourth and fifth principle all have in common that more often than not it is preferred to keep things simple. They are:

- Start small and then add.
- Avoid mega-models.
- Use metaphors, analogies and similarities.
- Do not fall in love with data.

Zeigler (1976) offers another approach on keeping it simple. He has defined four methods of simplification. By dropping irrelevant components of the model and grouping other components, coarsening the range of variables and also using random variables to describe parts of the model, simplicity is achieved.

2.4.2 Conceptual Model

The main goal of conceptual modelling is to create a common ground which according to Pace (2002) can be used by all involved parties in the simulation project such as the modeller, client and domain expert. Robinson (2008) also sees other benefits generated by the conceptual model such as:

- Minimization of wrongfully set requirements.
- Facilitation of higher credibility.
- Guidance during the development of the computer model.
- Provides a basis for model verification and validation.

According to Robinson (2004), the conceptual model is made up of four integral parts: objectives, inputs, outputs and model content. Objectives are sorted into two types, the modelling objectives and the general project objectives. The former describes the purpose of the model. The general project objectives, on the other hand, dictate the project time-scales and requirements the model needs to fulfil. Such requirements could be flexibility, run-speed and ease-of-use. Well defined objectives are essential as slightly different objectives may result in entirely different models even though they are modelled after the same system. The inputs of a conceptual model may be seen as factors that can be altered in order to change the behaviour of the model. In contrast, the outputs present the user with a reading of the model's reaction to the inputs. The outputs are used for determining if the objectives have been reached or why they haven't. The last component of the conceptual model is called the model content which simply put consists of representations of, e.g. machines, workers and their interconnections. The model content may be split into two dimensions defining the boundaries of the real system that is to be included in the model and the level of detail for each component to be modelled.

In general, when working with model content, various assumptions are introduced as a way to incorporate beliefs and uncertainties existing in the real system. It’s also common to introduce simplifications in order to reduce the complexity of the model. (Robinson 2004)

According to Robinson (2008), several research papers by leading researchers in the field of simulation have identified at least 11 requirements of a conceptual model. Some more relevant than others which led the author to focus on four of these that were commonly mentioned in the studied research papers. The purpose of these requirements is to determine whether the model is appropriate. Since the modeller rarely is a system expert but the client, it’s essential that the requirements are acknowledged and addressed by both parties before finalizing the conceptual model and moving on to the actual computer model. According to Robinson (2008), these four requirements are validity, credibility, utility and feasibility. Validity and credibility are two sides of the same coin. The former viewed from the modeller’s perspective and the later from the clients. They determine if the model is perceived to be strong enough to be developed into a computer model accurate enough for the purpose at hand. Validity and credibility are kept separate since the modeller and the client may have different perceptions of the model. Many times, the modeller judges the conceptual model to be ready, whereas the client doesn't. It's not unusual to add scope and detail to a model in order to satisfy its credibility. However, it's the modeller’s task to make sure that the model doesn't become too complex and cumbersome. The requirements for utility are stated through the general project objectives. They describe the models' usefulness and include questions such as flexibility, ease-of-use and reusability. Lastly, there's feasibility. A feasible conceptual model suggests that time, resource and data are available and of adequate quantity enabling the creation of the computer model. A model deemed infeasible suggests that one or all these prerequisites are lacking. Perhaps there is insufficient knowledge of the real system and the time available for the project is too short, or maybe the real system is extremely complex, and the modeller has insufficient skill to code the model.

2.5 Verifying and validating simulation models

Verification and validation were briefly described as steps in a simulation project in chapter 2.3. However, just like conceptual modelling they are believed to become a crucial part of this thesis work and therefore have been explained further in this chapter.

Model verification is defined by Sargent (2014) as “ensuring that the computer program of the computerized model and its implementation are correct” and model validation as “the substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model”. Sargent (2014) defends that there is not a unique correct or best approach/method to verify or validate every model. He claims that every simulation model presents a new challenge and that the model’s validity comes from its goals or purpose. If its purpose is to answer several questions, each question needs to be taken into account. He also defines a model as valid if the model’s accuracy is within the acceptable range of accuracy which should be defined early in the model development process.

Sargent (2014) lists three approaches for deciding if a model is valid:

- Letting the developers decide (a common approach).
- Letting the user decide.
- Letting a third party decide (often increases the model's credibility).

The author also lists four different validation and verification steps that need to be done:

- Data validity: to ensure that the input data of the model are correct.
- Conceptual model validation: the assumptions and structure are reasonable for the purpose of the model.
- Computerized model verification: to check that the conceptual model has successfully been translated into code.
- Operational validation: where most validation testing and evaluation take place since this is when the output of the simulation data is validated.

In the operational validation process, it's possible to find errors done in the previous steps, such as wrong data or/and assumptions. There are numerous ways to do an operational validation, which to choose depends heavily on if the system is observable or not. If the system is observable the output of the real system can be compared to the model's output. If it's not observable other techniques need to be used. (Sargent, 2014)

To validate a non-observable system Sargent (2014) suggest two methods: *"Explore model behaviour*" and "*Compare to other models*". With exploring model behaviour, the author means that it's important to check with experts of the system if the model outputs are reasonable considering the input. Various statistical tools (e.g., metamodeling and experimental design) can also be used to explore model behaviour and the author suggests that parameter variability-sensitivity analysis should generally be used. Variability-sensitivity analysis is important to the model's credibility because without knowledge of how important each parameter is, the prediction by the model becomes difficult to trust according to Norton (2015) and it can also find parameters that are not important to the output of the model (these parameters should be simplified or removed from the model).

The other way to validate a non-observable system is according to Sargent (2014) to "compare to other models". To be able to know whether the output data of the model is valid, this is compared to another model of the system, or the real-world system. Three basic approaches can be used:

- Use of graphs to make a subjective decision.
- Use of confidence intervals to make an objective decision.
- Use of hypothesis test to make an objective decision.

One must be careful when comparing data via graphs (Sargent 2014), as in practice, it's often difficult to use confidence intervals or hypothesis. One must ask if the data are comparable and if there is enough data available to consider it statistically valid.

2.6 Finding optimal solutions using a simulation model

It's seldom that a simulation model is created without a purpose. In the manufacturing industry, they often serve as a decision support, e.g. when a bottleneck needs to be found or correct buffer levels set. However, simulation is not an optimisation tool by itself. That is why it's often combined with optimisation.

2.6.1 Optimisation

Law (2007) claims that one of the key purposes in analysing a simulation model is to find a combination of input factors that generate an optimized output(s). He also claims that usually, the input factors of interest are the inputs that are controllable such as facility design or operational policy. In a complex system, the combination of these inputs could potentially be hundreds of thousands or more. So, to find an optimal solution one would need to evaluate all possible logical combinations. To make matters more complex, randomness dictates that one simulation run per combination will not suffice, but *n* number of simulation runs per combination are required.

In order to avoid simulation of all possible inputs *n* numbers of times, different optimum-seeking methods have emerged over the years, Law (2007) lists them as follows:

- Metaheuristics.
- Response- surface methodology.
- Ordinal optimisation.
- Gradient-based procedures.
- Random search.
- Sample- path optimisation.

Simulation-based optimisation of manufacturing systems is often carried out by two separate modules according to Pedrielli, Matta, Alfieri and Zhang (2018). A simulation module (the simulation model) is used to predict system performance and an optimisation module (often based on an optimisation algorithm) to generate the best system configuration. Law (2007) explains that the output of the optimisation module (e.g., the system configuration) is sent as input to the simulation module. The output from the simulation module (e.g. the system performance) is then fed back as an input to the optimisation module, which generates a new output (e.g., system configuration).

2.6.2 Simulation-based Multi-Objective Optimisation

Goienetxea Uriarte, Urenda Morris and Ng (2018) describe an approach when the goal is to optimise more than one objective and how a correct utilization of this method presents the decision makers with near-optimal solutions. Quite often these objectives can be contradicting e.g. lower manufacturing cost but a higher throughput. When there are two or more objectives to be achieved at the same time, then simulation-based multi-objective optimisation (SMO) is the approach to be employed. When working with SMO, the outputs from a simulation model, the optimisation objectives, and the decision variables are entered into an optimisation algorithm. The algorithm begins an iterative process where it uses the simulation model to run evaluations with different values in the decision variables in-between runs. The algorithm compares the current solution produced by the simulation model after each run with the previous one and selects the best alternative. According to Kim & Ryu (2011) the best solutions can be then plotted into a scatter chart and form a so-called Pareto front (figure 3).

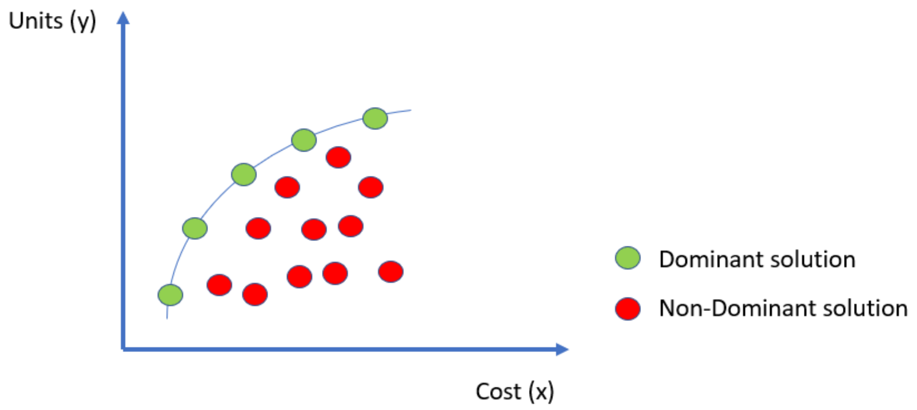

Figure 3. Pareto front as interpreted from Goienetxea Uriarte, Urenda Morris and Ng (2018)

The Pareto front is made up by solutions that are better in at least one objective and not worse in any other objective Deb (2001). These solutions dominate the others and are therefore seen as dominant. In regard to each other, the dominant solutions are trade-offs since it's up to the decision-makers to decide whether low cost or more units are desirable, as in the example.

2.7 Simulation, Lean and optimisation

Goienetxea, Urenda Morris, Ng and Oscarsson (2015) defend that Lean, simulation and optimisation are seldom used together, despite having the same objective: supporting decision makers in the design (and improving) of systems. One of the reasons according to Goienetxea et al. (2015) is that simulation engineers and Lean-managers often work apart from each other. The authors defend that if an organization is working towards becoming Lean all its process should be Lean, including the simulation process. The authors also point out that simulation and optimisation need to be in the Lean tool-box, not be excluded and performed by simulation engineers with no understanding of the Lean philosophy. The combination of Lean, simulation and optimisation will lead to a better result than applying them alone. Lean and simulation both have their limitations but by combining the two, much of their weaknesses will be absent by the other’s strengths. The authors argue that adding optimisation to this combination will reduce the time required to find a near-optimal solution to the problem under analysis.

2.8 NSGA-II

The Non-dominated Sorting Genetic Algorithm (NSGA) is a multiple objective optimisation algorithm. The algorithm uses an evolutionary process which include selection, genetic crossover, and genetic mutation in order to find solutions for the Pareto-front. The population of solutions is sorted into sub-populations based on their Pareto dominance. Similarities between members of each sub-group are then evaluated. The resulting groups and the similarity measures are used to promote a diverse front of non-dominated solutions. In later years an improved version, NSGA-II has been developed. (Brownlee, 2012)

According to Deb, Pratap, Agarwal, and Meyarivan (2000) high computational complexity as well as the absence of elitism and user-specified parameters which affect the result led to the development of NSGA-II which differs from its predecessor by the following three traits:

- Fast non-dominated sorting approach.
- Fast crowded-distance estimation.
- Simple crowded-comparison method.

2.9 Sustainability and simulation

According to Kuhlman & Farrington (2010), sustainable development is today viewed in terms of three dimensions which need to be in harmony: social, economic and environmental.

- The rights, needs, well-being and justice for the individual are important elements of the social sustainability dimension. Some of these elements are quantified and others more qualitative. This means that in practice, the definition of social sustainability varies depending on the context. However, various efforts have been made to define and quantify social sustainability. Two well-used proposals are the UN Millennium development goals or Human Development Index. (Kungliga Tekniska Högskolan, 2015a).
- Environmental or ecological sustainability includes quality of air, land and water, biodiversity, stability of climate systems and everything else that is connected to the Earth´s ecosystems. (Kungliga Tekniska Högskolan, 2015b).
- The economic dimension of sustainability has two fundamentally different definitions. It´s either understood to be economic development without a negative impact on the other dimensions of sustainability, or just as economic development, i.e. it’s considered sustainable as long as the total amount of capital increases. (Kungliga Tekniska Högskolan, 2015c).

Some basic principles that support sustainable development are listed by Mulder (2006) as:

- Resource consumption should be minimized.
- Preference should be given to renewable materials and energy sources.
- Development of human potential.
- Contribution to the common good and not just the private good.

Mulder (2006) also lists numerous unsustainable activities such as e.g. overconsumption, degradation of the environment or to stimulate selfishness.

According to Boulonne, Johansson, Skoogh and Aufenanger (2010), simulation has served as an effective tool for decision makers in tackling the major challenges of the manufacturing industry. These challenges include cost- reduction, shortening lead time, improving quality and supporting sustainable development. An example is presented by Kuhl and Zhou (2009) where energy consumption, carbon emissions (such as CO and CO_2), pollutants (such as NO_x), and total hydrocarbon emissions are introduced as parameters in a simulation model of a logistics and transportation system. Such projects are a great example of how corporations could potentially lower their environmental impact if they work actively with a strong simulation methodology.

2.10 Frame of reference summary

The intent of the frame of reference has been to lay down a solid theoretical foundation regarding the methods employed during the project. By doing this, the project has a better chance of avoiding unnecessary mistakes and thus reaching a satisfactory result. The frame of reference of this thesis work combines elements from three main categories deemed relevant for the thesis: Simulation, Optimisation and Lean-Production. Chapter 2.8 also explained the link between simulation and sustainability. The following literature review chapter aims to create a link between the methods presented in the frame of reference with the project by studying the outcome of previous work aiming at similar goals.

3. LITERATURE REVIEW

The main goal of this thesis work is to deliver a buffer optimisation via a discrete event simulation model of a yet to be built post-assembly line and engine packaging area known as Konpack. The model will be developed according to Volvo GTO's current flow simulation process. The purpose of this being to critically examine the written process methodology with how it currently is used. Critique and improvement suggestions will be drawn from literature. This chapter will examine previous studies regarding how to work with simulation in a standardized way and using simulation models for buffer optimisation in a manufacturing system.

3.1 Simulation methodology and standard

Ehm, McGinnis and Rose (2009) mean that the discussion of existing simulation standards is not often listed in the simulation research and application community, this despite the need for a standard and a shared syntax describing manufacturing systems. Tolk et al. (2011) also point to the lack of standardization in the simulation field. The authors make the point that due to the special nature of simulation, parts of the simulation community regard it as a separate discipline from software engineering hence leading to the creation of a sub-culture. Furthermore, the authors point out that a common theory that aligns simulation, modelling and application is required and this along with some cultural changes in the simulation sub-culture would drive standardized solutions. A successful standard, according to the authors, needs three pillars: to be valuable, desirable and reasonable. The standard is valuable if it makes the work cheaper, faster or better and makes economic sense. It's desirable if it fixes a real problem, and reasonable if it's in line with the current research and is technically mature. If one of these so-called pillars doesn't exist, the standard will fail.

Sturrock (2017) offers different guidelines to create successful simulation projects. Mostly, he agrees with the method presented by Banks et al. (2010) (see chapter 2.3), although the author added some interesting points which he believes, if followed, many common mistakes can be avoided. These are:

- Understand who all stakeholders are: It might not just be the ones who ordered the project, but also people affected by the results of the project. Knowing how your stakeholders define success and getting to know the real reason for it (it might be some hidden agenda by the stakeholders), will also help in making the project successful.

- Create a functional specification: This should include objectives, level of detail, data requirements, assumptions and control logic, analysis and reports, animations and finally due date and agility.

- Build and verify the model: In model building, two different approaches can be used: "breadth-first" or "depth first". The "breadth-first" approach is to make the model as simple as possible, then add a level of detail if needed. The other approach "depth-first" says that you should select a small portion of the model and model it as detail as possible then simplify it if possible. Both approaches have their advantages and disadvantages. To verify the model the most obvious methods to use are to watch the animation and to cautiously observe the output data.

Another take on simulation methodology is presented by Goienetxea, Urenda and Ng (2018). They introduce the concepts of Lean paired with Simulation-based Multi-objective Optimisation (LeanSMO). The authors mean that individually, neither Lean, Simulation nor Optimisation provides decision makers with complete solutions. Separated, the methods struggle to visualise the desired state, often leading to a trial and error approach. LeanSMO on the other hand, combines Lean, simulation and optimisation in an attempt to provide a more holistic methodology. According to them, the combination that is LeanSMO, offers decision-making based on facts rather than on intuition, best guesses and previous experience alone. Figure 4 is inspired by Goienetxea, Urenda and Ng (2018) and provides a visual comparison between the different approaches.

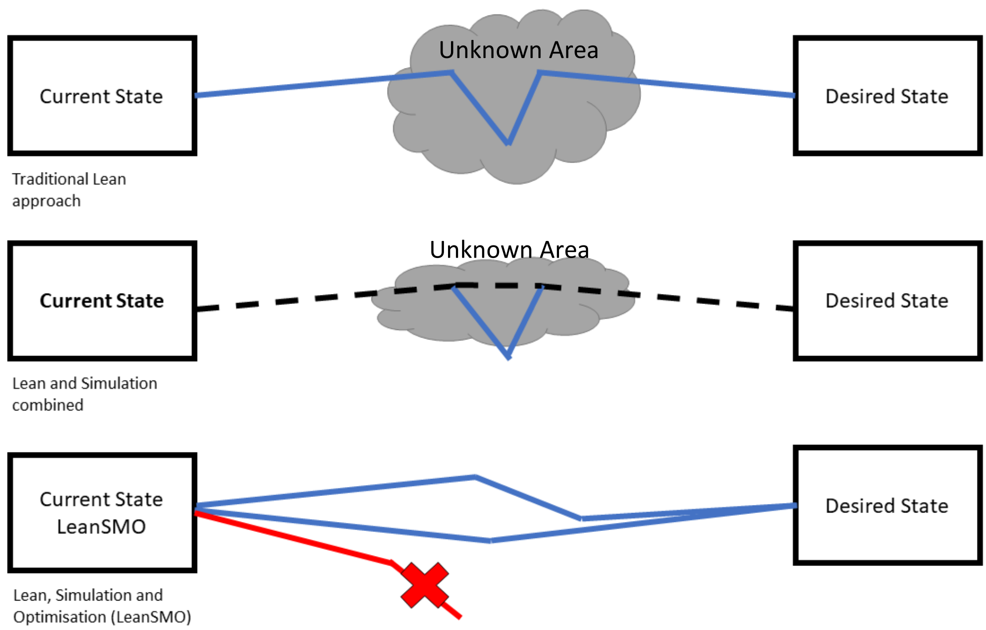

Figure 4. Comparison between the different approaches

According to Goienetxea, Urenda and Ng (2018) LeanSMO has three main purposes:

- Education: Using simulation in order to communicate lean concepts and educate the personnel in standard working procedures of the organisation.
- Facilitation: Since a simulation model can provide the personnel with a basic understanding of the process, it can be used to ease the implementation of improvement events such as kaizen or value stream mapping events.
- Evaluation: Simulation can be used to evaluate the current state, the future state and the implementation.

By utilizing these, a connection can be established between LeanSMO and the company.

3.2 A framework for Simulation model verification and validation

George Box, a well-known statistician as cited by Carson (2002) said: “All models are wrong, but some are useful.” With this phrase in mind, Carson (2002) explains the importance of self-criticism as a model developer. Without it, the last part of Box's saying might not become true. The author explains that a sense of protective ownership in the model might grow during the development of a complex and demanding model. This could be counterproductive since this type of behaviour might lead to oversights and unwillingness to acknowledge shortcomings in the model. It also happens that model developers with a strong ownership feeling might even feel attacked when their model is reviewed and questioned. Therefore, Carson (2002) reminds the reader to remember that “All models are wrong.” and that it should be seen as a common practice that a senior model developer reviews models created by newer model developers in order to have a reasonable assurance of model accuracy. The model developers’ ability to be self-critical and allow others to question their work is a prerequisite for a successful work.

After a careful explanation of this precondition, Carson (2002) also delivers a framework for simulation model verification and validation:

- Test the model for face validity - Create a scenario and run the model. Then examine all the model’s outputs and question if they are reasonable.
- Test the model over a range of input parameters - This step can be seen as a stress test. The model is run over the broadest range of input parameters that are probable to change during the course of experimentation. Examine trends in the model's measures of performance, e.g. throughput. Be on the lookout for performance outliers - outputs that are strongly deviant from trends or expectations.
- Compare model predictions to past performance of the actual system - This is done where appropriate. If no past performance data exist, it's also acceptable to make the comparison to a baseline model of the existing system. When modelling a system yet to be built, one should compare the model's behaviour and predictions to specifications and assumptions.

Carson (2002) explains that an entirely scientific validation of a simulation model is not achievable when designing a new system. This is due to the lack of a real-system as a foundation for any comparisons that need to be made. When faced with this problem, the model developer has to inspect and verify the model's performance at a micro-level.

In addition to the framework, the author also presents the reader with a list of verification and validation techniques that could be useful for certain types of models:

- Force the model through rare events and extreme cases. Evaluate the model response.
- Identify output values that indicate suspicious model behaviour.
- Identify internal system conditions that indicate incorrect model behaviour
- Before beginning the formal experimentation phase, one could do extensive testing by making lots of runs over a wide range of input parameter settings. Then monitor if outputs react as expected to changes in inputs (e.g., throughput should go up if machine speed is increased.).
- Models containing vehicles and operators walking from task to task should be checked for vehicle and operator lockups. Lockups may occur due to broken control logic.

- Monitor current statistics over time. When studying timelines major modelling errors might be revealed such as a resource not being active for a long period of time, although they perhaps should be used frequently.
- Also, use timelines to view WIP in all major subsystems. Count entities in all parts of the model and make sure that all are accounted for.
- Use animation for verification of model behaviour at micro-levels.
- Examine output parameters other than the primary ones. These could be measures for individual resources, operations or entities. Use reason and identify those that are clearly out of line.

Lastly, Carson (2002) points out that no model can be verified or validated to 100%. Models are simply a representation of a system and thus the behaviour of the model is merely an approximation to the real system's behaviour.

3.3 Simulation for buffer optimisation in a manufacturing environment

Traditional analysis methods and tools aren't sufficient enough to analyse complex and dynamic manufacturing environments such as those in the automotive industry (Dengiz, Tansel Iç and Belgin, 2015). The authors mean that since automotive production systems are of a stochastic nature, the use of simulation models is recommended in order to fully understand and explain how a specific system reacts to different factors like, e.g. demand. Dengiz, Tansel Iç and Belgin (2015) also defend that a simulation model combined with optimisation is a powerful tool to have and utilize when improving current production lines but also when constructing new ones. By combining simulation with optimisation, the authors managed to improve the production efficiency of a paint shop department in an automotive company in Turkey.

Siderska (2016) presents the many advantages and possibilities with simulation and in particular when simulating with Siemens Plant Simulation. She determines that the use of digital simulation models has become a necessary activity during the development of new- and optimisation of current production lines. The author uses a model created in Plant simulation in her study in order to optimise the production flow at a nail manufacturing plant. The study did, in a successful way, identify the system bottlenecks and increase throughput with nearly 70%.

Combining simulation with other methods while working in a manufacturing environment has proved to be useful, especially when the goal is to optimise production lines and raise productivity. This is concluded by Zupan & Herakovic (2015). The Authors managed to achieve a productivity increase of nearly 400% while conducting a study combining DES with line balancing.

The buffer allocation problem is explained by Weiss, Matta and Stolletz (2018) as the trade-off issue between throughput and WIP. The authors claim that due to varying availability and random processing times, too small buffer sizes may lead to a reduced throughput, as blocking and starvation effects might occur. Large buffers, on the other hand, cost more but may neutralize these effects and thereby increase throughput. To solve the buffer allocation problem, one must first, according to Costa. Alfieri, Matta and Fichera (2015) define the end goal, e.g. maximize the average profit or minimize the average WIP. Nevertheless, it's often desired to find the minimum number of total buffer space while achieving a given throughput, Gershwin and Schor (2000) define this as the "primal buffer allocation problem". A similar definition to the "primal buffer allocation problem" is given by

Enginarlar, Li and Meerkov (2003) when they define the Lean Level of Buffering (LLB) as the smallest buffer capacity required that meet the desired throughput and line efficiency. According to the authors, it's convenient to measure the buffer capacity in units of average downtime when trying to demine the LLB. The reason being, that a buffer's main function in a production line is to reduce the interference caused by random breakdowns.

According to Costa et al. (2015), the buffer allocation problem is one of the most challenging problems when designing a manufacturing system. The authors mean that to solve the buffer allocation problem an evaluation method and a generative method are required. The evaluation method calculates the throughput rate for a certain buffer configuration and the generative method uses this to optimize the buffer configuration. A strong way to combine an evaluation method and a generative method is suggested by Pedrielli et al. (2018) by embedding a simulation model with an optimisation model.

Zhang, Matta, and Pedrielli (2016) identify buffer levels as a well-known topic in manufacturing system research. The authors also point out that recent research has shown that discrete event simulation optimisation frameworks can optimize buffers in different production lines and that production lines have been successfully modelled using discrete event simulation tools for several years. Frantzén and Ng (2015) give numerous examples of successful simulation projects. In one case, it was possible to reduce the total number of buffers by 44% and still reach the desired throughput. In an additional example provided by them, the throughput increased by 10% by having a bigger buffer before the bottleneck. Pehrsson, Frantzén, Aslam, and Ng (2015) also provide an example of an aggregated line simulation model that gave many interesting results. They used optimisation algorithms and included the dimensioning of the different buffers in the system while reflecting on things such as lead time, the buffer sum and throughput. Ameen, AlKahtani, Mohammed, Abdulhameed, & El-Tamimi (2018) make the conclusion that simulation is a fast, accurate and simple way of solving the buffer allocation problem when compared to other methods. The authors also state that buffers can only improve the efficiency of a production line to a certain level. When this level is met, increasing the buffer-size will not improve the efficiency of a production line.

3.4 Summary of literature review

This literature review has indicated that simulation-based optimisation can be a powerful contributor for achieving near-optimal solutions in a manufacturing environment. However, the model needs to be verified and validated. The literature review does also provide valuable information on how a standard and a simulation methodology should be designed, and this will be used in the evaluation of Volvo GTO's current simulation methodology. The literature review also makes a strong case for using simulation-based optimisation in order to optimise buffer levels in a manufacturing system. Chapters 1-3 have introduced the problem at hand as well as provided a theoretical foundation and studied the outcome of relevant work previously done by other projects. The following chapter, Method, presents the chosen methodology to conduct the project based on the knowledge gained during the previous chapters.

4. METHOD

This chapter aims to explain the chosen methodology for the thesis work. First, the different steps to conduct the project are briefly explained and later, the existing data collection methods are described. How the methodology actually was executed will be presented in chapter 5.

The overall project methodology is based on Tonnquist's (2018) project management methodology. However, all parts concerning the creation of the simulation model and optimisation are based on the methodology described in chapter 2.3. Using Banks et al. (2010) proposed 12-step approach was seen as fitting as this thesis first and foremost is a simulation-study. The case for using this methodology was further strengthened as this methodology also heavily influences Volvo's flow simulation process.

4.1 Project management methodology

Tonnquist's (2018) project methodology begins with a pre-study that advances to a planning phase, which after hand turns into an actualization phase, and finally ends with a completion phase.

- Pre-study - The main purpose of the pre-study is to reduce insecurity by providing knowledge about the project at hand. This is achieved in multiple steps. The stakeholders and their demands need to be documented and understood. A current state analysis should be done as well as any data collection. The project scope should be defined and finally, different solutions should be investigated.

- Planning phase - The purpose of this phase is to decide upon a methodology for the actualization phase. A plan for how to achieve the project goals and all activities leading to them need to be created.

- Actualization phase - When previous steps have been accomplished, the knowledge gained along the way is put to use in an attempt to produce and deliver results (Tonnquist 2018).

- Completion - Tonnquist's (2018) last step is called completion and is dedicated to the evaluation of the project in order to extract knowledge and conclusions.

4.2 Data generation

The following sections introduce the different existing methods for data generation.

4.2.1 Quantitative and qualitative methods for data generation

Depending on what's being researched, data collection can be categorized into two different approaches that individually may contribute to a study with a different category of data. Again, depending on the research carried out, this data can be complementary or used separately. Both Malterud (2014) and Erikson and Wiedersheim-Paul (2001) describe this and define the two approaches as quantitative and qualitative. The quantitative approach focuses on numerical data whereas a qualitative study centres on verbal communication and observations. According to Edling (2003), the quantitative method has one big advantage, when compared to the qualitative one, as it is based on mathematical and statistical analysis. The quantitative methods and analysis are well known and documented. This makes them easier to compare with similar studies and also easier to present the result to clients and other stakeholders.

Edling (2003) defend that the qualitative studies are primitive and fragmented. Jacobson (2007) points out that although quantitative methods are cheaper and have a calculable degree of certainty which makes general conclusions possible, they do not offer any depth. They tell, e.g. how many employees are dissatisfied but not exactly why. In contrast, qualitative methods offer the why to the question above, however, the results may be too detailed and/or hard to interpret and therefore hard to draw a definite conclusion to the study.

4.2.2 Interviews

Bogdan and Biklen (1992) consider interviews as being an excellent tool for data gathering since the method is aided by the respondent being able to mediate using his/her own words and body language. This gives the interview qualitative data which offers a deeper understanding of what's being researched. Denscombe (2010) shares this opinion and ads that interviews as data gathering method are particularly suitable whilst exploring more complex matters such as feelings, experiences and delicate questions. Denscombe (2010) describes three forms of research-interviews: The highly structured interview, the semi-structured interview and the unstructured interview. While conducting a highly structured interview the researcher has a clear agenda and has full control of the direction of the interview. The questions are mostly direct. Opposite to the structured interview, during the unstructured interview, the respondent is allowed to talk freely and with lots of room for discussion and open questions. Somewhere in-between is the semi-structured interview. This form of interview offers the respondent some room for discussion and open questions, but the interviewer controls the direction of the interview steering it in a desirable heading. Denscombe (2010) also points out four key factors to consider while planning an interview: the choice of relevant questions, choice of respondent, permits and arrangement.

4.2.3 Observations

According to Oates (2006), observation is a form of qualitative data collection and is defined by Graziano and Raulin (2013) as an empirical process of using one's senses to identify and record facts. The authors discuss that although performing observations is considered by many as the most basic and fundamental part of a research study, it is essential that the observation phase is preceded by a thorough procedures-design phase to determine what should be observed when it should be observed, and where the observations should take place. By doing this, the researcher ensures that the data gathered by observation is relevant for the conducted research. This is called structured observations by Oates (2006). Bryman (2008) names a counterpart as unstructured observations. This type of observation doesn't have a clear goal nor method, instead, the observer observes as much as possible. This might be useful when later determining what to study further with structured observations. Oates (2006) defends that by observing, a survey is done by observations, meaning that a correct sample size needs to be set in order to guarantee that the phenomena observed are not a one-time occurrence.

4.3 Chosen method

Tonnquist's (2018) project methodology has been chosen to conduct the project. The main reasons being that it's simple to understand and follow but also familiar to the students as it was covered by their education. However, all parts concerning simulation and optimisation follow Banks et al. (2010) 12 steps approach. The methodology followed to conduct this thesis can be seen in figure 5.

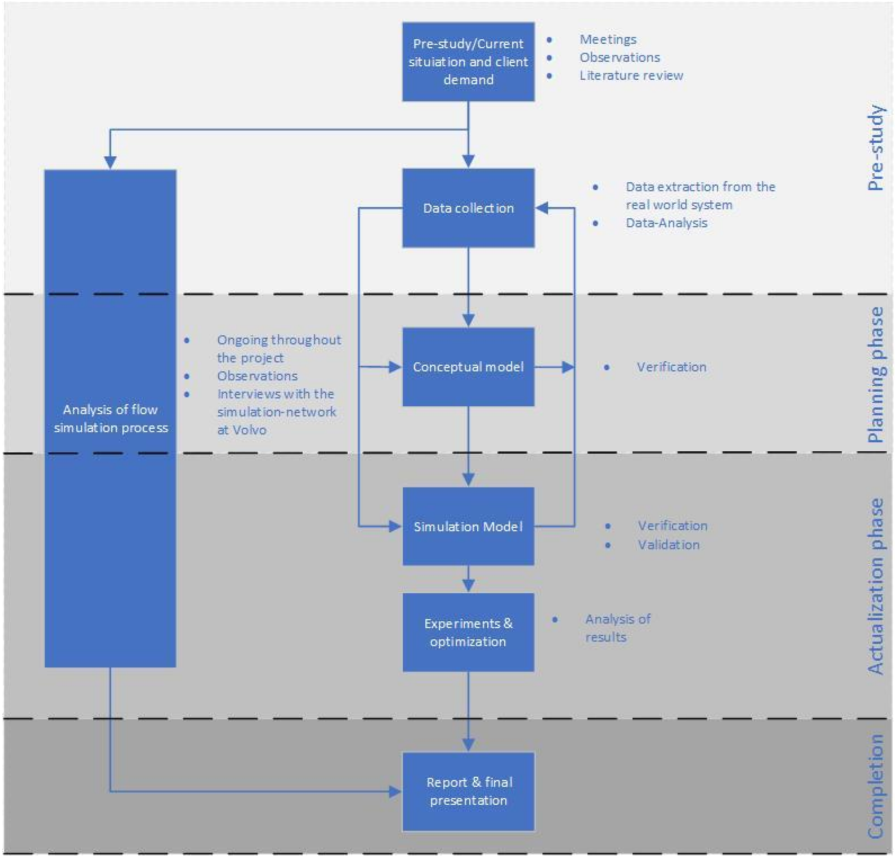

Figure 5.Project methodology combining Banks 12-steps (Banks et al. (2010)) and Tonnquist (2018) project methodology

Each of the main steps represented in figure 5 are briefly explained in the following paragraphs and in detail in chapter 5.

4.3.1 Pre-study

The project began with a comprehensive pre-study in order to fully comprehend the problem at hand, the stakeholders' demands and reasons for instigating the project. The purpose of the pre-study has also been to give the researchers a possibility to familiarize themselves with the organization and the real-world system that was studied. Since this system was in the process of being replaced, there also was an essential need to understand both the system to be replaced and the new system to be implemented as well as the reasons for this change. When all the points mentioned had been addressed and defined, a literature and a frame of reference study was performed as previous work in the same field provide useful information and guidelines for the simulation project.

4.3.2 Pre-Study - Data collection

When the literature part of the pre-study finished, the data collection began. It has been focused around two central problems, data needed for a valid simulation model and data needed for an evaluation of the current simulation process at Volvo GTO. The later has been an on-going process consisting of unstructured and structured interviews, unstructured observations during meetings, and own experiences and findings while working as simulation engineers at Volvo. The data collection for the simulation model has mainly consisted of quantitative data extraction from Volvos data system although structured and unstructured observations also occurred.

4.3.3 Planning phase

The planning phase has mainly focused on constructing a conceptual model which has been used for verification purposes and to choose the software to build the simulation model. Since the system to be modelled is yet to be constructed, the lion share of the verification was performed face to face with the stakeholders. During the planning phase and throughout the rest of the project, one of Volvos production technicians has had daily involvement in the model creation process. The purpose has been to prevent the finished model from being a one-time tool. Ideally, and in line with the stakeholders' requirements, the model should be used in future work, but the literature review has proven it hard to realize without the clients' involvement during the model construction and simulation phase. Therefore, the production technician has been part of the simulation project every step of the way so that the finished model easily can be utilized after the delivery to Volvo.

4.3.4 Actualization phase – Simulation model & optimisation

When the conceptual model was verified, and a suitable simulation software was chosen, the construction of the simulation model began. After the development of the simulation model, the verification was done face to face with the client. Later on, the experiments and buffer optimisation were performed. The experiments, as according to Banks et al. (2010) have been based on the needs and requests of the client. These experiments were also defined by insights gained during the modelling process.

4.3.5 Completion - Analysis, report & presentation

The output from the simulation-based optimisation, experiments and simulation process evaluation were analysed in this step. The findings were compiled into this report and an oral presentation was given at the University of Skövde and at Volvo GTO.

4.4 Method summary

In this chapter, the chosen methodology based on the knowledge gained during the previous chapters has been presented. The following chapter will explain how the chosen method was implemented and executed in detail.

5. EXECUTION

This chapter will describe how the project implemented the steps presented in chapter 4. The structure of the chapter is based on figure 5 and thus it begins with a pre-study, followed by a planning phase before ending with the actualization phase. Each step accounting for its contribution to the journey from a pre-study to the creation of an actual simulation model used for optimisation. The last sub-chapter, 5.5, presents the evaluation of Volvo GTO's simulation process.

5.1 Pre-study

The first weeks of the pre-study were intense, with many meetings facilitating the familiarization of the area to be rebuilt as well as the re-build team and the project in general, but also with Volvo GTO as an organization. As suggested by the Lean philosophy, Gemba was also utilized for this purpose. This meant that extensive observations were made of the re-build area but also neighbouring parts of the factory in order to get a complete perspective of the whole system. During meetings with the re-build team, the new line was thoroughly discussed. The objectives and purpose of the re-build project were also given. Further, it was discussed what the stakeholders' expectations were in regard to the simulation-based optimisation project and what it would yield to their re-build project. The meetings with the re-build team also served as a possibility for the students to ask questions and for the re-build team to provide and explain requested data not yet available in Volvo GTO data-logging system.

The flow simulation process to be studied and evaluated in this thesis is conceived and routinely used by simulation engineers and production technicians at Volvo GTO. They converge once a week with the purpose of discussing and developing simulation as a tool at Volvo. During these meetings, which are called the simulation network, current simulation projects are also discussed. Therefore, it was vital to meet with them in order to discuss the matter of the flow simulation process evaluation. These meetings occurred on a regular basis throughout the project lifetime.

During the pre-study, unstructured observations were constantly being made. The observations ranged from observing actual work to observations of logistical routes and observations of processes before and after the re-build. Much of the knowledge gained during these observations would later be used in defining the actual system to be modelled and what data that was necessary to collect during the data collection.

5.2 Pre-study - Data collection

In accordance with the ruling project specification and Volvo's flow simulation process (figure 17), all production data collected and used while making the simulation model should be from 2017. Furthermore, data collection as a task, is defined by Volvo's flow simulation process as a requestor activity. This means that, all data necessary should be supplied by Volvo GTO. This condition was not fully met as Volvo only supplied some of the necessary data. The bulk of the input data had instead to be manually collected via Volvo's data-logging systems. The following sub-chapters will explain which data that was deemed necessary and ultimately was gathered by the simulation project, but also to separate the data supplied by Volvo as this data mainly consists of estimations and calculations.

5.2.1 Variants

Figure 6 explains the relationship between unique engines, engine types, engine flows and customer flows. The engine type describes what type of engine it is in regard of the volume of the engine. The engine flow carries information about the route the engine takes through the factory. Lastly, the customer flow determines where in the world the customer is located.

The pre-study and data collection revealed that there was no need to implement individual unique engines into the model as all necessary production data were accessible at an aggregated level. It was deemed sufficient to use engine flows thus the different engine flows are introduced in the model as variants. Over 30 different variants were ultimately introduced.

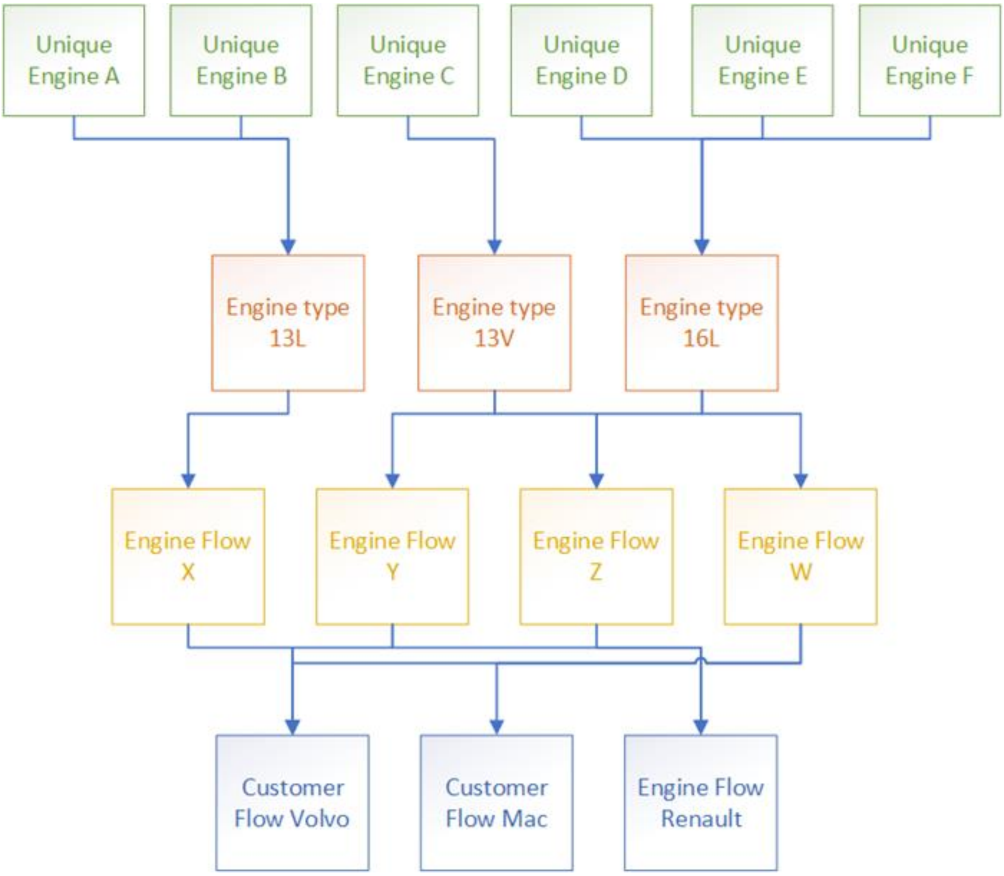

Figure 6. Relation between unique engines, engine type, engine flows and customer flows

5.2.2 Creation interval

The creation interval is the interval for which the model source creates entities (engines). Since it's a source parameter it's necessary to define what constitutes the source before the data can be collected. Volvo's initial suggestion as prime source proved to be unsuitable for this simulation project. Their suggestion did not consider limitations in their data-logging system. These limitations prevented the simulation project from modelling the suggested source in a rightful manner. Instead, the simulation project identified two source options which were considered and ultimately, after consultation with the re-build project team, a source definition was established. The two options and their corresponding definition can be found in chapter 5.4.3.1.

Defining the model source and extracting and interpreting data for the creation interval turned-out to be one of the most time-consuming steps of the simulation project. Due to the limitations of the data-logging system, the simulation project decided upon treating the real-world source as a gate, opening and closing, each time letting one engine through. The task at hand would, therefore, be to determine how often that gate opened during the production year of 2017. This was achieved by first determining which engine flows that were relevant for the simulation project. Not all engine flows at the production plant enters the system to be modelled (Konpack), these had to be filtered out. Otherwise, they would contribute to creating a shorter, and therefore, erroneous interval. Secondly, data for all remaining flows was extracted and sorted according to the shift when the gate opened. By doing this, the number of gate openings per shift and day could be determined. This data was then fed into DataFit, a module within Plant Simulation, in order to identify the correct distribution for its representation in the simulation model. Ultimately, using this method, a probability distribution was identified for each shift and thus creating the creation interval.

5.2.3 Processing times & availability

Since the system to be modelled (Konpack) is under construction, some data had to be estimated. Therefore, data regarding cycle times and availability within Konpack, are based on calculations and estimations from the re-build project team. However, all processing stages previous to Konpack have processing times obtained using a similar method as the one described in the previous section. The only difference was in the filtering of engine flows. This time, it was necessary to determine how often a workstation outside of Konpack (a pre-system activity) actually sent an engine to a receiving station within Konpack. The case is similar as with the source, not all engines processed at a pre-system activity are necessarily sent directly to Konpack. Therefore, it became obvious to filter these in order to not create too short processing times. This was achieved by using a document provided by Volvo. Unfortunately, due to sensitive information, this document is not included in this thesis report. In the same way, as in chapter 5.2.2, a shift-depending interval between engines was obtained and used as processing time.

Since it is an interval between engines that is obtained from historical production data for the year 2017 an assumption was made that the interval between engines should already contain the availability for the source and the pre-system activities. Consequently, no separate availability is calculated and added for the source and the pre-system activities.

5.2.4 Logistics

Logistics between the source and the pre-system activities are not covered since it is outside of the projects scope. All other data regarding transportation of engines is based on assumptions made by forklift operators, team-leaders and the re-build project team.

5.2.5 Shifts

Varying working hours for the production processes within Konpack as well as outside were identified as a variation contributor. Since variation is very important to incorporate as realistically as possible shift objects with correct working hours were created. This data were supplied by Volvo.

5.2.6 Missing data, simplifications and assumptions

During the data collection it became evident that some simplifications and assumptions had to be made. These are listed in Appendix 1.

5.3 Planning phase - Conceptual modelling

The pre-study and data collection resulted in a conceptual model and functional specification. The importance of a good conceptual model has been given in chapter 2 and 3. Therefore, while constructing the conceptual model the objectives, inputs and outputs of the model, as described by Robinson (2004), were defined as:

- Objectives – The model should primarily be able to perform an optimisation of the Konpack engine buffer. It should also be able to find the optimal configuration of sequence positions. Secondarily, the model should be able to answer whether the workstation ExtraEM is needed or not.
- Inputs – The model input consists of all pre-system processes which produced engines destined for Konpack during the year 2017.
- Outputs – The model output is the Loading dock of the manufacturing plant.

Robinson (2004) also talks about the content of the conceptual model. In the case of Konpack the model content consists of an engine buffer, the new packing line (CBU-line), sequence positions, post-assembly stations called docks, an interim buffer called "Out" and a source. Furthermore, over thirty different variants were identified.

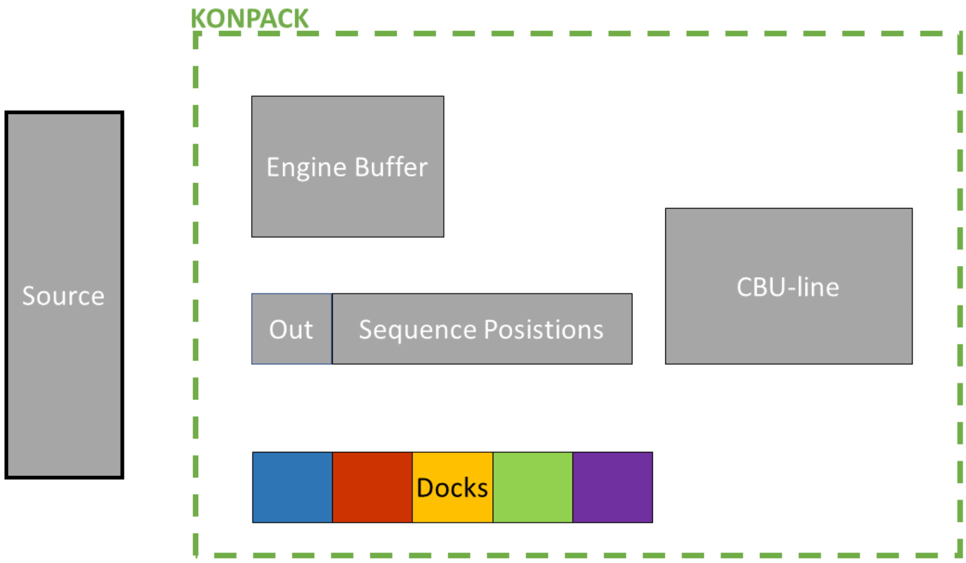

Figure 7. Simplified version of the conceptual model. See appendix 2 for the full version.

The source supplies the engine buffer with engines. The engine buffer contains storage space for up to 66 engines and is loaded and unloaded by forklifts. The sequence positions determine which engines are to be handled next by the docks. These, on the other hand, are manual stations mainly responsible for customer customization of the engines. The "Out" buffer next to the sequence positions is a small interim buffer used for storage of engines finished by the docks. The last main object of the conceptual model is the CBU-line which packages the engines for further transport. Apart from the source, the objects described above are what from now on will be referred to as Konpack (see figure 7).

Approximately half of the engines delivered by the source are transferred to the CBU-line and then exit the system scope. The rest are delivered to different docks. Some of these engines then exit Konpack via the out buffer, going back to the source before returning, for a second and sometimes a third time, through the system before exiting the model. For the engines that are going to the docks, the idea is that the main engine buffer supplies the sequence positions using a forklift. These are the positions that the docks manually collect engines from.

There are two reasons for this, somewhat tedious, way of delivering engines. The first being safety. By doing it this way, workers and forklifts do not share the same workspace as the space is divided by the sequence positions, see figure 8. The second reason is that knowing which engines currently occupies the sequence positions, gives the material supplying personnel time to prepare material for the docks. Even though material supply is not a part of the simulation study, capturing the sequence of engine movement and the physical limitations (number of sequence positions and docks) is very important for the re-build project team and thus important for the model.

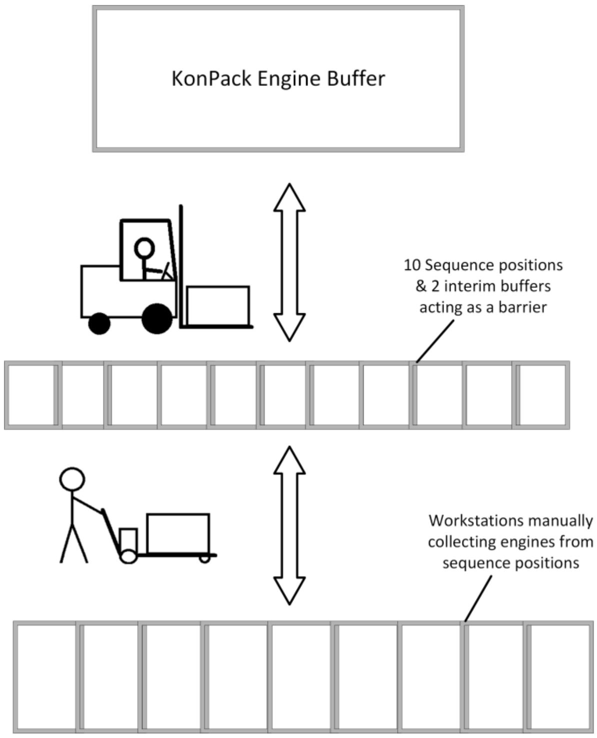

Figure 8. Sequence positions acting as a barrier between workers and forklifts

The CBU-line consists of multiple manual stations and one automated station. They package the engines making them ready for further transport to the customer. The CBU-line have two entry points, one for engines travelling straight from the source without any post-assembly and the other entry point for engines that are coming from the docks. The later having priority over the first. The last activity in the CBU-line is considered being the exit point of the model and will always be available.

The pre-study, data-extraction, and analysis of the extracted data indicated that the real-world system is relatively complicated. It consists of many different engine flows. After main line assembly, some of the flows enter and exit Konpack multiple times, each time via different pre-system activities. These are called “pre-system activities” because they precede the system to be modelled (Konpack) but are still significant in regard to performance. This led to one of the main issues at this point in the project, how to treat the model source. Two options where considered:

A.) The first pre-system activity, common for all engine flows (the final assembly) creates all engines, hence becoming the prime source. The succeeding activities up to Konpack are simplified down to a buffer and a station each and called pre-system activities. This option is represented in figure 9.

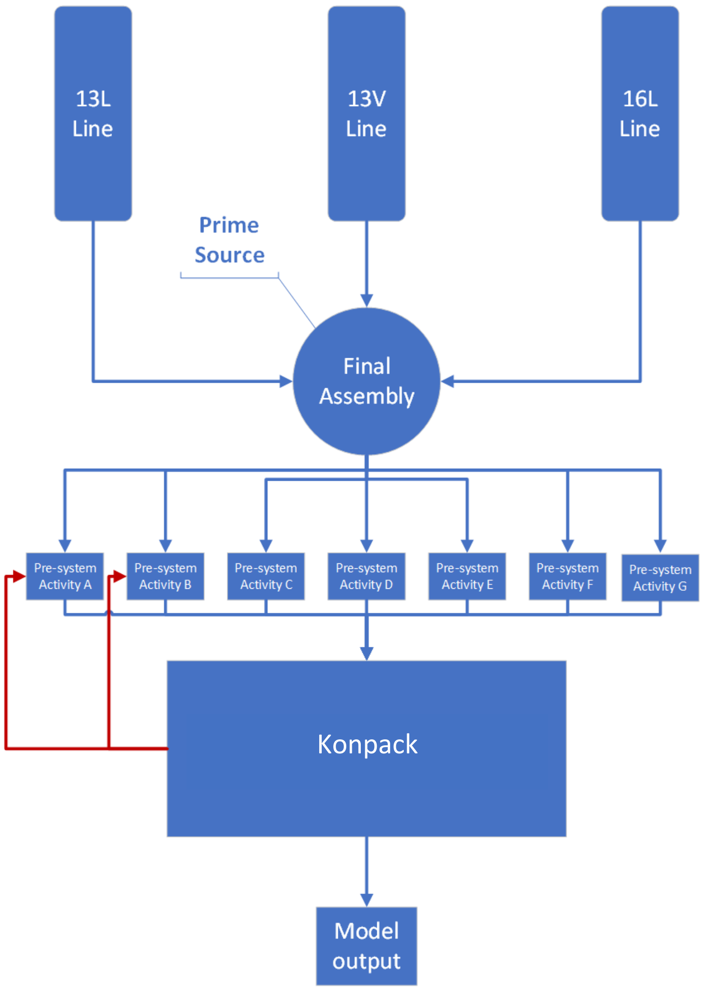

Figure 9. Option A

B.) All pre-system activities after the final assembly (the selected source in option A) but before Konpack are considered as individual sources creating engines separately of each other, and thereby, collectively creating an engine source. This option ignores the final assembly and what happens earlier in the production. This option is represented in figure 10.

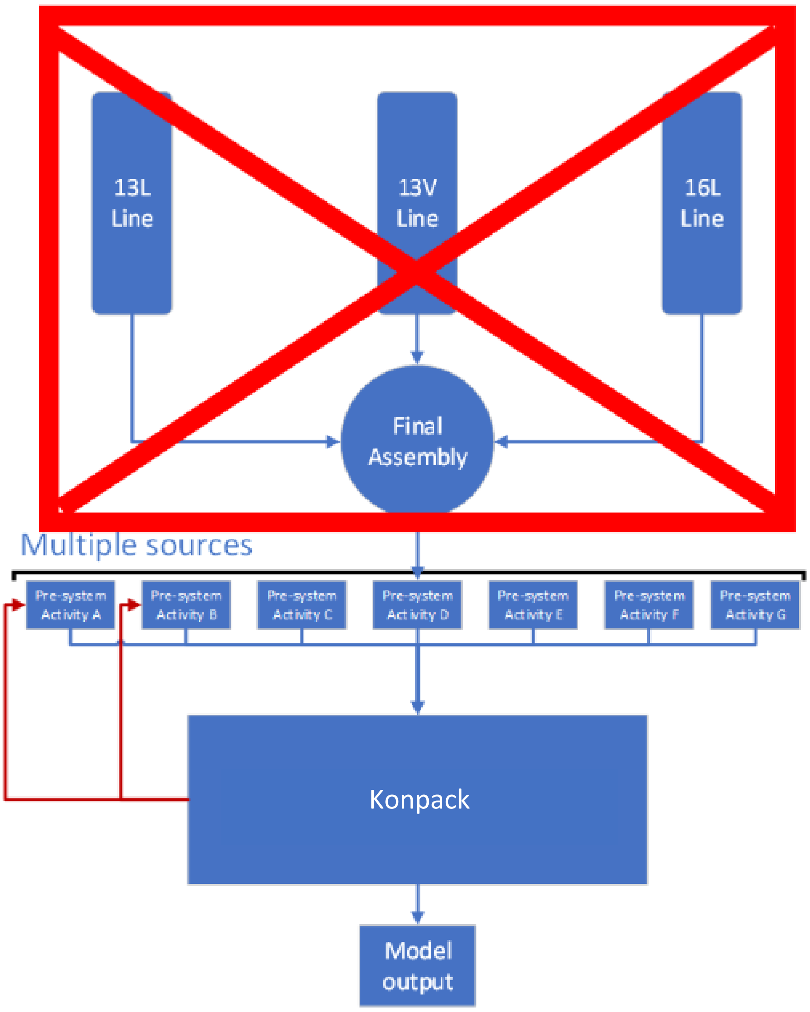

Figure 10. Option B.

Option B was initially selected, but due to how Volvo's data-logging system works and the fact that engines sometimes go back to the source created duplicate notations of engines in the data-logging system. Without a simple way of filtering those out, it became very difficult to get reliable data. For this reason, option A was selected and new data were gathered.

When the conceptual model was completed, a meeting with the stakeholders took place. At this meeting, the validity, credibility, utility and feasibility of the conceptual model were discussed. Ultimately the conceptual model was deemed valid by all parties. During the validation meeting, it was discovered that despite the carefulness taken while revising the project specification, members of the re-build team which hadn't been present in this process until this point in the project, expressed that they had additional requirements which were not stated in the agreed project specification. Since this discovery was made rather late and to some extent contradicted other requirements set by Volvo, these were agreed to be treated as optional requirements. These optional requirements are listed in chapter 5.4.1.

5.4 Actualization phase - Simulation model

Once the conceptual model was valid and accepted by all stakeholders the construction of the simulation model could commence. This chapter will present the requirements, the software selection and ultimately, the constructed flow simulation model and how it was verified and validated.

5.4.1 Stakeholders' requirements

At the start of the project, the researchers and the stakeholders from the company agreed upon a project specification which stated the client requirements regarding the model and its expected result.

Initial stakeholder requirements (Req.), related to the objectives of the project are:

- Req. 1 - Optimisation of multiple buffers.
- Req. 2 - Possibility to use the model for future evaluations of Konpack once the real-world counterpart has been constructed.
- Req. 3 - Model and optimisation results being ready in January 2019.

However, after thorough discussions with the stakeholders, it was discovered that an additional set of requirements existed. But, since those weren't stated in the agreed project specification and were discovered rather late in the project lifetime, the additional requirements were listed as optional.

Optional requirements (OptReq):

- OptReq1 - A user-friendly graphic user interface (GUI).
- OptReq2 - The ability to read lead time for entities from their source to the first system buffer they enter.
- OptReq3 - The possibility to allocate/change resources in the docks.
- OptReq4 - The possibility to change shifts for the docks.

5.4.2 Software comparison and selection

The two commercial simulation software which were considered for this thesis work were FACTS Analyzer and Siemens Plant Simulation. Both software are used by the Volvo GTO in their flow simulation projects. Additionally, the students conducting this thesis are educated in both FACTS and Plant simulation, making these two software packages the obvious candidates for this flow simulation project. Selecting between these two candidates is also in line with project requirement 2, making it possible for the stakeholders to use the simulation model for future evaluations of Konpack, once this project is finished.

In order not to be hindered by software capabilities, a comparison was made between the two alternatives (table 1). The comparison focused on the two software's possibilities to model the real-world system and fulfil all the stakeholders' requirements. It was deemed important for the project to try to fulfil the optional requirements, if there was time left and the initial stakeholder requirements had been fulfilled. Choosing the correct software could support this.

Table 1. Flow simulation software comparison

Stakeholder requirements and real-world demands	FACTS Analyzer 2. Vers. 3.0.5	Plant Simulation 14.2
Req. 1: Optimisation of multiple buffers	Yes	Yes
Req. 2: Possibility to use the model for future work	Yes	Yes
Req. 3: Model and optimisation results ready in January 2019	Possible	Yes
OptReq. 1: A user-friendly graphic user interface (GUI)	Not possible	Yes
OptReq. 2: The ability to read lead time for entities from their source to the first system buffer they enter	Not possible to select two points and measure lead-time between them for a specific entity	Yes
OptReq. 3: The Possibility to allocate/change resources	No.	Yes
OptReq. 4: The possibility to change/remove shifts	No. The shift object in conjunction with the resource object is not functional in the current version.	Yes
Real-world demand 1: Set a possibility for a shift to occur	Limited, through timetabling.	Yes
Real-world demand 2: Use all identified distributions	Gumbel, Pareto and Loglogistic are not available in current version.	Yes

After careful deliberation, testing and consultation with the stakeholders, the university supervisor and examiner, and considering the project requirements, FACTS Analyzer was deemed not sufficient enough to effectively model the complexity of the real-world system. Although FACTS is a very powerful software for fast modelling, is very user-friendly, and has a strong optimisation engine, the limited possibility to introduce programming and the impossibility to create a GUI were seen as too big hurdles to overcome. Hence, Siemens Plant Simulation was selected as the software to be employed to create the simulation model.

5.4.3 The simulation model.

The simulation model is not that different from the conceptual model described in chapter 5.3 due to the work effort during the pre-study and conceptual model phases of the project. The simulation model was developed in stages, where each new version added a layer of new features. Developing the model in this manner has two major benefits. It provides a solid library of backup files and it also eases error detection. The final model took two weeks to construct and can be seen in figure 11. There are five versions of the model. One version for the buffer optimisation and four clones used for the different experiments conducted later in this study.

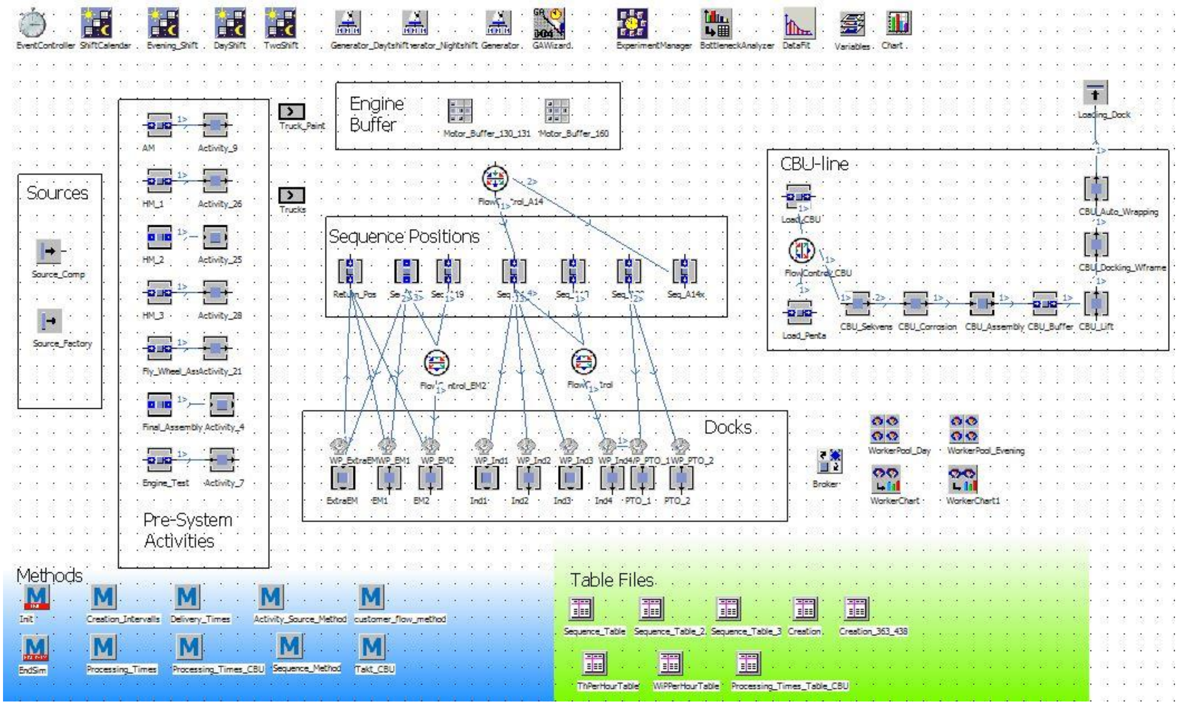

Figure 11. Screenshot of the simulation model. A larger version is available in appendix 3.

Figure 12 follows one entity's journey through the flow simulation model. The idea is to give a brief understanding of the model before examining each section in greater detail in the following chapters. However, before reading further, it is important to understand the difference between docks and activities since these terms are somewhat intertwined and frequently used from now on. A dock is a Konpack specific term and is equivalent of a workstation. It's a physical place where the engines are modified according to customer specifications. An activity is a certain type of work that is carried out in docks but also at other stations outside Konpack. An activity could be fitting the engines with a cooler, mounting them on wooden frames or painting them at the paint shop. Docks are tied to specific activities and only carry out those activities.

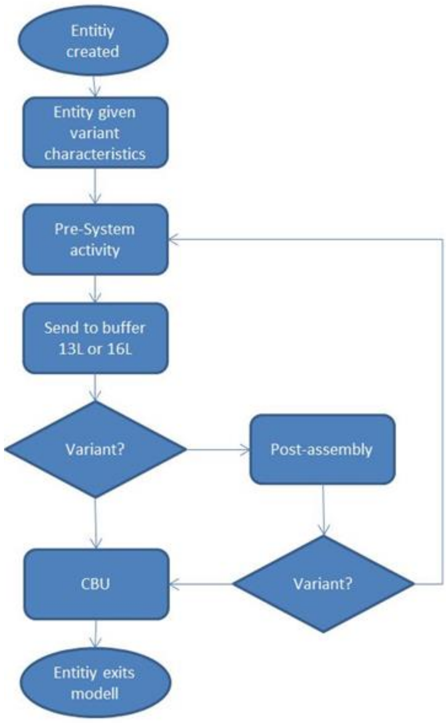

Figure 12. Flowchart of an entity's journey through the simulation model.

5.4.3.1 The sources

The sources of the model (Source_Factory and Source_Comp) are mainly responsible for two things. They create entities with a certain interval and proportion. The interval for which the sources create entities is obtained by using distributions based on historical production data. Using an interval between engines instead of a cycle time is due to limitations in the data-system from which the input data were gathered from. The interval represents how often the real-world source actually sent an engine to Konpack during the year 2017, see figure 13.

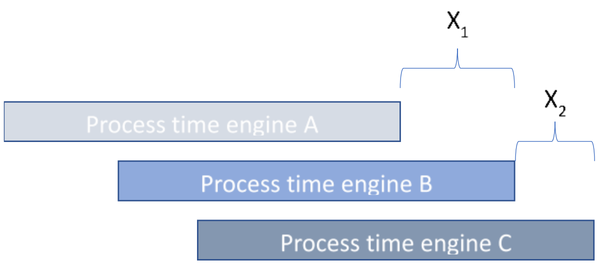

Figure 13. Interval between engines.

X_1 and X_2 in figure 13 represent the interval between engines at the real-world source. X_1, X_2… X_n were collected separately for every shift for all days of 2017. This data was then fed into DataFit for distribution identification and selection. The selected distributions were then implemented and are used by Source_Factory. Source_Comp, on the other hand, is different. For less than 3% of all engines, it wasn't possible to obtain accurate data. In these cases, only the produced amount at the end of the year was known. Therefore, the amount produced is divided by actual historical production hours resulting in a fixed interval not generated by a distribution. This interval is then used for creating the affected engines in Source_Comp.

The model does not include unique engines but engine flows (for the difference between a unique engine and an engine flow see figure 6). This is due to that in the real-world system it's the engine flow which dictates the processing times for the different steps of the manufacturing process. Consequently, Source_Factory and Source_Comp use the probability of creating an engine that belongs to a certain engine flow rather than a unique engine. This greatly minimizes the number of unique entities that must be incorporated into the model, making it more easily understandable and run faster. Source_Factory and Source_Comp retrieve this probability from a table file which is based on historical production data provided by Volvo.

When the proper interval between engines (takt) has been determined and an engine of a certain engine flow has been created, Source_Factory and Source_Comp need to know where to send the engines. This information is gathered from different engine flow sequence tables which are based on documents provided by Volvo. These contain the exact work sequence for all the engine flows handled by the model. For an example, see figure 14 below.

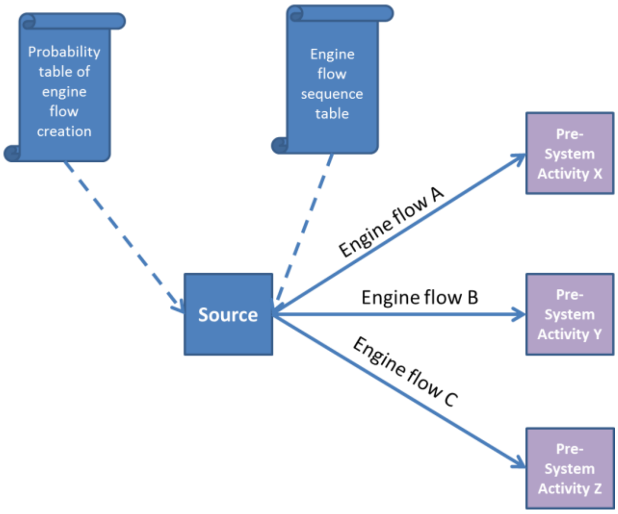

Figure 14. Simplified example of how sources read table files and distribute engines.

5.4.3.2 The pre-system activities

Succeeding the sources are the so-called pre-system activities. These are sections of the plant carrying out specific activities. The pre-system activities are the paint shops (AM, HM_1, HM_2, HM_3), the Fly_Wheel_Assembly, the Final_assembly and Engine_test. These activities do not belong to the Konpack re-build project but are very important since they create variation in delivery times to Konpack. The processing times for the pre-system activities are calculated in the same fashion as the source "Source_Factory", meaning that it's rather an interval between engines sent to Konpack rather than a processing time which is used. The reason for this is that the majority of the pre-system activities do not measure cycle time, only engine arrival time is registered. Because of this, the pre-system activities have been aggregated in the simulation model, present as a buffer and an operation per activity. Apart from creating variation, the pre-system activities have another important function in the flow simulation model as they keep track of how many times an engine has entered Konpack. This information is then used to link the engines with the right sequence tables ensuring that the engines move appropriately through the model.

5.4.3.3 Forklifts

The moving of engines between the pre-system activities and the Konpack engine buffers is handled by four forklifts divided into and represented by two conveyor objects. The number of forklifts, their delivery times, and availability are set according to the re-build project group.

5.4.3.4 Konpack - Engine buffers

The engine buffers are called “Motor_Buffer_130_131” and “Motor_Buffer_160” in the model. 13-litre engines go into “Motor_Buffer_130_131” and 16-litre engines are stored in “Motor_Buffer_160”. In reality, the two engine buffers share the same physical area and can be seen as one buffer, but due to physical limitations and safety regulations the 16-litre engines are not allowed to be stored on the second level in the buffer. This limits the number of positions for the 16-litre engines. Consequently, a division of the buffer area was considered necessary. The joint maximum capacity of the two buffers is 66 engines. The store object-type is used for the two buffers in the simulation model rather than perhaps the more obvious buffer object. If there is a demand for a specific engine, the store object enables that engine to exit the buffer without the need to be first in line as is the case with the buffer object.

5.4.3.5 Konpack – Sequence Positions

A sequence position is a physical space between the engine buffer and the docks acting like a transitional buffer. The total number of sequence positions is ten, plus two out positions which are used in the same fashion but for engines travelling back to the pre-system activities. For reasons explained in chapter 5.3, the sequence positions are where the docks collect engines from.

The docks are each locked to one or two activities, out of a total of six possible activities. Thus, the sequence positions also are activity specific, meaning that they only allow an engine to enter to a position, if that engine is in need of the same activity as a sequence position is specified for. An example is illustrated in figure 15.

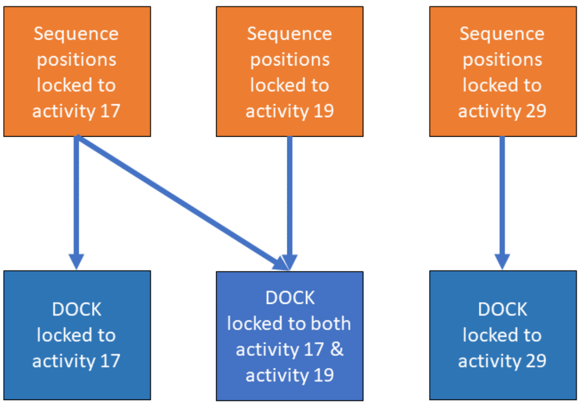

Figure 15. The relation between sequence positions and docks.

By balancing how many sequence positions one activity may have, it is possible to ensure that the right amount and proportion of engines are presented for the docks so that the docks always have work to do. The sequence positions in the simulation model also link the engines with a customer flow. This is done because much of the data supplied by the re-build project team was calculated based on customer flows rather than engine flows. The customer flow attribute does therefore determine what the process time will be in the forthcoming activities.

5.4.3.6 Konpack – Docks

The docks are comprised of nine manual workstations. Each with its own distribution-based customer flow dependent cycle time, availability and MTTR. The input data for the docks have been supplied by the re-build project team. As mentioned before, the docks' main task is to carry out predetermined activities to customize the engines. Each dock requires one worker to operate.

Two docks differ from the other in regard to functionality, these are PTO_1 and PTO_2. In the real-world system, they occupy the physical space next to each other and they also share the same two activities, activity 14x and 29. Activity 29 can be performed at both docks at the same time, meaning that two engines can be assembled simultaneously. However, engines that trigger activity 14x require the space of both docks in order to be handled, meaning that only one engine can be assembled at a time.

Common for all docks is that they all are active during the day shift and all are inactive during the night shift. This is not the case during the evening shift when some are inactive, meaning that no production is allowed at these docks. Another common attribute for the docks is that the workers collect engines manually from the sequence positions and deliver finished engines to either the out position or to the CBU-line, this is also done manually. Because of this, the docks have been given a recovery time in the model as a compensation for the time it takes for a worker to collect and deliver an engine.

5.4.3.6 Konpack – CBU-Line

The CBU-line is a semi-automated line consisting of four manual workstations, one automated wrapping station and two buffers. The transportation is handled by a conveyor and lift system. The first buffer in the CBU-line also works as a takt generator. It ensures that an engine is not delivered to the next station unless a certain amount of time has passed. The only exception to this rule is if the stations ahead are empty, in which case the buffer instantly forwards the engine to the next station. This is an attempt, according to the re-build project team, to create a pulling rather than a pushing system as defended by the lean philosophy.

The CBU-line has two entry points in the model, Load_CBU and Load_Penta. Engines coming straight from the pre-system activities enter the CBU-line via Load_CBU and engines coming from the Konpack Docks enter via Load_Penta. Load_Penta always has priority over Load_CBU. The last station in the CBU-line, the CBU_Auto_Wrapping marks the end of Konpack and hence the system to be modelled.

5.4.3.7 Loading dock

After being processed by the CBU-line, engines arrive at the loading dock. Although the loading dock is outside of the project's scope, the model needs a drain and thus, this is the function of the loading dock in the model. In other words, it's responsible for removing the finished engines from the flow simulation model.

5.4.3.8 Flow controls

The simulation model uses four flow controls for directing the engine flows. FlowControl_A14 determines which engines that go to activity 14 or activity 14x using a fixed percentage based on historical production data. The other three flow controls are used for giving priority to certain engine flows.

5.4.3.9 Workers

Workers in the simulation model are only used in the Konpack docks (not counting the forklifts). They all have the same attributes meaning they work equally as fast and with the same precision. Seven workers are active during the day shift and three during the evening shift. No work is done by the workers during the night. Workers were added to the model since some docks are deactivated during evening shifts leading to that the worker/dock ratio changes, e.g. the day shift has all the docks active meaning that seven workers share the responsibility for nine docks. The evening shift, on the other hand, has three workers sharing the responsibility for six active docks. The number of workers for each shift and at what time the docks operates or not has been introduced in the model according to the estimations provided by the re-build project team.

5.4.4 Verification & validation

According to Banks et al. (2010), a computerized representation of a real-world system must be verified and validated before it can become a simulation model, ready to be used for e.g. a buffer optimisation. The main focus when entering the process of verification and validation was to ensure that all the input parameters and logical structure behaved correctly. Equally as important was that the stakeholders were satisfied and believed in the model. This was achieved in four steps. The first step was creating variables which were used to monitor all entities and flows in the model. Apart from offering a quick view of the system status, creating the variables proved to be an excellent opportunity to dissect the model and question variables indicating numbers not in line with what was expected. After identifying and correcting a couple of minor mistakes, it became apparent that just because the inputs and outputs of the model initially seemed right, it didn’t mean that what was going on within the model was correct.

The next, very important step of the verification and validation process is to make a steady-state analysis and replication analysis. The purpose is to determine when the flow simulation model reaches a stable state and a desirable accuracy. For the model to be deemed behaving correctly, it had to replicate the production outcome of 2017. This meant that the targeted throughput to achieve was between 4,6-4,8 entities per hour. As seen in figure 16 the flow simulation model reaches a stable state after approximately 500 hours. Therefore, the warm-up time was set to 83 days and 8 hours. The replication analysis (table 2) confirms that 20 replications were sufficient in order get a confidence level of 95%. The simulation horizon is based on actual production days during the year 2017 and is therefore set to 318 days and 8 hours (including warm-up time).

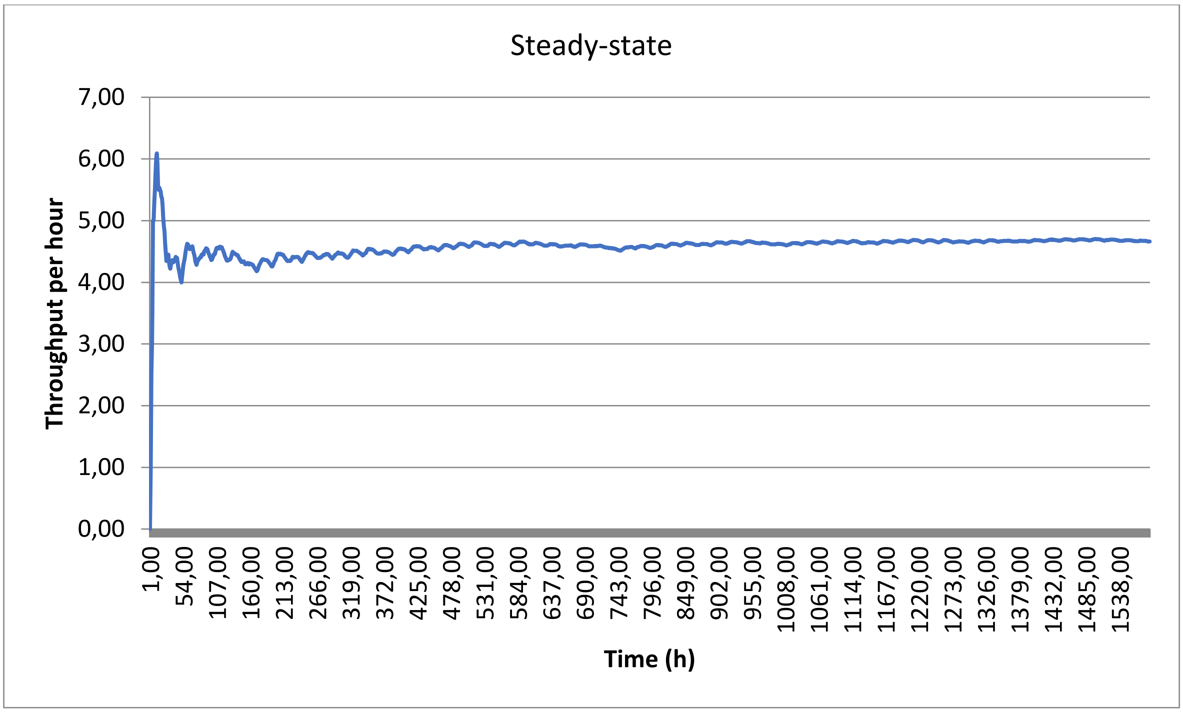

Figure 16. Steady-state

Table 2. Replication analysis

Output	Confidence level	Num replications used	MEAN	STDEV	Standard error (with students t distribution)	Relative precision	Absolute precision	Number of simulations needed	Num replications OK/NOK	Maximum span of the confidence interval		Confidence interval Min	Confidence interval Max	Confidence interval Span
TH	0,95	10	4,649	0,065	**0,05**	**0,014**	**0,065**	**5,117**	**OK**	0,13		4,6	4,7	0,1
LT	0,95	10	29702	3097	**2215,46**	**0,061**	**1800,000**	**15,149**	**NOK**	3600		27500	31900	4400
WIP	0,95	10	48,02	4,238	**3,03**	**0,052**	**2,500**	**14,706**	**NOK**	5		45	51,1	6,1
TH	0,95	20	4,656	0,06	**0,03**	**0,014**	**0,065**	**3,733**	**OK**	0,13		4,63	4,68	0,05
LT	0,95	20	30076	3163	**1480,33**	**0,060**	**1800,000**	**13,527**	**OK**	3600		28600	31600	3000
WIP	0,95	20	48,508	4,439	**2,08**	**0,052**	**2,500**	**13,811**	**OK**	5		46,4	50,6	4,2

The next step was to create a verification and validation document (appendix 4). The idea of this document was to cover all assumptions, methods and details about each object in the model. Just like when creating the variables, creating this document proved to be an excellent opportunity to question assumptions, methods and ultimately the logical structure of the model.

The fourth and final step, as suggested by Carson (2002) and Sargent (2014), was a meeting with all stakeholders for face validation. The model was explained partly by demonstrating and partly by using the verification and validation document presented in appendix 4. The stakeholders were encouraged to question the model but also to ask questions if anything was unclear. According to Sargent (2014), validation by a third party could further strengthen this process. Therefore, one of Volvo's simulation engineers was invited to a separate meeting. He was asked to give his opinion regarding software-related decisions and model logic. Ultimately, the flow simulation model was approved by all parties and therefore deemed verified and valid.

5.5 Actualization phase - Evaluation of Volvo's simulation process

Volvo's Simulation methodology is quite similar to Bank's 12-step model (Banks et al. (2010)), described in chapter 2.3. There are however some differences and digression.

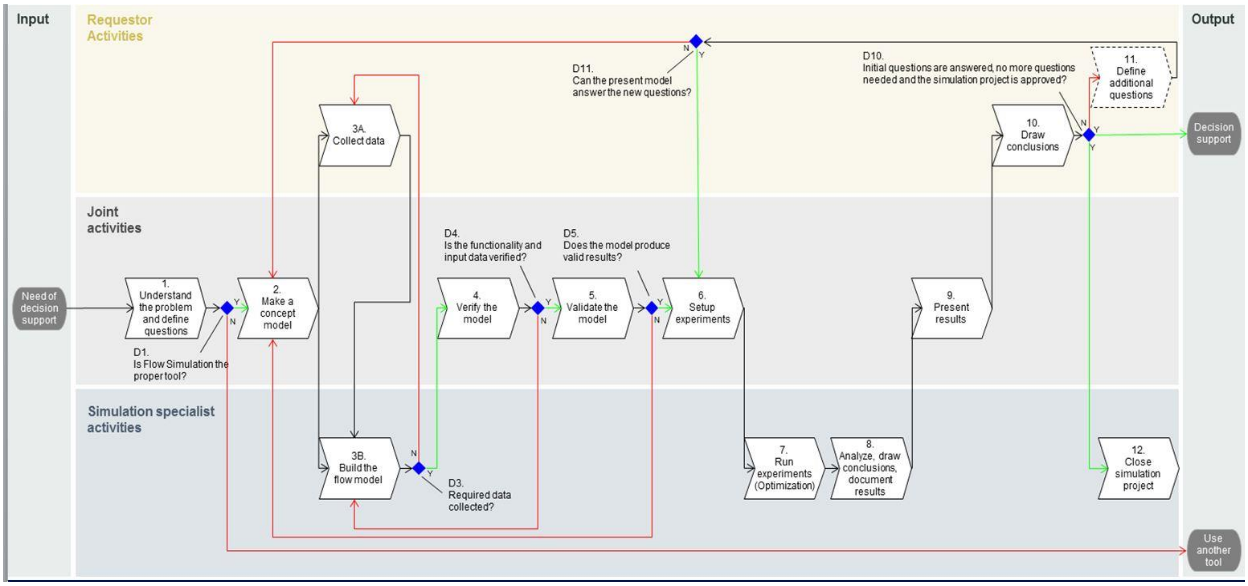

Figure 17. Volvos flow simulation methodology.

Volvo's simulation methodology is presented by the flowchart seen in figure 17. The main difference between Banks-12 step model (Figure 2) and Volvo's simulation methodology is the addition of an underlying layer describing the responsibilities of each party within a simulation project. There is also some digression within the individual activities.

The goal of the flow simulation process evaluation is to follow each step presented in figure 17 and evaluate each activity. The evaluation will be based on knowledge obtained from the frame of reference, the literature review, the simulation project conducted during the thesis work and insights gained during meetings with the simulation network. The result of the analysis will hopefully help to improve the flow simulation process and future projects by providing an outsider's perspective. The evaluation might also offer an insight on how much Volvo as an organisation has adopted flow simulation. The activities presented in the flowchart are described and discussed in chapter 6.4.

5.6 Execution summary

This chapter has described the thesis work execution phase. Due to a pre-study which mainly centred around an extensive familiarization process and thorough data collection a conceptual model was created. Following the verification and validation of the conceptual model, a simulation model was conceived and made ready for optimisation and experimentation after an additional round of verification and validation. The final sub-chapter introduces the evaluation of Volvos' flow simulation process, which was performed while conducting the simulation project.

6. RESULTS

This chapter explains and presents the results of the optimisation and experiments conducted. Firstly, the process of buffer optimisation is described. This is followed by experiments using buffer levels based on the optimisation. The aim of the experiments is to test the flow simulation model but also to serve as a value-adding measure.

6.1 Buffer optimisation

The goals of the optimisation are to find parameters that minimize buffers and maximize throughput. However, a consideration will be taken to reducing lead-time and WIP, as well as not blocking the main source while examining and analysing the results of the optimisation. This is in line with the principles of the lean philosophy.

In chapter 2.6.1 and chapter 3.3, strong arguments were made about the benefits of using simulation-based optimisation. Consequently, this was done to conduct the buffer optimisation. The optimisation algorithm employed has been NSGA-II. As inputs to the optimisation, engine buffer capacity and sequence positions configuration were chosen. As seen in table 2, 20 replications were needed to reach a confidence level of 95%, consequently creating the need for lots of iterations for each solution (different sequence position configuration and buffer capacity). In order to limit the solutions to be tested (with regard to real life limitations), only possible sequence positions configuration and buffer capacities were tested. Additionally, the optimisation was limited to 10.000 different solutions. The result can be seen in the graph in figure 18 where the dominating solutions are highlighted in green, representing the Pareto front.

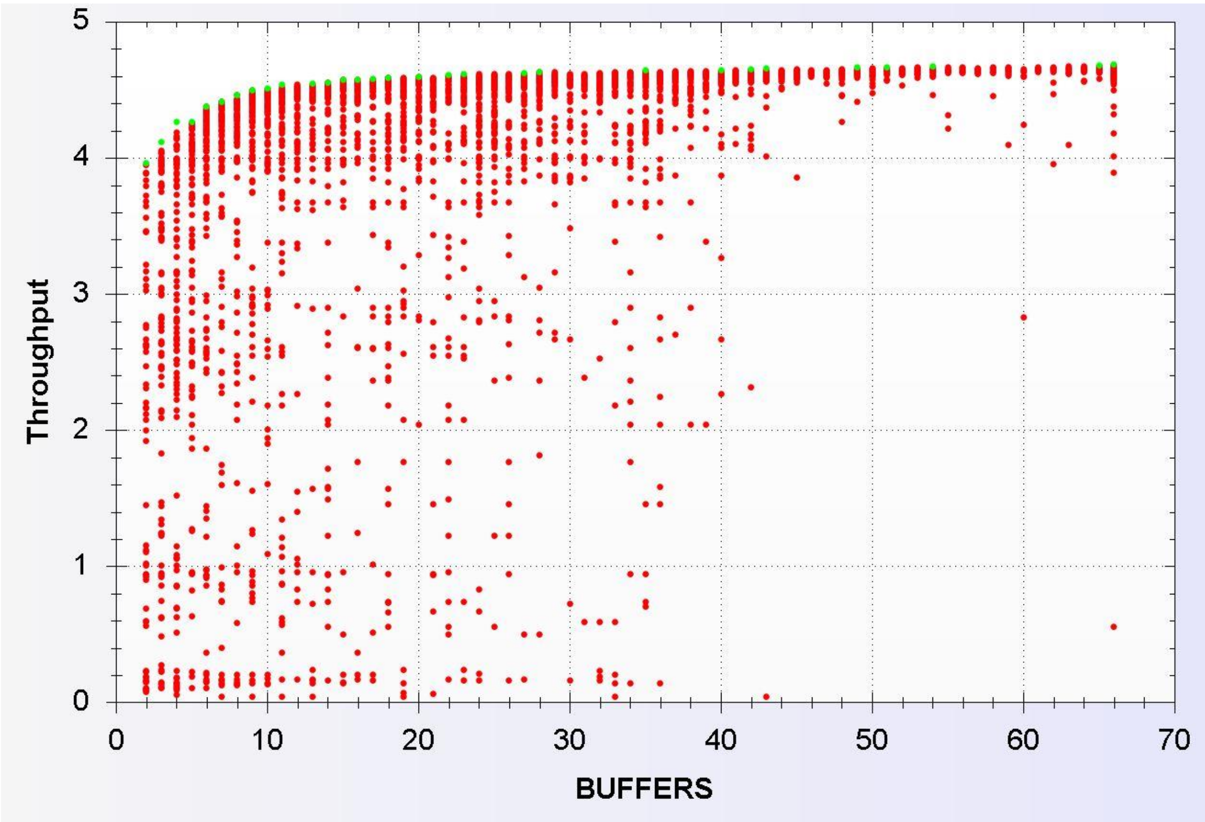

Figure 18. Pareto front based on system throughput and total buffer capacity.

The data were then filtered so that only dominant solutions were studied. As seen in figure 19, throughput increases until it reaches a buffer capacity level of around 20-30 (30%-47% of initially planned maximum capacity).

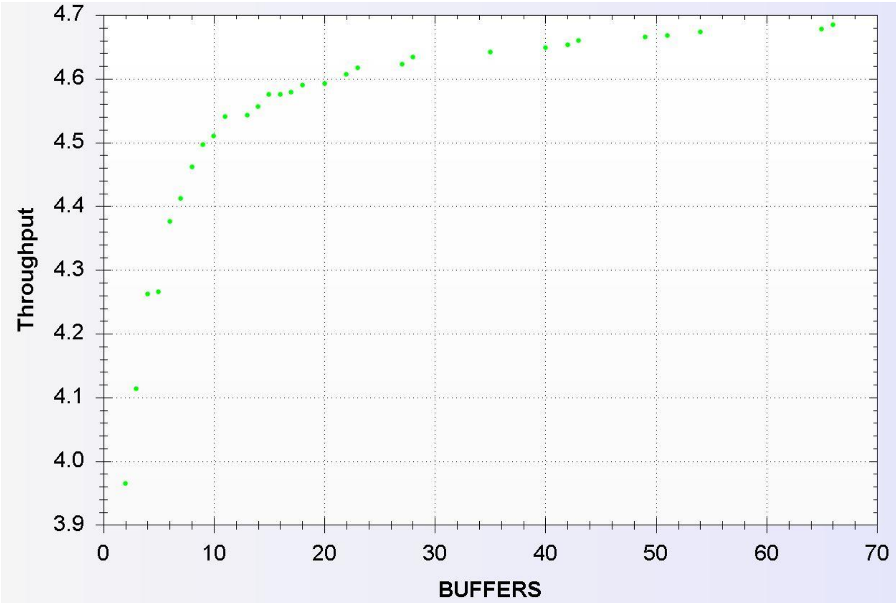

Figure 19. Filtered Pareto front based on system throughput and total buffer capacity.

In accordance with the flow simulation project aims, the optimal solution needs to take WIP, lead-time and the blocking portion of the source into consideration as well as throughput. As seen in figure 20 and Figure 21, lead-time and WIP increases with higher buffer levels.

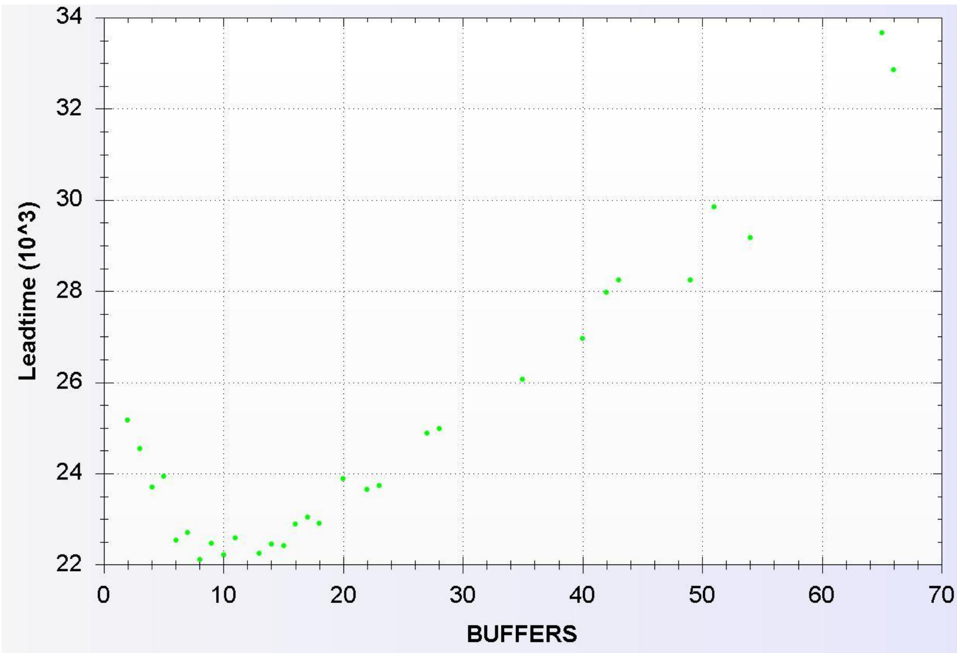

Figure 20. Filtered Pareto front based on average lead-time and total buffer capacity.

As seen in figure 20, the lead time shortens when approaching a buffer capacity of 10. The lead-time then increases as the buffer capacity becomes greater than 10. This anomaly might at a first glance seem odd. However, without a Konpack engine buffer, the blocking portion of the pre-system activities and the source increases. This leads to a lower throughput, as seen in figure 19, but a very low lead-time (figure 20) and WIP (figure 21) due to small buffers in the pre-system activities. It is important to remember that the lead-time presented is only true for Konpack, a very small part of the production plant. In reality, the blocking of the model's source means that the rest of the production plant would be affected, leading to an overall higher total lead-time.

Buffer capacity 10 seems to be the break-point where an increment in the Konpack buffer stops relieving the previously blocked pre-system activities and thus lowering the lead-time. With a higher capacity than 10, the throughput is significantly increased at the cost of lead-time and WIP, as seen when comparing figures 19-21.

This is a good demonstration of what happens when sub-optimisation is pushed to an extreme. Indeed, it is possible to reduce the Konpack engine buffer to low levels (15-20) and yet still achieve an acceptable throughput, lead-time and WIP. Nevertheless, it is important to see the whole picture by taking into account that this approach most likely will create problems earlier in the production.

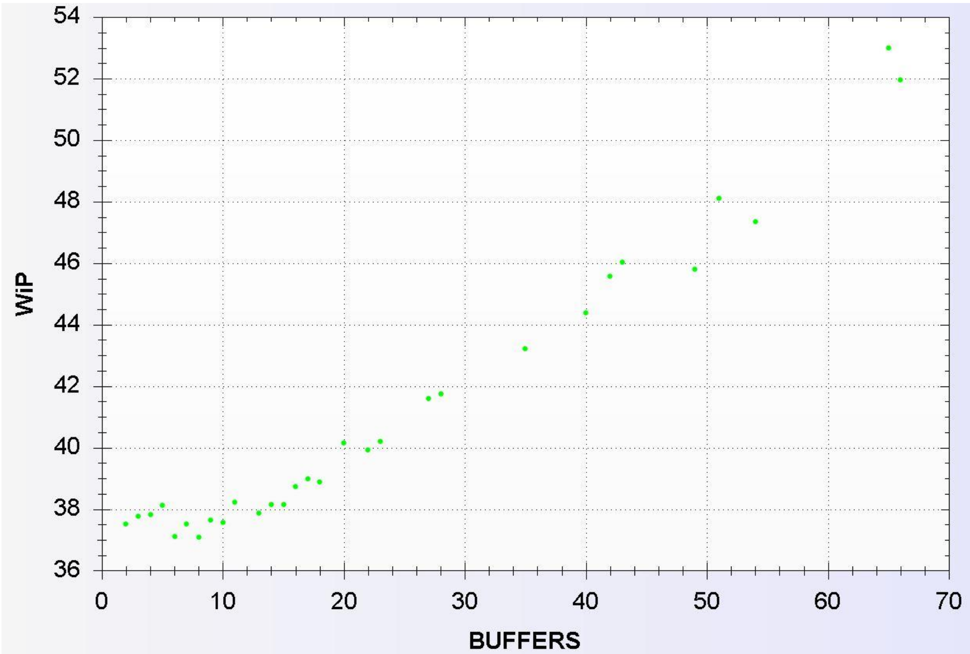

Figure 21. Filtered Pareto front based on system WIP and total buffer capacity.

The last parameter to consider for the optimisation is the blocking portion of the source. In the model, if the source is blocked it means that the pre-systems activity buffers are full because the Konpack engine buffer is full. A high blocking portion in the source could, therefore, mean a disturbance of the activities before Konpack due to a full engine buffer, and therefore, this parameter should be minimized. Some blocking portion (<0.01) is unavoidable due to the variation in the pre-system activities. As seen in Figure 22, the blocking portion of the source decreases with higher buffer levels.

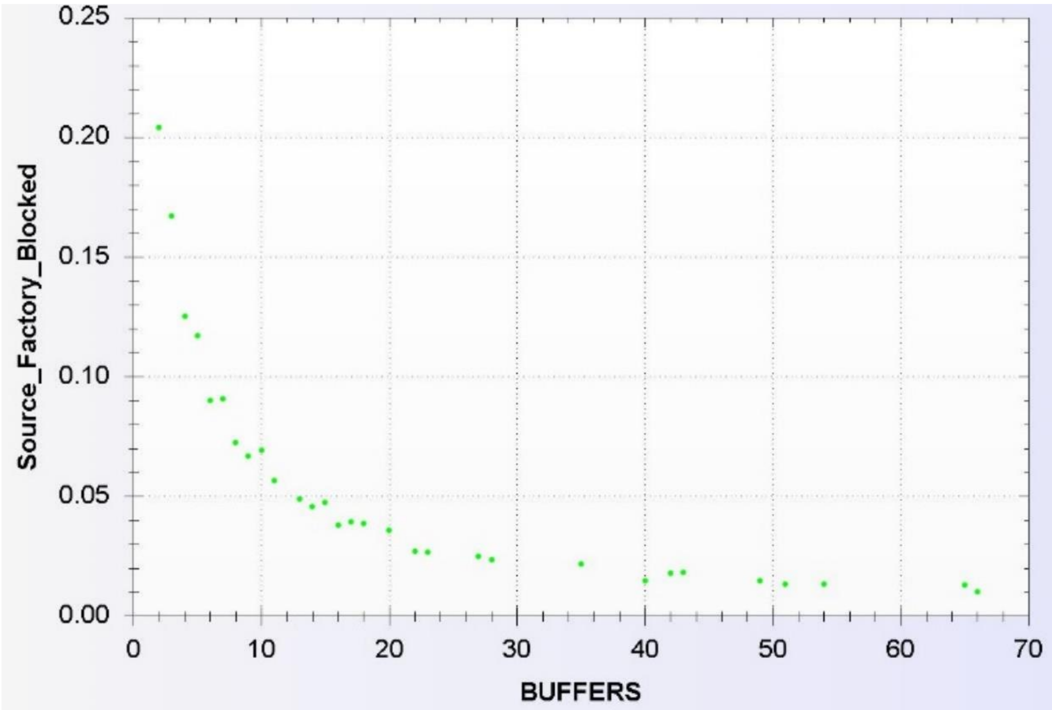

Figure 22. Filtered Pareto front based on the blocking of the source and total buffer capacity.

When examining the complete data from the optimisation (figure 18) it becomes notable that sequence positions configuration plays an important role in system performance. Therefore, the sequence positions configuration was reviewed to search for optimal solutions.

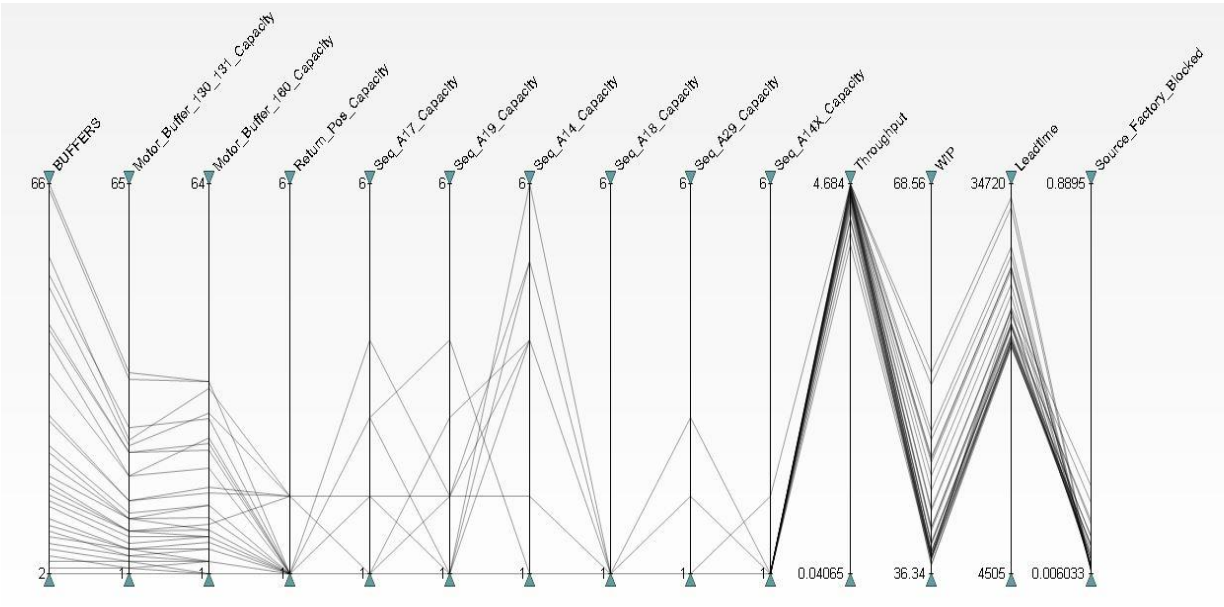

Figure 23. Parallel coordinates.

In figure 23, each dominant solution is represented with a line that tells which configuration of buffers and sequence positions that gives what outputs. Figure 23 is also available as a table in appendix 7. To determine near-optimal buffer level, a trade-off between WIP, lead-time, the blocking portion and throughput needs to be done. If the objective is to find the lowest lead-time and WIP while still meeting the targeted throughput as discussed in chapter 3.3, two solutions where found and can be seen in figure 24. However, those solutions don't have the lowest blocking portion that meets the desired throughput, and therefore are considered as sub-optimal solutions for Konpack.

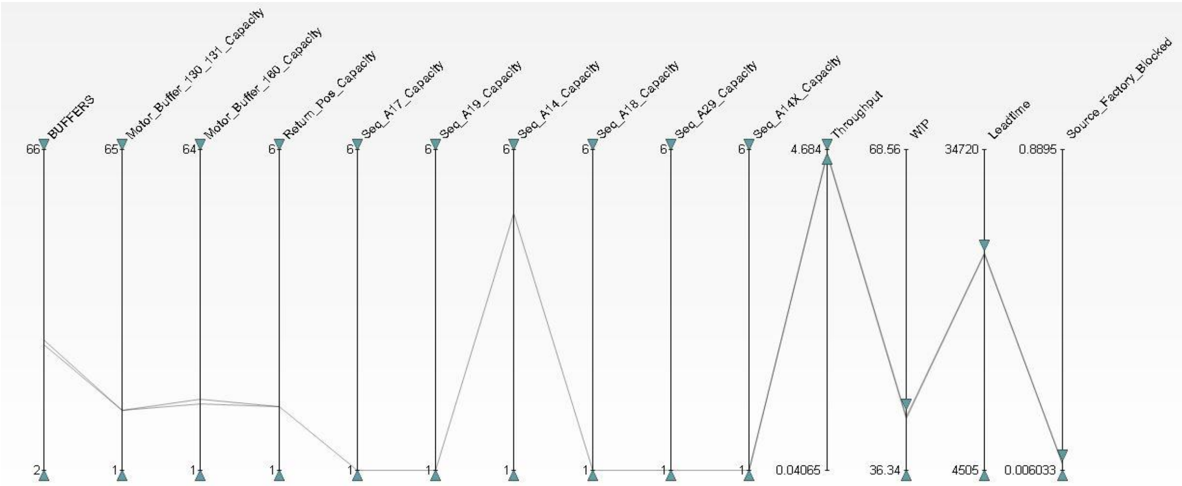

Figure 24. An example of a system configuration with lowest lead time and WIP which meets the required throughput levels.

In the experiments presented in chapter 6.2, the dominant solutions with the lowest blocking portion while still achieving a desired throughput were considered. These solutions were thought to have the least negative impact on the processes before Konpack. An additional requirement was the use of two "out positions" (Return_Pos_Capacity in figure 23-24) as this was stated by the re-build project team as preferable. Ultimately, one solution was selected for the experiments and is highlighted in appendix 7.

6.2 Experiments

Experiments were performed in order to demonstrate how the system most probably will react to certain scenarios, given that the settings from the optimisation are applied. Not only is this valuable for the stakeholders but might further build the models validity. This is achieved as the results from the experiments can be compared to preconceptions of how the future real-world system would react if exposed to the same scenarios.

The result from the buffer optimisation coupled with the analyses for steady-state and number of replications were introduced to the simulation model while creating four model clones, one for each experiment. The only difference between the clones is the experiment-specific parameters which are explained separately for each experiment. Using clones ensures that the experiments were performed in an equal but isolated environment not interfering with each other. The experiments were selected after consultation with the stakeholders. Their request was that the experiments, beyond being useful for the re-build project team, would be selected based on the weaknesses of the flow simulation model. Consequently, a SWOT-analysis (figure 25) focusing on the strengths, weaknesses, opportunities and threats of the simulation model was created and used when preparing the experiments.

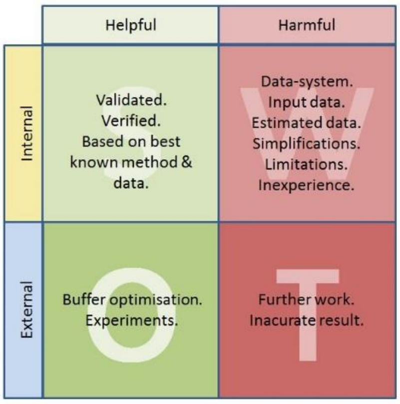

Figure 25. Flow simulation model SWOT-analysis

The main weakness of the model was thought to be the possibility of poor-quality input data due to estimations and simplifications. The possibility of an inaccurate result leading to bad decisions and also the need for continuing with this project but lacking personnel and expertise to do it was listed as a threat. The SWOT-analysis, project aims, requirements of the projects, and general requests were discussed during a meeting with the re-build project group resulting in the following four experiments to be run using settings from the buffer optimisation:

- Test the flow simulation model’s reaction to a volume increase and explain the outputs.
- Determine what happens if the estimated times in the docks/activities are overestimated.
- Test how the flow simulation model reacts to a dramatic increase in demanding engines i.e. engines that enters and exits Konpack multiple times.
- Is the dock ExtraEM needed?

The following sub-chapters explains how the selected experiments were executed. Each sub-chapter ends with the conclusions drawn based on the results.

6.2.1 Experiment 1 – Increased production volume

The aim of this experiment is to test how the model handles an increase in yearly production. A preconception was that a small increment was possible without any serious negative effects. In order to evaluate this, a variable used for controlling the takt of the source was implemented into the model. The result of the experiment can be studied in table 3.

Table 3. Results of experiment 1.

Takt increase	Delivered engines	avg. Throughput	Avg. Lead time	Avg. WIP	Source Factory Blocked	Buffer 13L Blocked	Buffer 16L Blocked
0%	26173,35	4,641	7:38:04.6559	44,86	1,21%	4,22%	2,03%
5%	26729,85	4,74	10:52:12.3368	60,45	5,53%	15,19%	7,00%
7%	26779,15	4,75	11:47:13.7610	64,98	7,68%	18,63%	9,35%
8%	26700,35	4,73	12:12:34.3227	66,85	8,84%	21,03%	9,21%
10%	26651,4	4,73	12:54:15.9976	70,28	11,06%	23,90%	10,91%
20%	26254,6	4,66	14:47:42.1389	78,39	23,86%	42,61%	6,57%
27%	22576,7	4,00	14:22:33.9596	76,93	39,24%	55,92%	0,98%
40%	NP	NP	NP	NP	NP	NP	NP
10% Modified.	29437,15	5,22	4:49:32.9202	34,99	0,01%	0	0

The model reaches a peak of 26779,15 delivered engines at approximately 7% takt increase. However, the increase in actual engines is not 7%. This is explained by the source being blocked approximately 7,7% of the simulation time. A 40% increase was not possible to evaluate due to that the increase in certain extra system straining engine flows becomes too significant. By filling up the engine buffer, the sequence positions and the activities within Konpack, they clog up the system making it come to a halt. However, by reading and interpreting Table 3 it becomes clear that by each increment in takt, the source and engine buffers become more and more blocked. This indicates the Konpack activities as a probable bottleneck of the system.

A theory evolved that a much higher production volume could be achieved by increasing either manpower in the Konpack activities or by changing which activities that are active during the evening shift. This was proved by running the model at a 10% takt increase at the source, with the same manpower but changing so that all activities were active for both the day and the evening shift. The outcome is presented in table 3 labelled as “10% Modified”. The number of engines delivered was increased by 10,7% when compared to a 10% takt increase with default settings. The lead time also dropped from almost 13 hours to under 5 hours.

The conclusion drawn from this experiment is that the real-world system in its default state will probably not be capable of significant increases of volume. However, the flow simulation model can be adapted to variations in volume by balancing active/inactive activities leading to the belief that this is possible for the real-world system as well. A more detailed result of 10% modified and the regular 10% increase can be studied in appendix 5.

6.2.2 Experiment 2 – Overestimated cycle times

The flow simulation model's biggest weakness is perhaps the estimated cycle times for the Konpack activities. Since the activities are going through a major overhaul all the cycle times are based on previous experience, estimations and simplifications made by the re-build project group. The purpose of this experiment is to examine how the model will behave if the estimated cycle times are too low. Therefore, an increase, up to 20%, in the cycle times was tested. To achieve this, a cycle time controlling variable was implemented. If testing for 10%, the model will first calculate the cycle time using distributions and then multiply it with a factor of 1,1.

Table 4. Results of experiment 2. Default system settings.

Cycle time increase	Engines delivered	Avg, Throughput	Avg, WIP	Source F, Blocked	Buffer 13L Blocked	Buffer 16L Blocked
0%	26253	4,65	45,63	1,48%	5,13%	2,47%
1%	26093,8	4,63	48,50	1,87%	6,05%	2,94%
3%	25796,7	4,57	53,14	3,10%	9,63%	4,22%
5%	25440,35	4,51	55,96	4,48%	12,58%	5,61%
10%	24406,7	4,33	67,02	9,76%	24,61%	8,82%
20%	22350,7	3,96	76,74	19,58%	42,89%	9,77%

One could argue that by interpreting Table 4 a conclusion could be drawn that the model is very sensitive to wrongfully estimated cycle times. The reason for the sensitivity could be uncovered by studying the fact that both the source as well as the 13 and 16-litre engine buffer becomes blocked by increasing cycle times. This indicates that the Konpack activities are either too slow or not manned during the right hours. A case could be made that increasing the engine buffers could partially solve this problem, however, doing this strays from the simulation project's aim to combine lean production philosophy with simulation. Instead of increasing manpower or engine buffers, one could try to find the bottleneck activity and make sure it is utilized to its fullest. This could not only increase throughput but make the system less sensitive to wrongfully estimated cycle times.

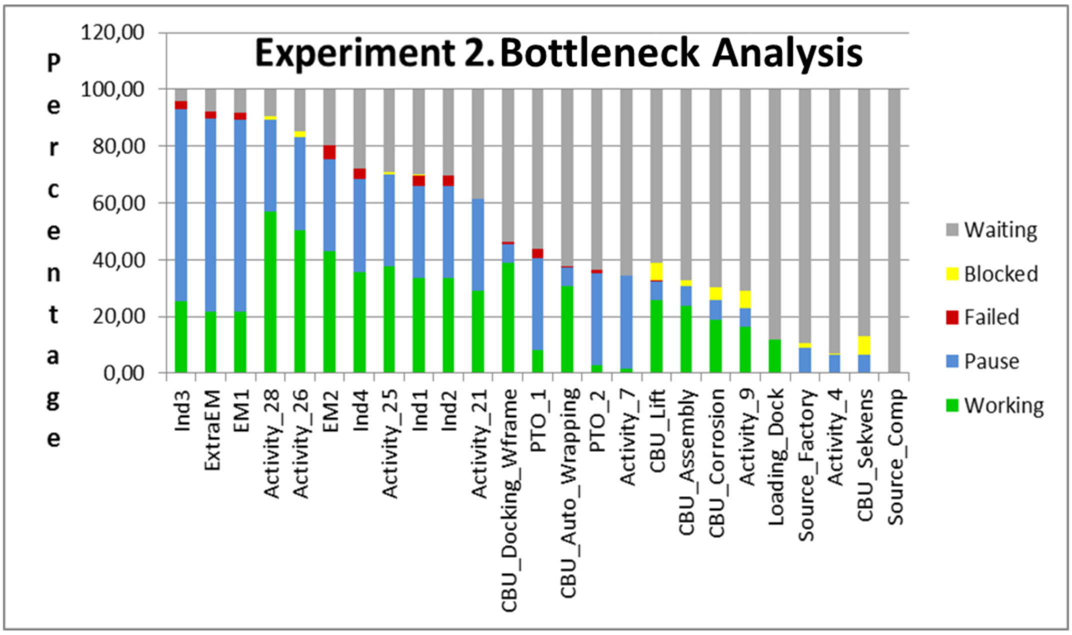

Figure 26. Identifying Ind3 as a bottleneck.

By performing a bottleneck analysis using Plant simulation's built in feature, the dock Ind3 is pinpointed as a bottleneck activity, see figure 26. Instead of increasing manpower, Ind3 was activated during the evening shift instead of the docks PTO_1 & 2 which were less susceptible to be bottlenecks. The result being that when raising the cycle time by 5% the 13-litre buffer only gets blocked 4,13% compared to the default system settings with 12,58% blocked time. Moreover, the 16-litre buffer drops from 5,61% to 3,16%. Another positive impact of the experiment is that the Source_Factory was blocked only 0,17% as opposed to 1,48% in the flow simulation model's original state, see table 4 and 5.

Table 5. Results after removing the bottleneck Ind3.

IND_3 added to evening shifts responsibilities							
Cycle time increase	Engines delivered	Avg, Throughput	avg, Lead time	Avg, WIP	Source F, Blocked	Buffer 13L Blocked	Buffer 16L Blocked
0%	26240	4,65	5:27:24.4429	35,14	0,17%	0,65%	0,48%
5%	26215,3	4,65	7:49:39.0836	45,86	1,45%	4,13%	3,16%

This experiment has shown that the model is sensitive to wrongfully estimated cycle times. However, by adjusting active activities during the evening shift it is possible to compensate for overestimations. This experiment also makes a strong case for performing an optimisation with manpower and active activities during certain shifts as variables and/or goals. The experiment results after the bottleneck analysis can be studied in greater detail in appendix 6.

6.2.3 Experiment 3 – Dramatic increase in demanding engines

The purpose of this experiment is to determine if Konpack is capable of a dramatic volume increase of two engine flows, flow 364 and flow 365. These flows return to Konpack multiple times during their lifetime before exiting the system. Since they take much more time and system resources than the average engine flow, they are seen as system straining by the stakeholders. Additionally, another engine flow, flow 363, is removed from the simulation model since it's going to be discontinued. The engine flows 364 and 365 are increased by 750 engines each, resulting in an increase of 148% and 65% respectively, when compared to the actual production during 2017. On the other hand, since all engines that compose the 363 flow, roughly 250 engines, are removed, the new added production total introduced to the model is 1250 (750+750-250) engines yearly. This leads to an expected total volume of about 27500 engines, hence this will be the target volume for the model to achieve. This experiment was requested by the stakeholders since this change might be a likely scenario in the near future. Thus, any indications of how the real-world system would tackle such a task would be of great value.

When initiating this experiment, the model comes to a halt after a couple of days into the simulation. A brief bottleneck analysis (figure 27) indicates that docks EM1 and ExtraEM are the bottlenecks of the system. This is due to the fact that all added engines in this experiment pass through activity 17 and since this activity only has one shared dock open during evening shifts and none during night shifts, this creates a problem.

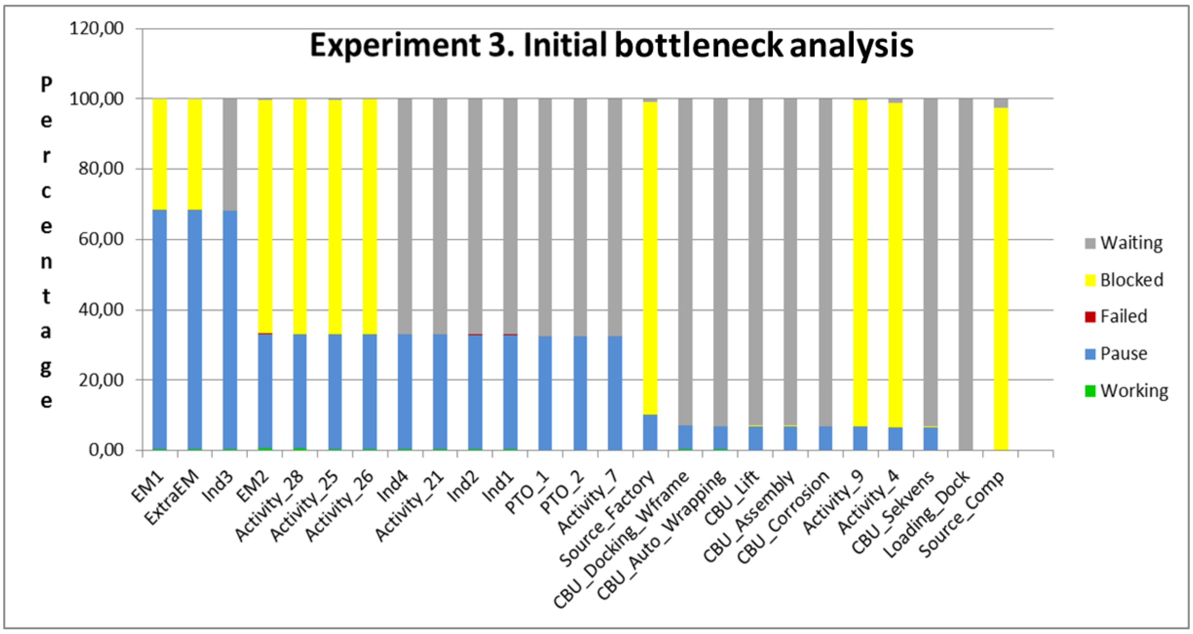

Figure 27. Identifying EM1 & ExtraEM as bottlenecks.

Keeping in line with the Heijunka principle from the lean production philosophy (chapter 2.1.1), adding the two bottleneck stations to the responsibilities of the evening shift, rather than increasing manpower or buffers, solved the issue. After a second bottleneck analysis (figure 28) Ind_3, which as in the previous experiment is the bottleneck of the system, is also added to the evening shifts responsibilities.

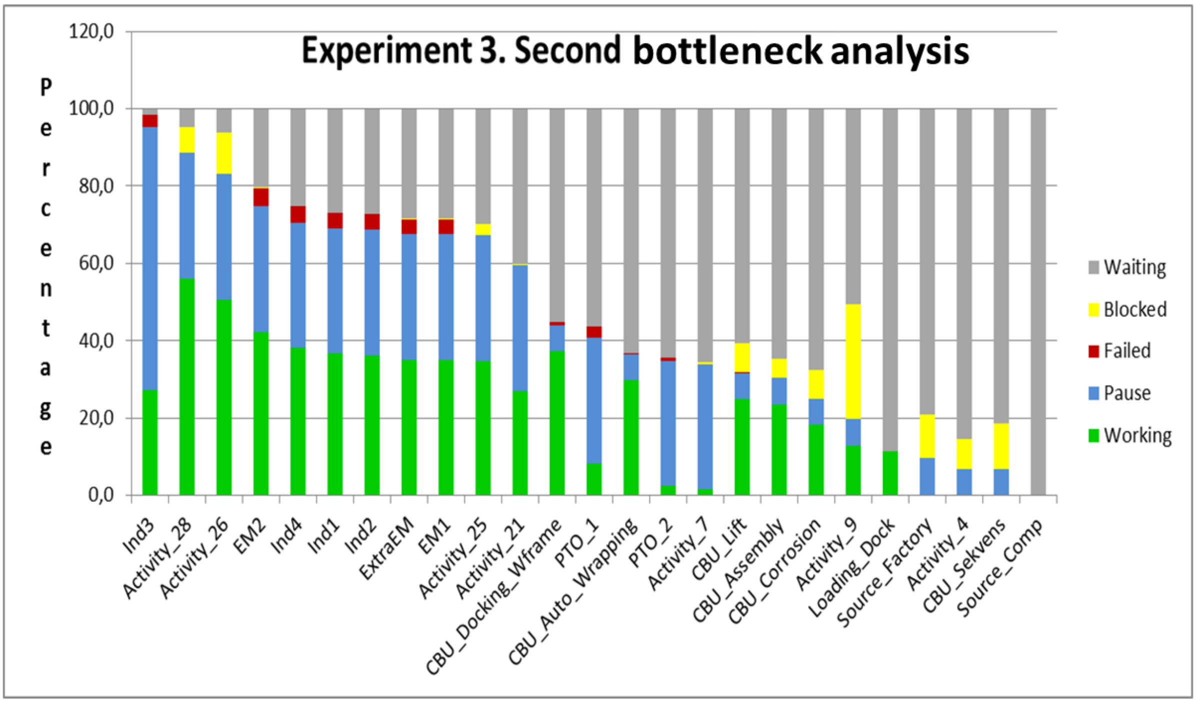

Figure 28. The second bottleneck analysis identified Ind3 as a bottleneck.

The result is a flexible system that surpasses the initial state in every measurable way. The system now handles the strain added by the new engines (see table 6 for details). This is achieved without improving cycle time, adding manpower or increasing buffers.

Table 6. The result after second bottleneck analysis. A much more flexible system.

	Avg. Throughput	avg. Lead time	Avg. WIP	Engines delivered	Source F Blocked
Original model	4,7	7:38:04	44,9	26 173	1,2%
Exp3. Added EM1, ExtraEM & Ind3 to evening shift	4,9	6:47:12	43,5	27 623	0,3%

Once again, the determining factor seems to be which docks are open during the evening shift. By keeping the three EM docks active during the evening, the model handles the strain added by the new engines, reaching a much higher average throughput than normal. This indicates that the real-world system will have a built-in overcapacity accessible through the balancing of active docks and manpower. Consequently, the benefits of an optimisation scenario with manpower, shifts and active/inactive docks as variables is further strengthened by this experiment.

6.2.4 Experiment 4 – Is the dock ExtraEM needed?

Since the beginning of the Konpack re-build project, there has existed a feeling among the re-build project team that the dock ExtraEM which sole function is to perform activity 17, perhaps is abundant. This experiment aims to answer that question and at the same time fulfil one of the simulation project's objectives, namely, to propose an alternate solution based on simulation data regarding workstations (docks).

Just like experiment 3, presented in the previous chapter, this experiment comes to a halt shortly after the simulation run has started. The reason for this is that by removing ExtraEM the possibility for an engine to receive activity 17 treatment, greatly diminishes. This partly explains why the system comes to a halt. The rest of the explanation is the same as in experiment 3, as the affected engines in this experiment are the same "demanding" engines as in experiment 3.

Learning from the previous experiments, a new sub-experiment was launched with a similar tweak as before, namely adding EM1 as an active dock during the evening shift while keeping the ExtraEM completely deactivated. The new configuration proved to be a vast improvement over the default configuration delivering approximately the same volume of engines but at a much lower lead-time and an average WIP almost 30% lower. The results can be studied further in table 7.

Table 7. Performance comparison of default and new configuration.

Default configuration: 2.5 docks during the day shifts, 0.5 docks during the evening shift						
Engines delivered	Avg, Throughput	avg, Lead time	Avg, WIP	Source F, Blocked	Buffer 13L Blocked	Buffer 16L Blocked
26252,90	4,65	7:49:43.0457	45,63	1%	5%	2%
New configuration: Removed ExtraEM, added EM1 as an active dock during the evening shift. 1,5 docks per day and night shift						
Engines delivered	Avg, Throughput	avg, Lead time	Avg, WIP	Source F, Blocked	Buffer 13L Blocked	Buffer 16L Blocked
26452,80	4,69	4:42:16.5157	31,82	0,00	0,00	0,00

The explanation to this is perhaps found by studying the graphs representing how the WIP-level vary during a period. By comparing the graphs in Figure 29 representing the new configuration and the default configuration, it becomes apparent that the WIP variation is much more even for the new configuration as opposed to the default configuration. This is due to the new configuration having an equal amount of docks capable of doing activity 17 in both shifts. The default configuration with its one shared dock during the evening shifts lags behind. This fills the engine buffer with a queue of engines, that the day shift seldom can deal with. This creates massive variations in WIP as well as prolongs the lead time. The new configuration, on the other hand, has a rather even production with lesser WIP variations. Consequently, the new configuration should be more desirable as lowering the process variation is a vital part of the lean-production philosophy, as described in chapter 2.1.1.

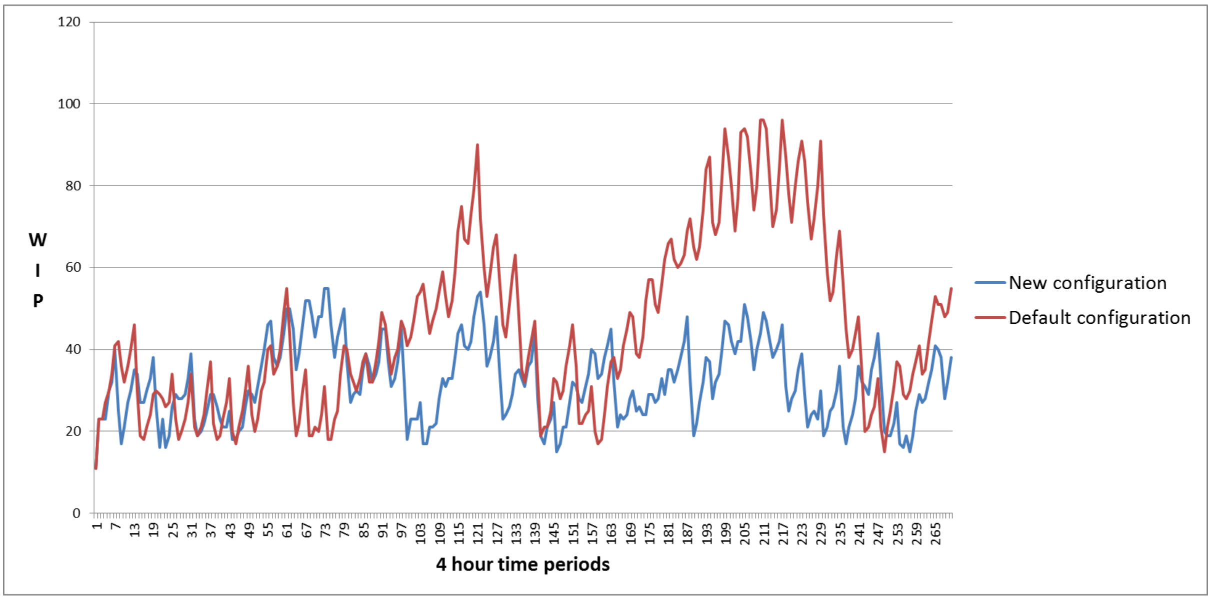

Figure 29. Comparison of WIP variation during a 45-day period.

This experiment concludes that if Volvo chooses to use the default settings for Konpack the ExtraEM dock is necessary in order to achieve production goals. But, by optimising the use of active docks during the evening shift, the ExtraEM becomes redundant. The elimination of ExtraEM frees space and resources, thus creating a more lean process at the same time.

6.3 User Interface

One of the main threats identified by the SWOT-analysis presented in Section 6.2 was the fact that, due to the lack of flow simulation expertise within the re-build team, no one would be able to utilize the model for future work upon the completion of this thesis work. By providing a flow simulation model with a graphic interface along with a short user manual and an educational session intended for the re-build project team, the hope is to overcome this issue.

The initial request made by Volvo was for a buffer optimisation which essentially is a one-time result consisting of parameters to be utilized in the production. However, with the incorporation of the user interface, not only is a buffer optimisation delivered but also a powerful tool to be utilized for future work, even in the hands of someone with limited flow simulation knowledge. To further ease the use, the user interface was developed with high end-user involvement, meaning that it went through a conceptual phase much like the one conducted during the construction of the simulation model. Consequently, the result is an interface which accommodates all end-user requests. A direct result of this is that optional requirement 2 was redefined. Instead of reading the lead time for entities from their source to the first system buffer they enter, Volvo requested the possibility to read the average lead-time in the Konpack buffer per activity, i.e. how long time an engine, designated for a specific activity at the docks, spends in average in the Konpack buffer.

Since the creation of the user interface and the educational session were optional requirements, these will not be covered further in this report. Screenshots from the user interface can be seen in figures 30-32.

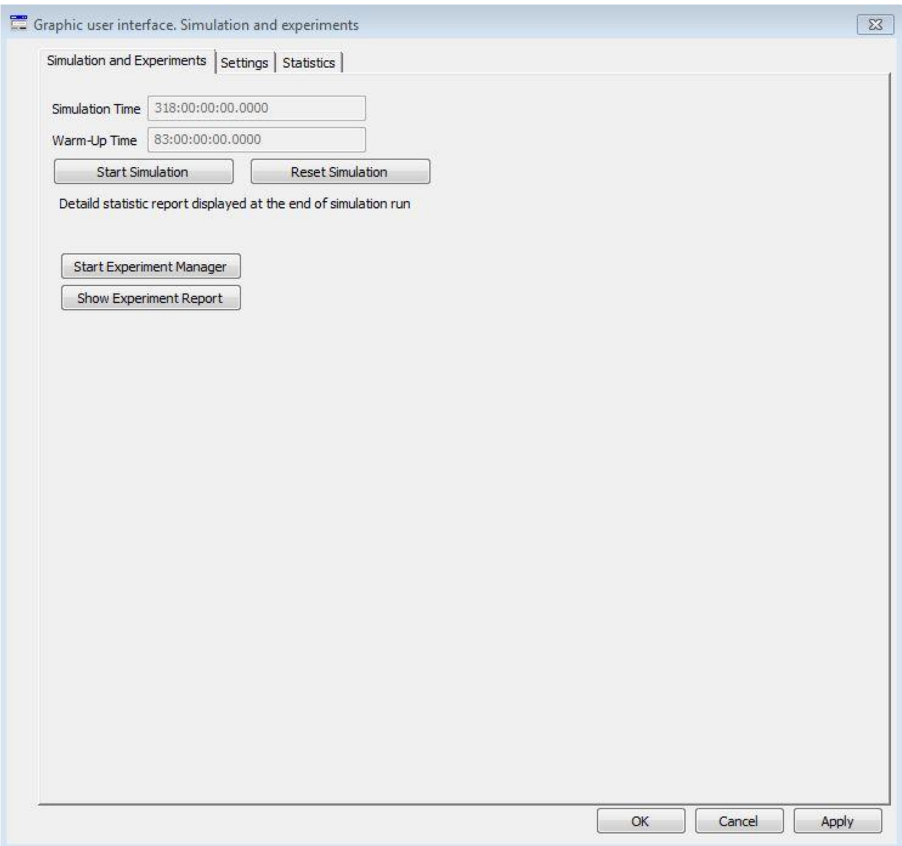

Figure 30. First page of the user interface. Interaction with the simulation model and experiments.

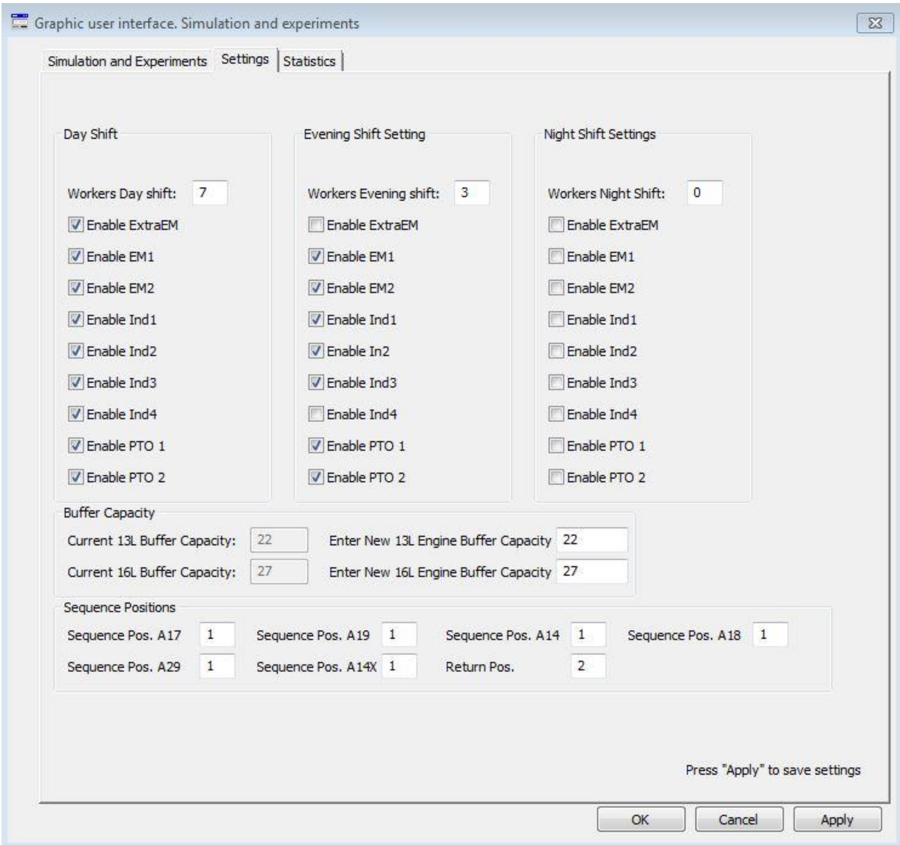

Figure 31. Second page of the user interface. Parameter settings.

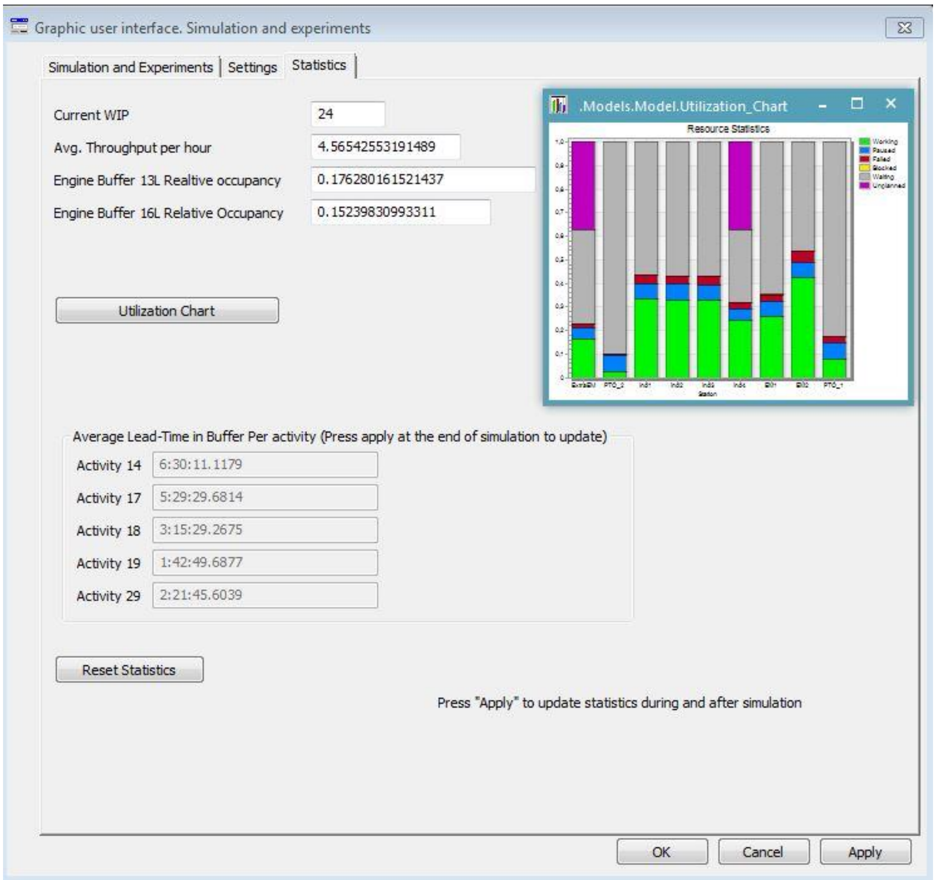

Figure 32. Third page of the user interface. Visualization of results and statistics.

6.4 Evaluation of Volvo's flow simulation process

As previously explained, the evaluation of the flow simulation process was conducted in parallel with the simulation project. In the following sub-chapters, the flow simulation process evaluation is covered in the same order as the steps in figure 17, i.e., the same order as the simulation project was conducted.

6.4.1 Understand the problem and define questions

An important step in this activity is to understand if simulation is the proper tool to be employed for the requested project. Since Volvo had already defined this thesis work and drawn the conclusion that flow simulation was the proper tool to address the project, no full evaluation of how this activity was conducted can be made. Even though this step was not fully analysed, it became apparent during meetings with the simulation network, that some kind of filter might be needed in future projects. This might prevent vague requests by requestors, taking up unnecessary time for the simulation specialist. This issue might resolve itself if in time more requestors at Volvo understand the possibilities and limitations of simulation as a tool for system design, improvement and decision-making support. An alternative might be some kind of template, facilitating the problem formulation and creating a basis for further discussions with the simulation specialist. It's the students' belief and experience that clear objectives and goals are vital for a simulation project's success.

6.4.2 Make a concept model

The importance of a good conceptual model is given in chapter 2.4. During talks with simulation specialists at Volvo, the impression was given that Volvo's Simulation methodology takes this step too casually. Conceptual modelling is cut down to a simple visualisation of the previous activity “understand the problem and define questions” (as seen in chapter 5.5.1), almost to the point that a simple napkin drawing would be sufficient. Far from the common ground which, Pace (2002) means should be the goal of a conceptual model. By studying figure 17, one can notice that the “Make a concept model” activity lacks a validation step. This might result in that the benefits of a concept model presented in chapter 2.4.2, such as minimization of wrongfully set requirements, guidance during the development of the computer model and a basis for model verification and validation, are lost. Robinson (2008) also emphasizes that it is essential that the conceptual model has validity, credibility, utility and feasibility before finalizing the conceptual model and moving on to the actual computer model. Therefore, a strong case for a validation step after the concept model activity could be made. This is also supported by Sturrock (2017) who means that there should be a validation step.

The flow simulation project presented in this thesis work, have had great benefit of such a step. Therefore, it's strongly recommended that Volvo reviews their concept modelling and also introduce a validation step in order to discuss validity, credibility, utility and feasibility.

6.4.3 Collect data

In Volvo's simulation methodology, see figure 17, it's clearly stated that data collection should be done by the requestor. However, this doesn’t seem to be the case, e.g., like in this thesis work, the requestor failed to deliver important data and the simulation specialist (the students) were forced to collect data from a database, which was very time-consuming. Simulation specialists at Volvo have also described previous simulation projects where they have been forced to gather data. Since simulation expertise at Volvo seems very rare, this appears to be a waste of resources. Data collection should be done by other personnel with greater knowledge of the real-world system to be modelled, i.e. production technician(s). How data collection should be handled in regard to simulation projects at Volvo needs to be further overviewed by Volvo.

6.4.4 Build the flow simulation model

Since each simulation project is unique and therefore each model unique, it becomes difficult to have a standardized way of building models. However, without any flow simulation model building standard as is the case at Volvo, it might become difficult for a simulation specialist to re-use or re-work a model constructed by another simulation specialist. In chapter 3.1 the lack of standards in the simulation field are pointed out by Ehm, et al. (2009) and Tolk, et al. (2011), hence the lack of standard at Volvo regarding the creation of flow simulation models might not be that surprising. However, as with all lean environments, there should be a desire to develop a shared syntax and a standard so that all simulation specialists at Volvo could interpret each other’s models. In addition to a shared syntax, a framework for how to select flow simulation software could be useful, e.g., something similar to table 1 could be used. In chapter 3.1, Sturock (2017) defines two approaches on model building: “breadth-first” or “depth first”. Which approach that is the best suited for flow simulation projects at Volvo is of course very project dependent and something the students believe therefore should be discussed before each project by the simulation network at Volvo.

6.4.5 Verify the flow simulation model

Volvo's simulation methodology points out that it’s important not to use models that are not correct. This is made, according to Volvo's simulation methodology by studying the animation of the simulation, control of input data and a steady-state analysis. This should be done as a joint activity by both the requester and the simulation specialist. Therefore, the project presented in this thesis work has done this (see chapter 5.4.4). Since each model is unique a more standardized way of verifying and validating a flow simulation model is seen by the students as difficult, which is also supported by Sargent (2014) (see chapter 2.6). Although, having a well-prepared document like the one in appendix 4, to use as a basis for any verification meetings with the requestors was proved to be very useful when carrying out the verification process in this thesis work.

6.4.6 Validate the flow simulation model

Validation is regarded by Volvo’s simulation methodology as the most complex step. Validation is made by comparing the results from the flow simulation to data from the real-world system. Or if the modelled system doesn’t exist, the results are compared to the best estimations or calculations. In this activity, a simulation specialist at Volvo does a replication analysis to determine the least needed number of replications in order to achieve a desirable accuracy. One criticism that could be made to Volvo's simulation methodology regarding validation is that it does not mention one of Sargent (2014) approaches: Letting a third-party evaluate the flow simulation model. By letting a third-party decide if the model is valid can increase its credibility, although, it is important to understand that a complete third-party evaluation is very time consuming and therefore very costly. Still, this project benefitted greatly from a third-party validation even though it was brief, approximately 1-2 hours, and focused mainly on the most important elements of the model. This not only increased the model’s credibility but also its usability as the simulation engineer performing the validation had improvement suggestions. Perhaps a similar third-party validation, focusing only on the most important elements of the model, could be adopted by Volvo?

6.4.7 Setup experiments.

Once a model is verified and validated it becomes a joint activity to set up experiments to run on the flow simulation model. Together, Simulation engineers and the requester define which “what if” questions to answer and optimisation(s) to be conducted. This activity may have some of the same issues as the first activity “Understand the problem and define questions” as the requestors in some cases lack the knowledge of what the flow simulation model is capable of. Also, some critique can be made regarding the fact that Volvo’s flow simulation methodology suggests that the optimisation should be defined at this late point. This contrasts with the preaching’s of Banks et al. (2010), who explains that this should be done at the very beginning of a simulation project.

6.4.8 Run experiments, analyse, draw conclusion and document results.

When the experiments are completed it is the simulation specialist’s job to analyse and document the results so that someone who doesn’t have experience of flow simulation can understand the results.

6.4.9 Present results

The results of the simulation project are, in Volvo’s simulation methodology, discussed with the requestor of the project and other interests. This proved to be an additional chance for flow simulation model validation. The initial optimisation results and the discussion around these made one of the requestors realize that some of the supplied data, in spite of being verified, proved to be wrong. The requestors were given a chance to correct the data and a new optimisation and experiments could be done. Something which most likely would have been missed without this step.

6.4.10 Draw conclusion and define additional questions

After the results of the simulation project have been presented, it is the requesters' choice if they want to close the simulation project or ask additional questions. The additional questions may require the project to go back to the activity “make a concept model”. It may be argued that if it required to go back to “make a concept model”, it should rather be seen as a new simulation project.

6.4.11 Close simulation project

After the simulation project has been approved by the requestor it becomes the simulation specialist responsibility to store the data and the result. The model should be commented so it's easy to re-use. A strength of Volvo's simulation methodology is that they have developed their own standard for how to document results.

6.5 Results summary

By performing a flow simulation optimisation, the project has been able to determine near-optimal solutions regarding the buffer capacity of Konpack. It is indicated that although a satisfactory throughput can be achieved with a relatively low buffer capacity, this would mean that lean-production would be overlooked as these solutions would create problems in other parts of the factory. Taking lean-production into consideration renders a possible buffer capacity of between 40-50. Regarding the conducted experiments a conclusion is drawn that Konpack will have a built-in overcapacity which can be accessed by an optimisation of active docks. Lastly, a user interface was created to ease the further utilization of the flow simulation model by personnel with limited simulation knowledge after the completion of this project. The interface is constructed according to the re-build project teams' requests and enables them to perform their own experiments, similar to the ones presented in Section 6.2.

7. DISCUSSION

The project has benefited from a thorough and well-made pre-study and planning phase, which led to a somewhat smooth actualization phase. The project can be claimed as successful as it has reached the aim and objectives described in chapter 1.3. A key point to the project success has been following the focus and delimitations described in Section 1.4. This helped the project not to get side-tracked as optional objectives and requests were added in the later project stages.

Even though the flow simulation model is verified and validated, it is important to be aware of potential sources of error when analysing the results. Since the model simulates a non-observable system, it has only been validated via system experts' best estimations. One concern is that the flow simulation model's level of detail is not sufficient and important factors have been overseen by the experts and us, for example logistical issues. Another concern is that the estimated cycle times and availability in the assembly stations and CBU could be incorrectly estimated. This may affect system performance greatly as the experiments suggest. The experiments also showed that the system is very variant dependent since too many engines of specific variants clog up the flow simulation model.

The data for the pre-system activities was collected through a very time-consuming data mining process. That process could have been more efficient if the data collection system was configured differently and if we had greater knowledge of the data system. With hindsight, obtaining more information and knowledge about the different available data collecting methods earlier and to a greater extent would have helped the project. On one occasion, the data collection had to be completely redone due to the lack of understanding of how the data system extracts data.

It can also be pointed out that the flow simulation model boundary was too narrow since the system is largely affected by activities before Konpack. Unfortunately, due to limitations in the data collection system and limited time, those have been very simplified. Perhaps a larger model that covers all pre-system activities in greater detail is required to better evaluate the optimal buffer level in Konpack. This would have been a much more time-consuming project and not suitable for this project's scale.

The evaluation of the flow simulation processes is only (with the addition of literature, observation and interviews) based on one project. It might be dangerous to draw conclusions from an evaluation with sample size one. Therefore, it should be treated as a base for further discussion and a guideline for future work. A major criticism that can be made against the evaluation is that it was conducted in a non-structural way and is not based on data. The reason for this is that the main focus of the project was the buffer optimisation. Initially, data mining was believed not to become a part of the project but in reality, it became a big part taking a lot of time otherwise dedicated to the flow simulation processes evaluation. This also impacted negatively on the extent of the evaluation. Originally, the evaluation should have also covered the simulation organisation at Volvo GTO. By strictly following the steps in the provided flow simulation process, and thereby excluding the simulation organisation, we were not able to evaluate how or if Volvo's simulation organisation works in conjunction with lean. However, while conducting our thesis, we were able to observe and experience how our work served an educational and facilitation purpose, much like it is described by the LeanSMO framework (Goienetxea, Urenda and Ng (2018)). It is our strong belief that, due to the high involvement by the re-build project team during the creation of the simulation model, the team gained new insights regarding the system they were constructing as well as its surrounding processes. In fact, we saw multiple changes to the re-build project being made as a direct result of this, as well as requests being made for our presentational material to be used in a facilitation purpose outside of our thesis. Unfortunately, this is a recipe that improvement possibilities regarding the flow simulation process evaluation were lost due to not incorporating the simulation organisation and therefore not being able to fully evaluate it from a Lean-SMO perspective.

We had much help from our supervisors at Volvo. They helped us with the initial acclimatization period and in addition to a weekly project status meeting they were always available when we needed support. However, this meeting only discussed the work done the previous week. Not once did we discuss upcoming project activities or the project timeline. This is partly our fault since we failed to communicate where the project was at a given point on the project timeline. Since the Volvo supervisors never asked about it, we thought it to be enough that we regularly reported the current status and project direction to our supervisor at the university. This proved to be a mistake as it turned out that the supervisors at Volvo were surprised by the fact that the project had moved on to the final stage and no more changes or requests on their behalf would be accepted. In retro-perspective, a project timeline should have been established and updated during the weekly project status meetings. This would have given our supervisors a better understanding of what was going on and what was possible or not at a given time.

8. CONCLUSIONS

The main aim of the thesis was to find an optimal buffer size in Konpack in order to ensure the desired throughput for the line. In order to achieve this aim and to satisfy the initial stakeholder requests, a number of objectives were defined. In the following paragraphs, each of the objectives and their outcome are presented.

- Deliver a verified and validated simulation model of the new post-assembly and packaging-line.

The project has resulted in a verified and validated flow simulation model of the new post-assembly and packaging-line known as Konpack. The flow simulation model is presented in chapter 5.4.3 and the verification and validation steps in chapter 5.4.4. In the previous chapter, some concerns regarding the flow simulation model's credibility are lifted and discussed.

- Propose an optimal buffer size for Konpack that allows desired throughput levels to be achieved. The proposition should be based on results obtained via simulation-based optimisation.

The flow simulation model was used for a simulation-based optimisation which suggests near-optimal solutions regarding buffer levels and sequence position configurations. The report presents the simulation-based optimisation results. What the optimal buffer size is, depends on the prioritisation of lead-time and WIP over blocking the source. From a manufacturing point-of-view, a lower WIP and the shorter lead-time that comes with it is desirable. However, in order to make the right decision one should have a broader perspective as changes made to Konpack will affect its neighbouring processes, a fact proven by the simulation model. By not adopting a holistic perspective, the benefits of Lean production are lost and since Volvo GTO strives after being a Lean organisation, it was relevant to suggest a system configuration which mirrors this. The suggested system configuration, which can be seen in Appendix 7, is believed to be the configuration that best balances lead-time, WIP and blocking of the source and therefore best fulfils the Lean-principles. The main conclusion drawn from the buffer optimisation is that the estimated maximum buffer capacity is sufficient. All pareto-optimal solutions are provided in appendix 7.

- Determine whether the workstation ExtraEM is necessary. Furthermore, present an optimal sequence position configuration while taking physical limitations into consideration.

Using the system configuration from the optimisation, four experiments regarding design and "what if"-scenarios were tested. The experiments indicate that Konpack has an overcapacity which can be utilized if the flexibility of the line is increased. This can be achieved by optimising active docks during the different shifts. If the optimisation of active docks is performed, experiment 4, which evaluated the need for the workstation ExtraEM, proves that the otherwise necessary ExtraEM becomes abundant.

- Additionally, propose an improved flow simulation process based on the identified advantages and disadvantages of Volvo GTO´s current flow simulation methodology.

In addition to the simulation model, optimisation and experiments, an evaluation of Volvo's flow simulation methodology has been conducted and is presented in Section 6.4. The conclusion drawn from the evaluation is that it is a good tool for flow simulation projects, although it can be improved. The overall flow simulation process structure is based on Banks et al. (2010) 12-step simulation study described in chapter 2.3. A differentiating aspect is that by visually dividing the flow simulation process activities between the requester and the simulation expert, Volvo has achieved a very clear and intuitive framework. Therefore, the students see no need for major changes. However, some potential for improvements was discovered such as the inclusion of concept model validation (Section 6.4.2), improved data collection (Section 6.4.3), a shared syntax, (Section 6.4.4) and a standard regarding flow simulation model building (Section 6.4.4). Additionally, by including a third-party during validation, (as described in Section 2.5 and Section 6.4.6) this process can be strengthened even further.

Regarding the optional requirements established for the project, three requirements out of four have been fulfilled as they were originally stated. The possibility to change shifts as well as allocating workers in the docks (optional requirement 3 & 4), were implemented prior to the optimisation. These features are now an integral part of the flow simulation model and were used extensively during the experiments. Optional requirement 1, namely the addition of a user-friendly graphic interface, has also been accomplished. The user interface construction process went through a conceptual modelling phase in which the re-build project team was given the opportunity to make requests regarding its functionality. The interface can be seen in figures 30-32. Optional requirement 2, the ability to read lead time for entities from their source to the first system buffer they enter, was redefined during the creation of the user interface. Instead, the re-build project team requested the ability to read the average lead-time in the Konpack buffer per activity, i.e. how long time an engine designated for a specific activity at the docks spends in average in the Konpack buffer. This feature was programmed and is now available as a statistic (figure 32) in the user interface, thus fulfilling the last optional requirement.

In this thesis work all three dimensions of sustainable development are affected. With the aid of simulation as shown in chapter 2.2, a real-world system can be modelled which enables different designs and what if-scenarios to be tested without affecting the real-world system. For example, a buffer optimisation with the goal of lowering WIP (which is the primal goal of this thesis work) will potentially lead to finding the parameters which grant minimum stock and shorter lead-time. This might save large investment costs as well as material savings, thus contributing to both economic and environmental sustainability. An improved simulation methodology (which is another focus of this thesis work) might lead to more and better simulation projects. The benefits of this could be significant. Another intriguing possibility is linking the objects in the flow simulation model with parameters for energy consumption and carbon emission in order to use the environmental impact generated by Konpack as an optimisation factor to be considered and used as a basis for future decision-making. The previously described experiments all showed that a more flexible version of Konpack is preferable in regards of production efficiency. A possible way of achieving this is enabling worker rotation, so that a worker may work at any position in Konpack. This could lead to less monotone work, improving mainly the ergonomic aspect but also giving the workers a higher competence and hopefully, vocational pride as a result. Altogether, this could improve the social sustainability.

Flow simulation at Volvo is a rather new tool employed in recent years. The simulation organisation is still in its starting phase although important strides have been made towards its development. Maybe the most significant among them being the establishment of the simulation network. However, flow simulation as a viable tool, even less as a tool within the lean toolbox, is perhaps not yet accepted throughout the entire Volvo organisation, leading to confusion regarding what simulation actually is and how it can be employed successfully. As discussed in future work, some important issues need to be addressed for flow simulation to become an even more contributing factor within Volvo.

9. FUTURE WORK

During the project, some interesting questions arose but were not handled since they weren't in the project scope. However, with some modifications to the developed simulation model, some of those questions might be answered. For instance, by selecting workers, shifts and active docks as parameters, a new optimisation could be made with the goal of achieving the right throughput at a minimal operating cost. Although the simulation model is to a large extent based on predicted data, the model is recommended to be updated when Konpack is implemented and operational. At this point, a new buffer optimisation could also be performed.

Regarding the experiments, they all concluded that a flexible system is preferable. Therefore, this should be taken into account by decision makers before starting to implement the new line. This flexibility depends on the ability of the workers to be able to work at any dock in Konpack. At the moment, this might not always be the case. Consequently, it is our strong recommendation that Volvo begins a training program making sure that all workers at Konpack can cover all docks.

With regards to the flow simulations process and simulation methodology, there are some factors that need to be examined further, for example, data collection. Having the right data is vital for the ability to draw the right conclusions from a simulation project. In Volvo's simulation methodology it is seen as the requestors task to acquire data. However, as of today, most of the future simulation project requestors at Volvo won't have adequate knowledge about what sort of data that is needed for a DES-simulation project.

If simulation is to become a common tool in Volvo's lean tool-box, we believe that more employees need to have a better understanding of simulation. Granted, not everybody can be a simulation specialist, but to have knowledge about the benefits and support that simulation can offer, will surely help to better define simulation projects in the future. Furthermore, the existing data collection methods need to be developed. Our impression is that many data collecting systems exist at Volvo GTO, but few are useful for simulation purposes. It became apparent during our time at the Skövde plant that terms like cycle time, availability or WIP are used differently within the organisation as well as in the data collection systems leading to unnecessary confusion. This makes the establishment of data relevance and quality unnecessarily difficult, thus, making it even more problematic for an employee without simulation knowledge to deliver quality input data to a simulation project. Our recommendation is that Volvo revises and standardizes the production terminology used by its employees. By making this first important step, the next one should be to update the data collection systems and adapt them to the new standard terminology. This would most likely reduce the challenges faced when collecting data for simulation projects.

During one of the meetings with the simulation network, it was implied that previously conducted flow simulation projects conducted by the simulation network, rarely were followed-up. This due to limited resources but also because this step was seen as the requester's responsibility. It is our opinion that it should be in the simulation network's own interest to follow-up projects in order to analyse the simulation project result with the actual outcome. This should help the network to reflect over unsatisfactory results as a way of improving themselves but also flow simulation in general at Volvo.

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APPENDIX 1

Simplifications and assumptions

- The working hours, shifts and breaks are supplied by Volvo.
- The simulation model is based on production data from the year 2017.
- The simulation horizon, 318 days and eight hours is based on actual production days of 2017.
- Warm-up time is set to 83 days and eight hours.
- 95% level of confidence leading to 20 iterations.
- Only scheduled production hours are simulated.
- The model is never blocked, meaning there is always a demand for engines.
- There's never a shortage of materials.
- All data provided by Volvo is deemed valid.
- There is a 25 seconds transportation time between stations in the CBU-line.
- Forklifts are only simulated between the pre-system activities and the engine buffer. All other transportation, forklifts and manual, is only simulated with a recovery time in objects.
- Forklifts have an availability of 100%.
- The pre-system activities consist of a buffer object and an operation.
- There's no separate availability or MTTR for the Source and Pre-system activities operations. Instead this is covered by the extracted interval distribution between engines per activity and source. Hence, the real availability and MTTR is present in this interval.
- Source_Comp compensates for all engine flows that are either: not possible to obtain from MS-BI or those are requested by Volvo to alter for experiments and are therefore not produced by the "Source_Factory". The takt is calculated according to: (Total number of engines to compensate) / (number of days with production). This gives how many engines should be produced per day as a compensation.
- All workers are of equal skill and competence.
- There's never a shortage of workers.
- It's an interval between engines based on historical production data that is used as processing time and creation interval for the source and the pre-system activities. Therefore, an assumption is made that the interval should already contain the availability for the source and the pre-system activities and therefore it is not calculated separately.

APPENDIX 2

The conceptual model

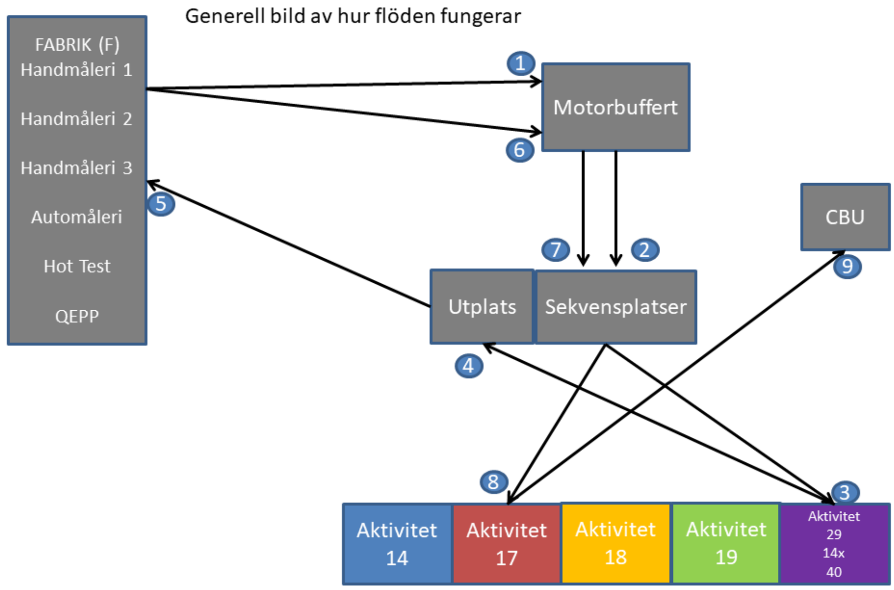


Figure 33. Screenshot of the conceptual model

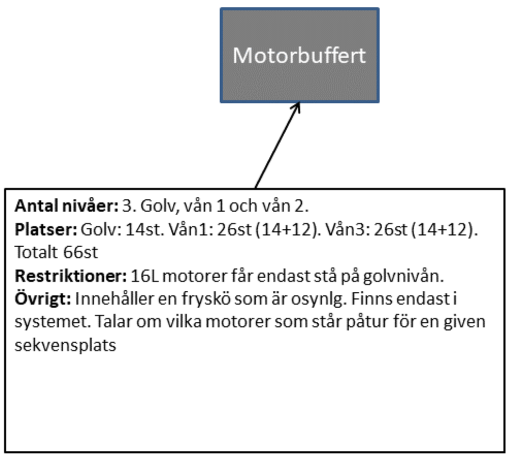


Figure 34. Description of the engine buffer.

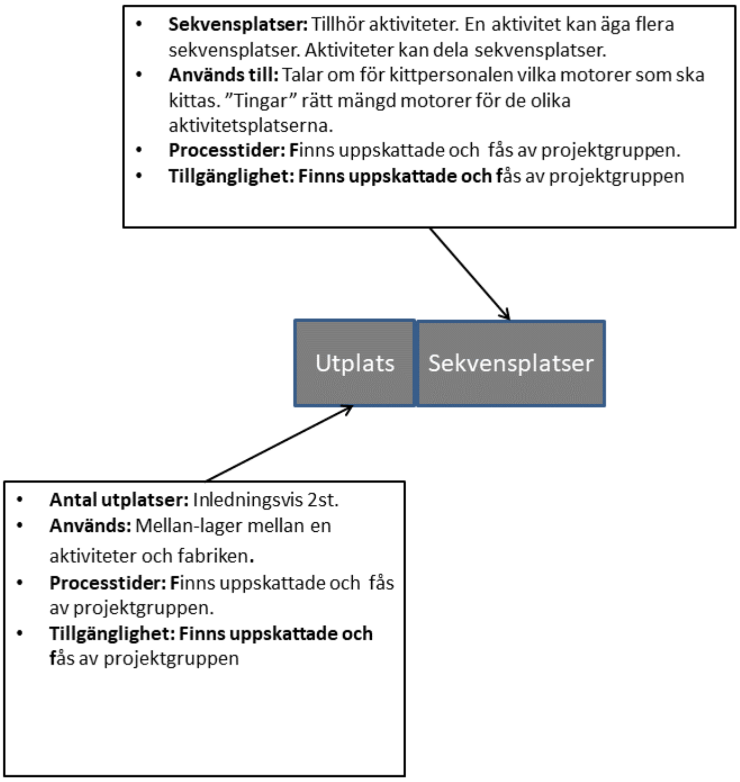


Figure 35. Description of the sequence & out positions.

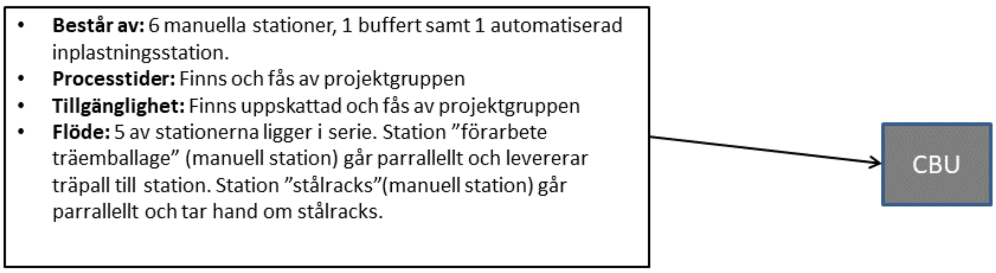


Figure 36. Description of the CBU-Line.

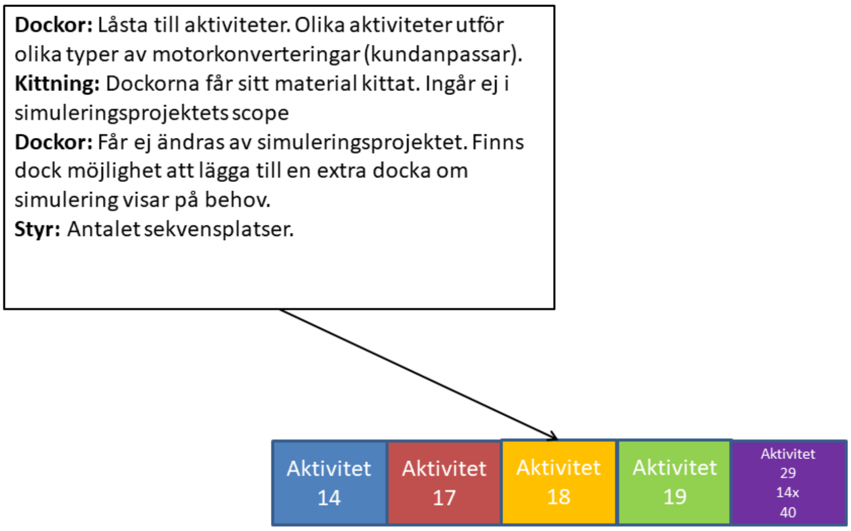


Figure 37. Description of the Docks.

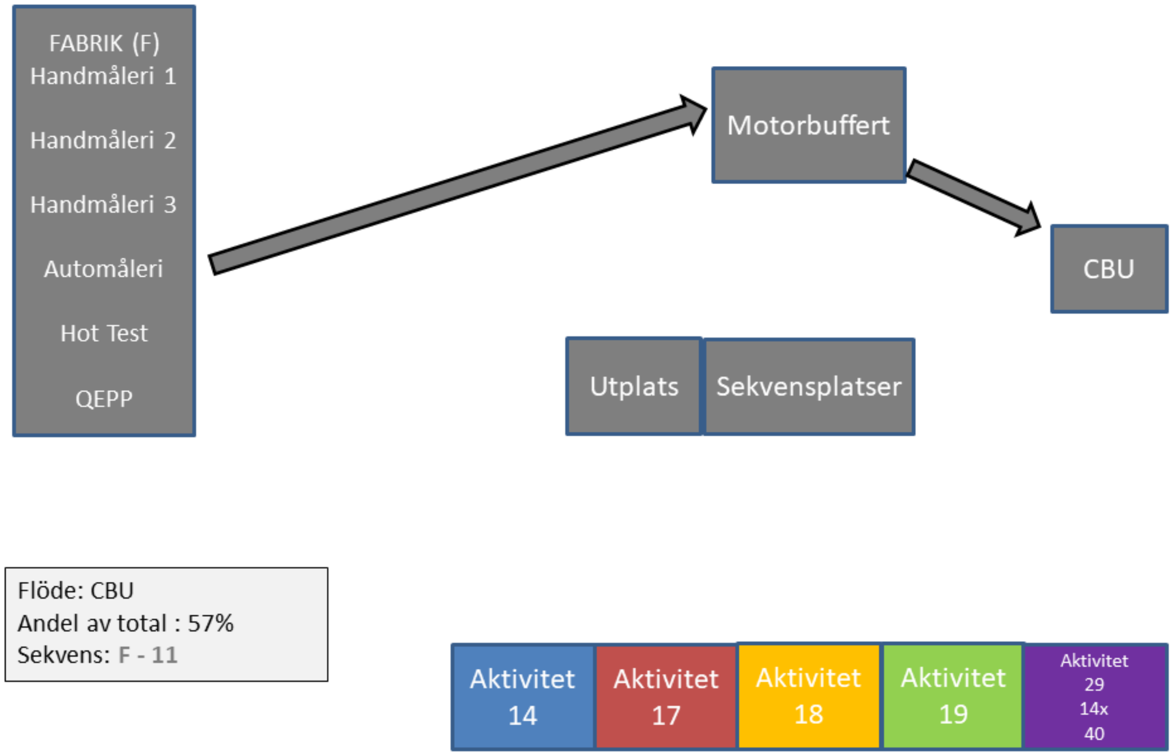


Figure 38. Flow identification A.

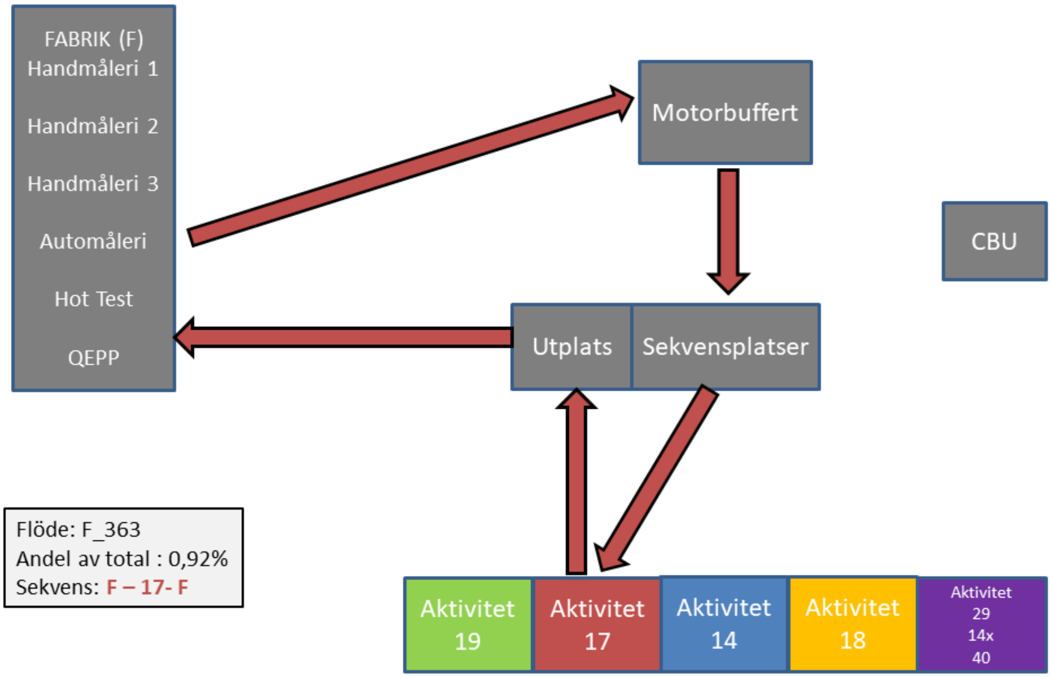


Figure 39. Flow identification B.

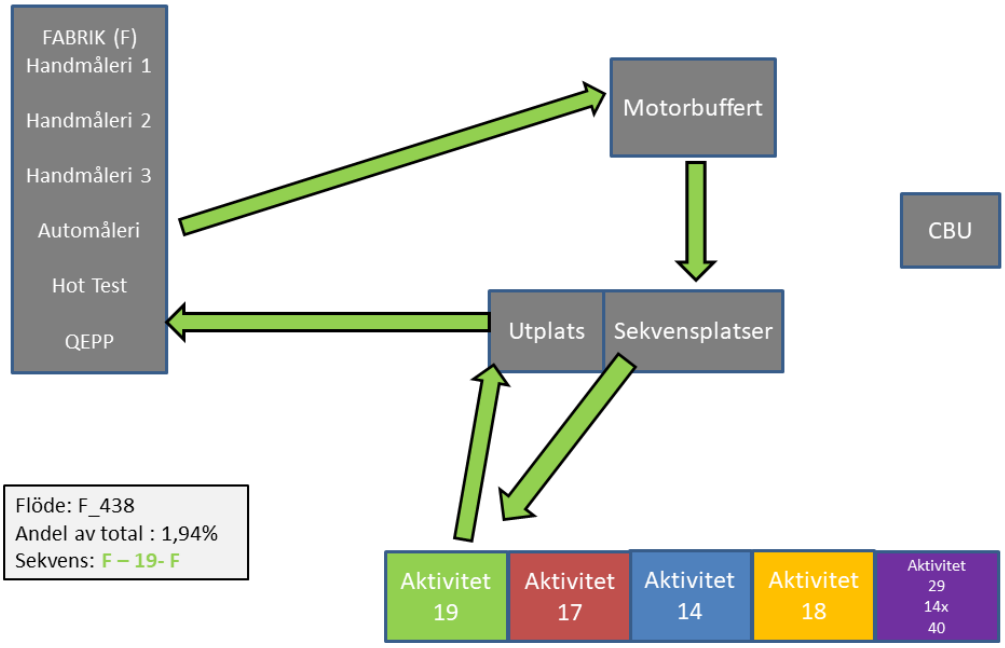


Figure 40. Flow identification C.

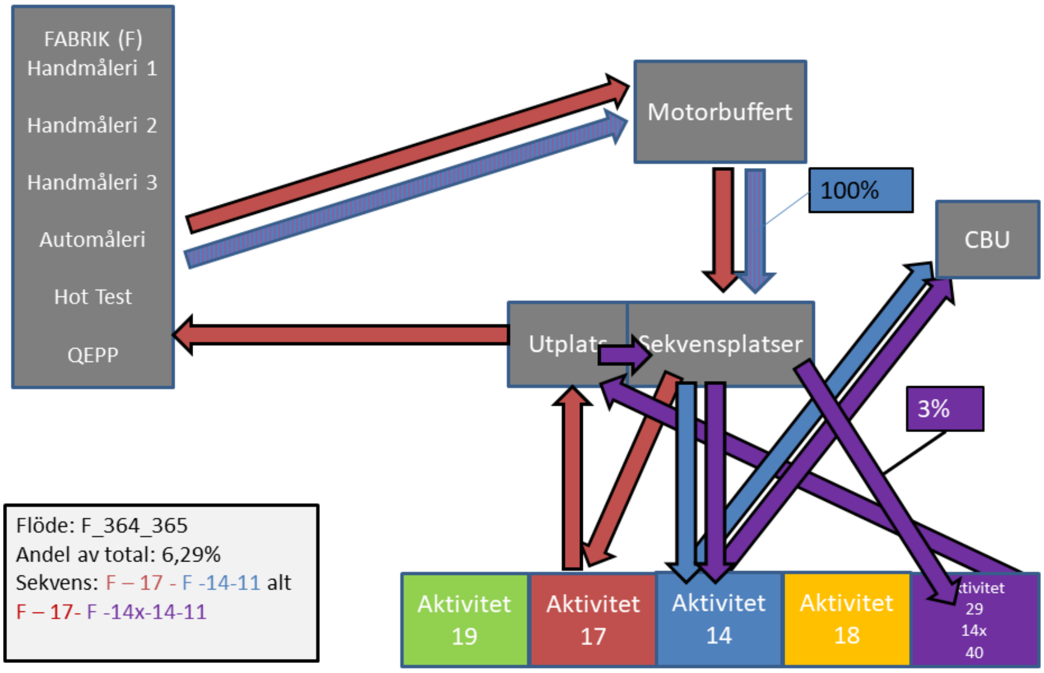


Figure 41. Flow identification D.

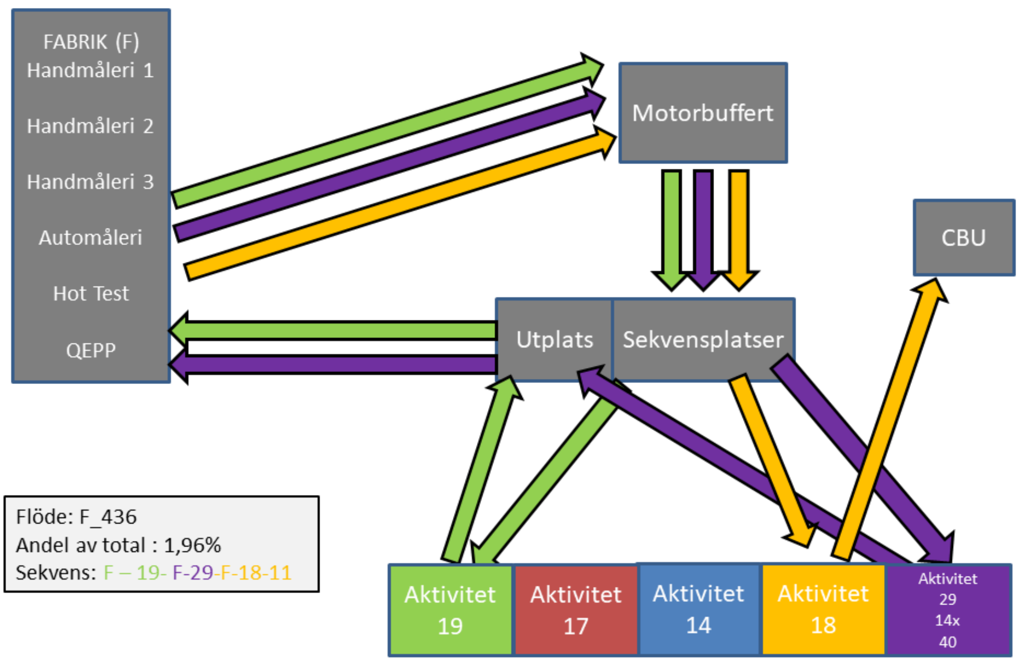


Figure 42. Flow identification E.

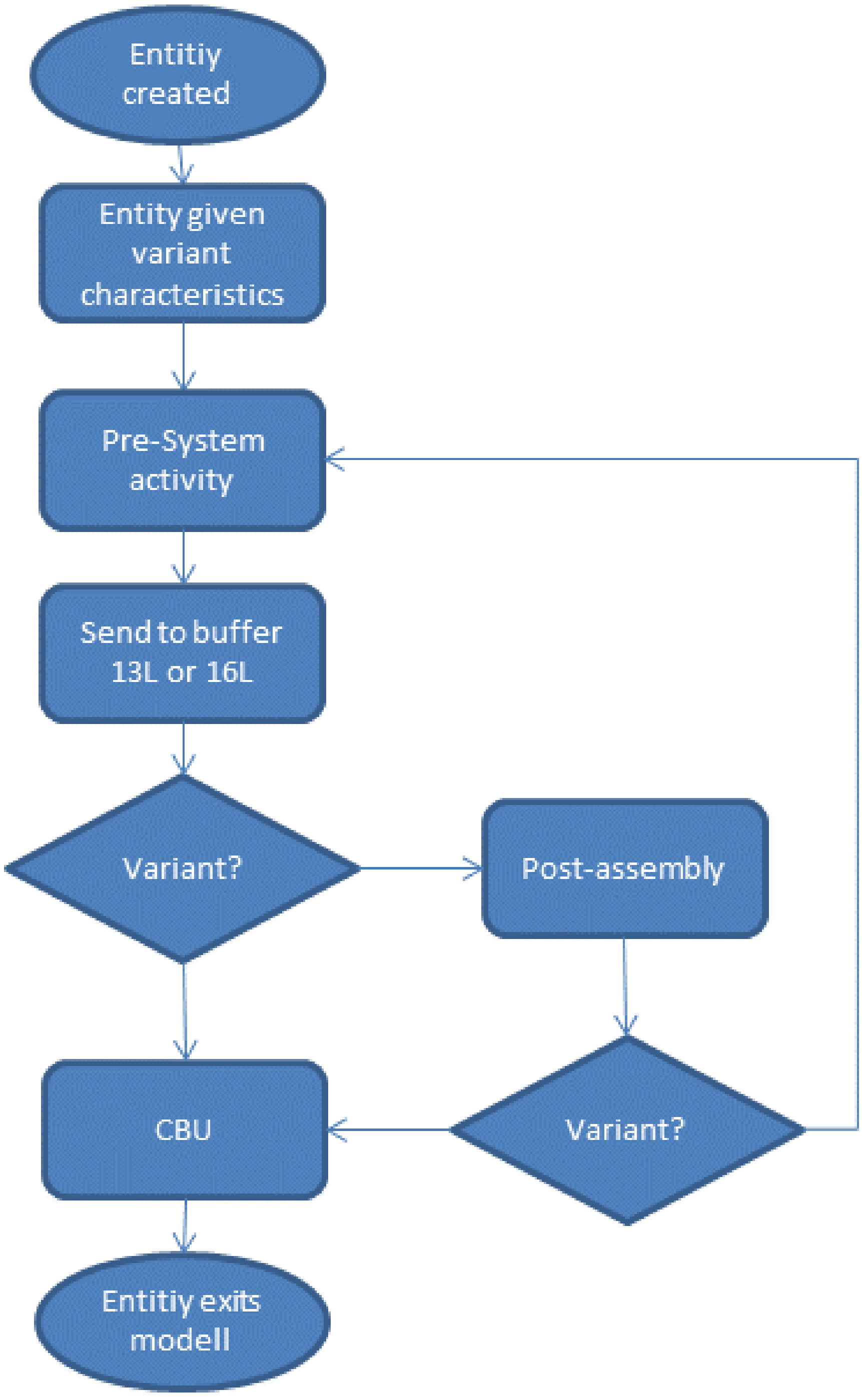


Figure 43. Flow chart of entity movement.

APPENDIX 3

Screenshot of final flow simulation model.

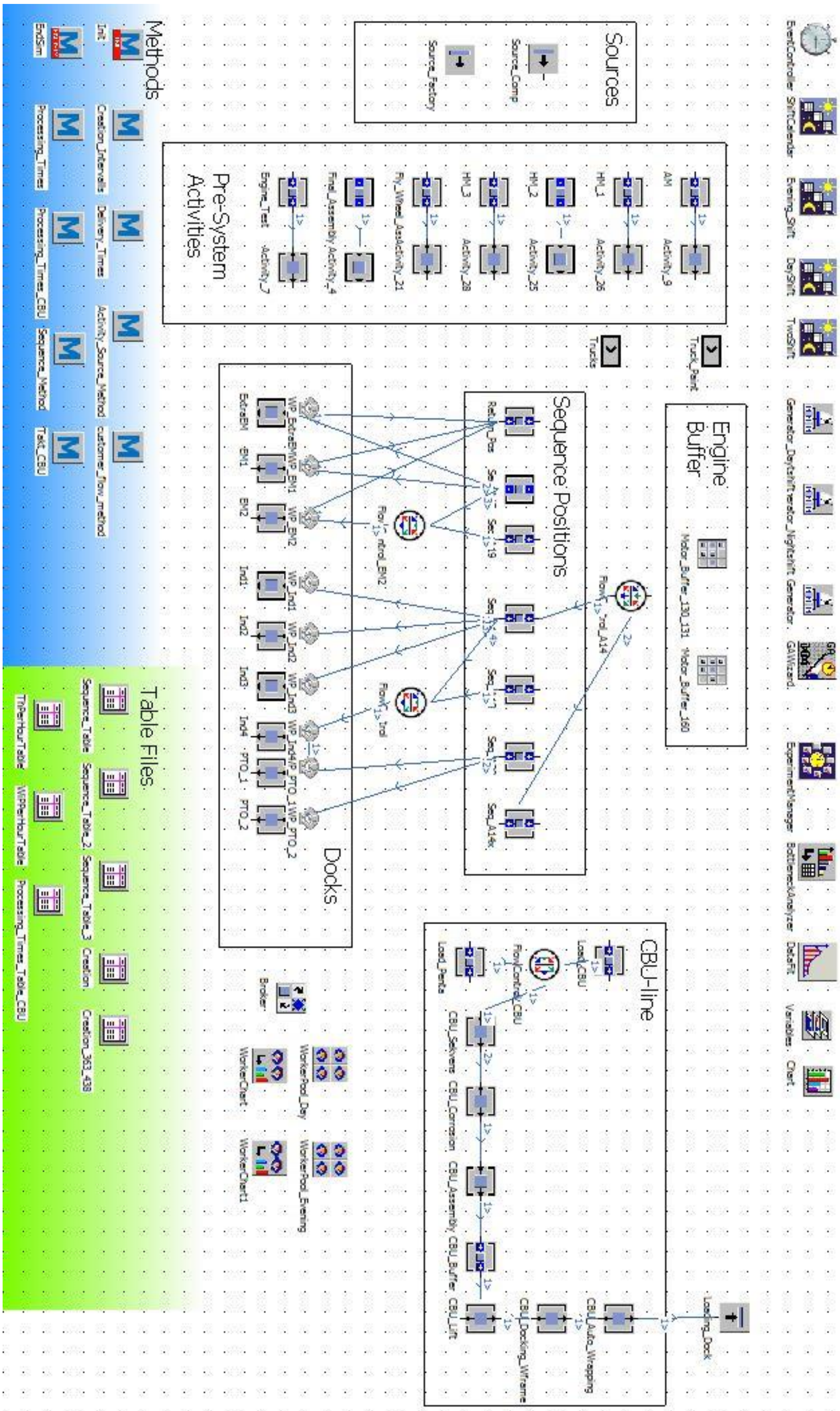


Figure 44. Screenshot of flow simulation model created in Siemen Plant Simulation 14.2

APPENDIX 4

Screenshots from the verification and validation document.

Namn på riktigt	Buffer	Operation	Skift	Lasttid (sek)	Trucktid T/R till Konpack	Truck i modellen
Automåleriet	AM	Activity 9	3	30	2	Truck_Paint
Handmåleri 1	HM_1	Activity 26	2	30	2	Truck_Paint
Handmåleri 2	HM_2	Activity 25	2	30	2	Truck_Paint
Handmåleri 3	HM_3	Activity 28	2	30	2	Truck_Paint
Svänghjul	Fly_Wheel	Activity 21	2	30	2	Trucks
Slutdel	Final_Assembly	Activity 4	3	30	2	Trucks
QEPP & HOT test	Engine_Test	Activity 7	2	30	2	Trucks

Samtliga aktiviteter räknar hur många gånger en motor/entitet vistats i KonPack. Baserat på detta väljs därefter rätt sekvens(tabellfil) för entiteten.

Processtiden för samtliga målerier är beräknad separat för dag,kväll och nattskiften samt under perioden v1-12 år 2017. Då underlag för exakta cykeltider/processtider för dessa saknas har MSBI använts för att avgöra hur många motorer som registrerats per skift och måleri. Detta har i sin tur omvandlats till ett intervall mellan motorer. Samtliga intervall har sammanställts och bakomliggande fördelningar har beräknats. Rådata och fördelningarna finns i separata dokument.

Buffertarna fyller två syften: 1. Underlätta tillbakaskickandet av motorer som går flera varv i Konpack. 2. Att se hur stor inverkan på lagerbildning KonPack står för hos dessa aktiviteter/kunder.

Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | Sekvensplatser | FlowControl | Dockor | CBU | Övrig

Figure 45. Verification & Validation - Pre-system activities.

Namn	Tid T/R till Konpack (min)	Antal truckar	Trafikerar
Truck_Paint	2	1	Målerierna - Konpack
Trucks	2	3	Sv,slutdel, motortest - Konpack

OBS!!

Transporter mellan motorbufferten och sekvensplatserna och sekvensplatserna och dockorna är inbyggt med en "recovery time" i såväl buffertarna som dockorna/aktiviteterna, denna är satt till 90sekunder i bufferten och 180 sekunder i dockorna.

Exempel: En motor lastas ut från buffert och körs till en sekvensplats, därefter kör trucken tillbaka för nästa upphämtning, detta tar 90sekunder. Under dessa 90 sekunder är bufferten ej tillgänglig för nya leveranser.

Exempel 2: En motor är klar i en av dockorna, denna levereras för hand till rätt mottagare och en ny motor hämtas. Detta tar montören 180sekunder, under tiden är montörens docka inaktiv.

Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | Sekvensplatser | FlowControl | Dockor | CBU

Figure 46. Verification & Validation - Forklifts.

Namn	Antal skift	Dag	Dagsraster	Kväll	Kvällsraster	Natt	Nattraster
Shift Calendar	3	07:10 15:36	0900 0910;11:45 12:15;14:00 14:10	15:46 00:36	18:00 18:10;20:00 20:30; 22:00 22:10	00:46 07:00	02:00 02:12
Dayshift	1	07:10-15:36	0900-0910;11:45-12:15;14:00-14:10				
TwoShift	2	07:10-15:36	0900-0910;11:45-12:15;14:00-14:10	15:46-00:36	18:00-18:10;20:00-20:30; 22:00-22:10		

Shiftobjekten används för att tala om för olika objekt i modellen vilka arbetstider som gäller

Fråga:
Stämmer arbetstiderna/rasterna?

Aktiviteter före KonPack | Truckar | **Skiftobjekt** | Motorbuffert | Sekvensplatser | FlowControl | Dockor | CBU | Övriga Antaganden

Figure 47. Verification & Validation - Shift objects.

Namn	Antal platser	Tar emot	Utlastningstid (sek)
Motor_Buffer_130_131	42	13L & 13V	90
Motor_Buffer_160	14	16L	90

Buffertarna stämmer av vilken entitet det är som besöker dem och avgör vilken som är lämpligast att skicka baserat på läget i sekvensplatserna. Detta görs i.o.m att objekttypen är en "Store ". Buffertarna stämmer även av vilken entitet det är som kommit in samt vilken runda den gör i Konpack. Utifrån det väljs rätt sekvenstabell som avgör vart entiteten ska härnäst.

Buffertarna har även en inbyggd felsökningsfunktion. Den läser av alla motorflöden som passerat genom buffertarna och sätter "True" på deras user attribute i bufferten. På så sätt kan man se om det står "true" på en 13L motor i 16L bufferten, då har den hamnat fel och flödet måste korrigeras. Detta kan läsas av i buffertarna under fliken user-defined

Aktiviteter före KonPack | Truckar | Skiftobjekt | **Motorbuffert** | Sekvensplatser | FlowC

Figure 48. Verification & Validation - Engine Buffer.

	B	C	D	E	F	G
1						
2	**Namn**	**Namn i modellen**	**Platser**	**Skickar till**	**Har prioritet till**	**Kopplar entitet till kundflöde**
3	Utplats	Return_Pos	2	-		
4	Sekvensplats 17	Seq_A17	2	EM1,ExtraEM,EM2		8188292,111(DT)
5	Sekvensplats 19	Seq_A19	2	EM2	EM2	40000029,40000043,40000044,40000045,40000046,40000054,40000102
6	Sekvensplats 14	Seq_A14	3	Ind1,Ind2,Ind3, Ind4		3,16
7	Sekvensplats 18	Seq_A18	1	Ind4	Ind4	4
8	Sekvensplats 29	Seq_A29	1	PTO_1,PTO_2		4
9	Sekvensplats 14X	Seq_A14X	1	PTO_1		17

Samtliga sekvensplatser kopplar entiteterna till ett kundflöde. Sannolikheten för ett givet kundflöde är beräknat utifrån dokument "simulering eftertider_v1804".

Exempel: En entitet anländer till sekvensplats 14. Utifrån data i dokumentet är det då ca 27% sannolikhet att den kopplas till kundflöde 3.

... | Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | **Sekvensplatser** | FlowControl | Dockor | CBU |

Figure 49. Verification & Validation - Sequence positions.

	A	B
1	**Namn**	**Funktionsbeskrivning**
2	FlowControl_A14	97,5% motorer till Sekvensplats 14, 2,5% går till sekvensplats 14X
3	FlowControl_EM2	Prioriterar entiteter från Sekvensplats 19 före Sekvensplats 18 som ska till EM2
4	FlowControl	Prioriterar entiteter från Sekvensplats 18 före Sekvensplats 14 som ska till Ind4
5	FlowControl_CBU	Prioriterar Load_Penta före Load_CBU

... | Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | Sekvensplatser | **FlowControl** |

Figure 50. Verification & Validation - Flow Controls

Namn	Skift	Beläggning Dag	Beläggning Kväll	Processtid regleras av metod:	Std.av	Tillgänglighet	MTTR	Skickar till	Dokument
ExtraEM	Dag	100	0	Processing_Times	5%	90	3min +-20%	Return_Pos	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
EM1	Dag/Kväll	100	40	Processing_Times	5%	90	3min +-20%	Return_Pos	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
EM2	Dag/Kväll	100	40	Processing_Times	5%	90	3min +-20%	Return_Pos	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
Ind1	Dag/Kväll	100	100	Processing_Times	5%	90	3min +-20%	Load_Penta	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
Ind2	Dag	100	0	Processing_Times	5%	90	3min +-20%	Load_Penta	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
Ind3	Dag	100	0	Processing_Times	5%	90	3min +-20%	Load_Penta	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
Ind4	Dag	100	0	Processing_Times	5%	90	3min +-20%	Load_Penta	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
PTO_1	Dag/Kväll	100	100	Processing_Times	5%	70%	60min +-20%	Return_Pos	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx
PTO_2	Dag/Kväll	100	100	Processing_Times	5%	70%	60min +-20%	Return_Pos	Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx

Samtliga tider är tagna från angivna dokument. Enligt mail från Josefin har 10% variation lagts på på de tider som saknade sådan. Dessa tider är komenterade i koden(metoden). Tider_exjobb_uppd_181024.xlsx, Beläggning till exjobb(2).xlsx

PTO_1 & PTO_2 fungerar enligt följande:
Om en aktivitet 29 motor anländer skickas den till PTO_1. Är PTO_1 upptagen skickas den istället till PTO_2. Om en aktivitet 14x motor anläder, väntar den i sin sekvensplats tills att båda PTO stationerna är lediga, därefter stängs PTO_2 av och PTO_1 processar motorn. När motorn är färdig skickas den via utposition till sekvensplats 14.

... | Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | Sekvensplatser | FlowControl | Dockor | CBU | Övriga Antaganden

Figure 51. Verification & Validation - Docks.

Objekt	Processtider regleras av (metod)	Cykeltid beroende av motorfamilj	Tillgänglighet	MTTR	Dokument
Load_CBU	90 sekunder	Nej	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)
Load_Penta	90 sekunder	Nej	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)
CBU_Corrosion	Processing_Times_CBU	Ja	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)
CBU_Assembly	Processing_Times_CBU	Ja	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)
CBU_Buffer	Processing_Times_CBU	-			
CBU_Lift	Processing_Times_CBU	Ja	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)
CBU_Docking_Wframe	Processing_Times_CBU	Ja	98,40%	6min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2), Trasigt emballage CBU.xlsx
CBU_Auto_Wrapping	Processing_Times_CBU	Ja	95%	10min +-20%	AvixReportOutput.pdf, Beläggning till exjobb (2)

Bufferten i CBU är förnuvarande satt till 1. Ledtiden genom bufferten är satt till 0sekunder.
Tid från station till nästa förutsätts vara inräknad i tiderna i dokument AvixReportOutput.pdf.

Två bud finns gällande tillgängligheten på automatstationen.
Enligt mail (20-9-2018) från Mathias Johansson ska cykeltiden 240s samt tillgängligheten 97% användas för automatstationen.

Dokument Beläggning till exjobb (2) från 29-10-2018 anger en annan tillgänglighet, 95% samt en MTTR på 10min.

Eftersom dokumentet beläggning till exjobb mottagits vid en senare tidpunkt än mailet från M.Johansson anses det vara mest aktuellt och därför har tillgängligheten och MTTR i detta dokument använts.

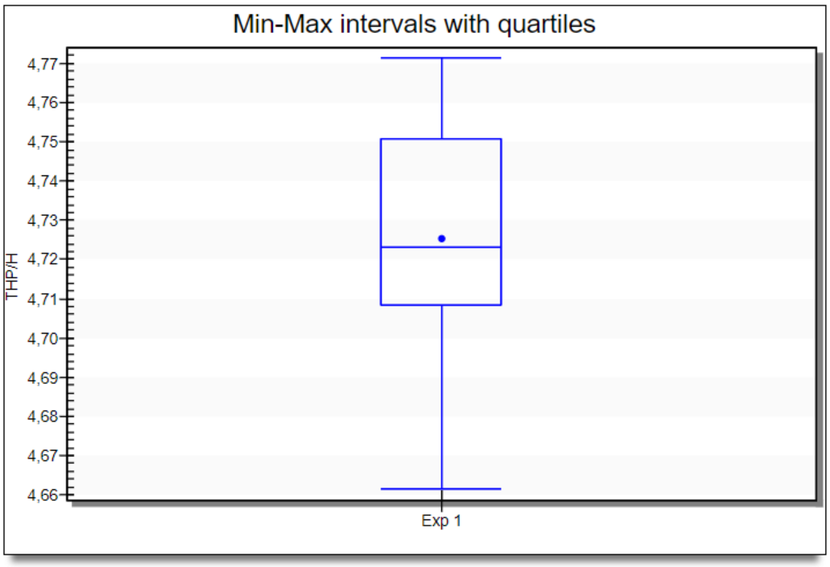
... | Aktiviteter före KonPack | Truckar | Skiftobjekt | Motorbuffert | Sekvensplatser | FlowControl | Dockor | CBU | Övriga Antaganden

Figure 52. Verification & Validation - CBU-Line.

APPENDIX 5

Experiment 1. Comparison of the two experiment runs ”10% increase” and ”10% modified”.

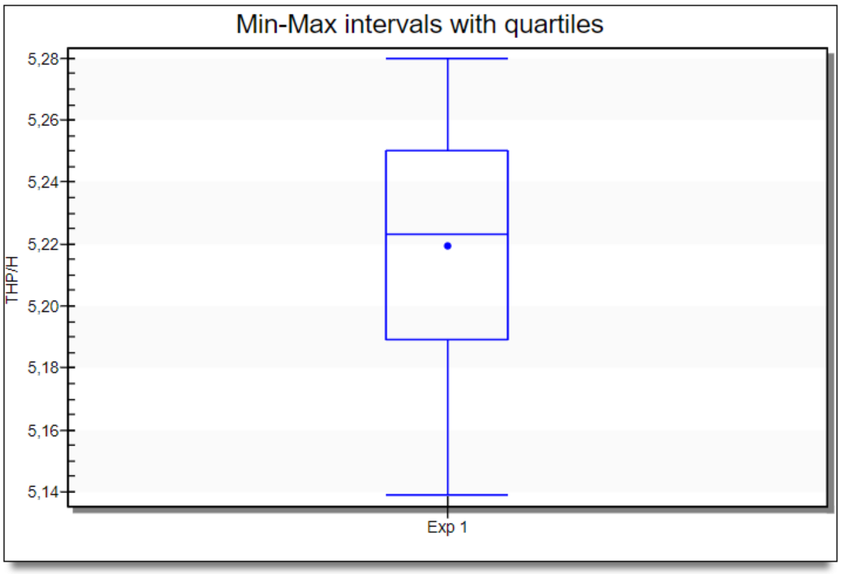
Evaluations of the output value 'THP/H'



Experiment	THP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	4.72541666666667	0.0304706325641209	4.66152482269504	4.77145390070922	4.71115112698936	4.73968220634397

Figure 53. Throughput/hour. 10% volume increase

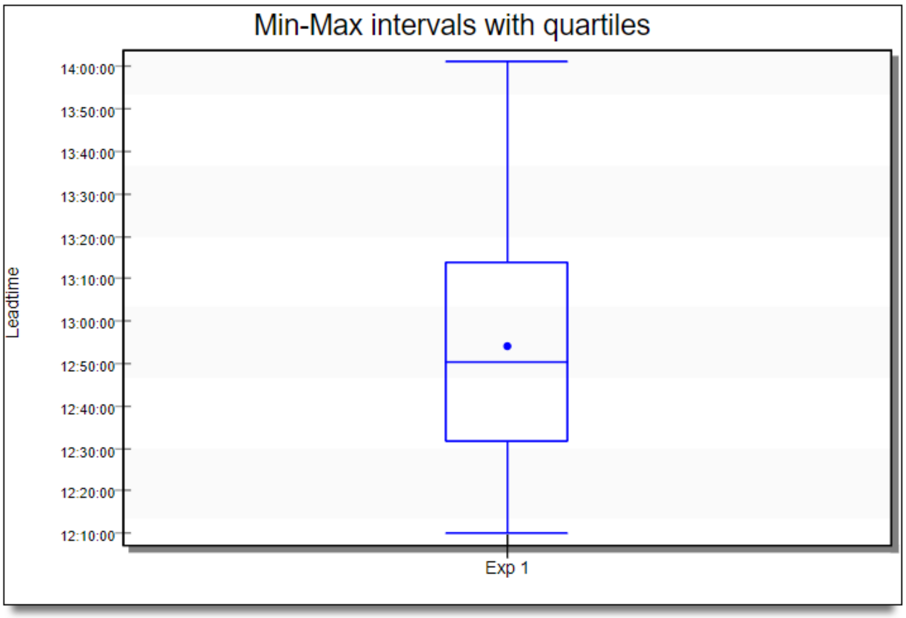
Evaluations of the output value 'THP/H'



Experiment	THP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	5.21933510638298	0.0383427112897824	5.13900709219858	5.27996453900709	5.20138406883597	5.23728614392999

Figure 54. Throughput/hour. 10% modified.

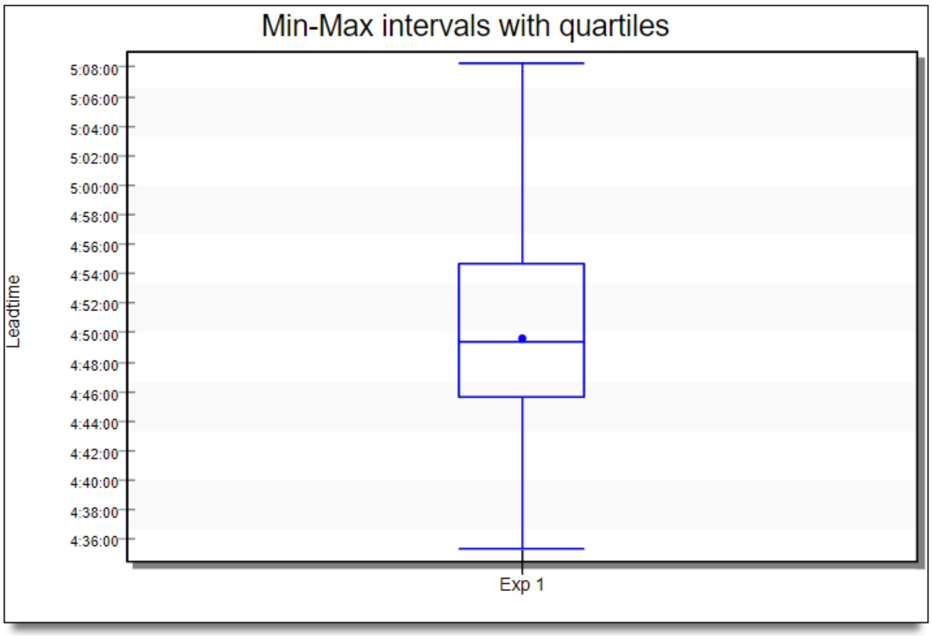
Evaluations of the output value 'Leadtime'



Experiment	Leadtime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	12:54:15.9976	28:50.9197	12:10:01.4032	14:01:18.8835	12:40:45.6270	13:07:46.3681

Figure 55. Avg. Lead-time. 10% volume increase.

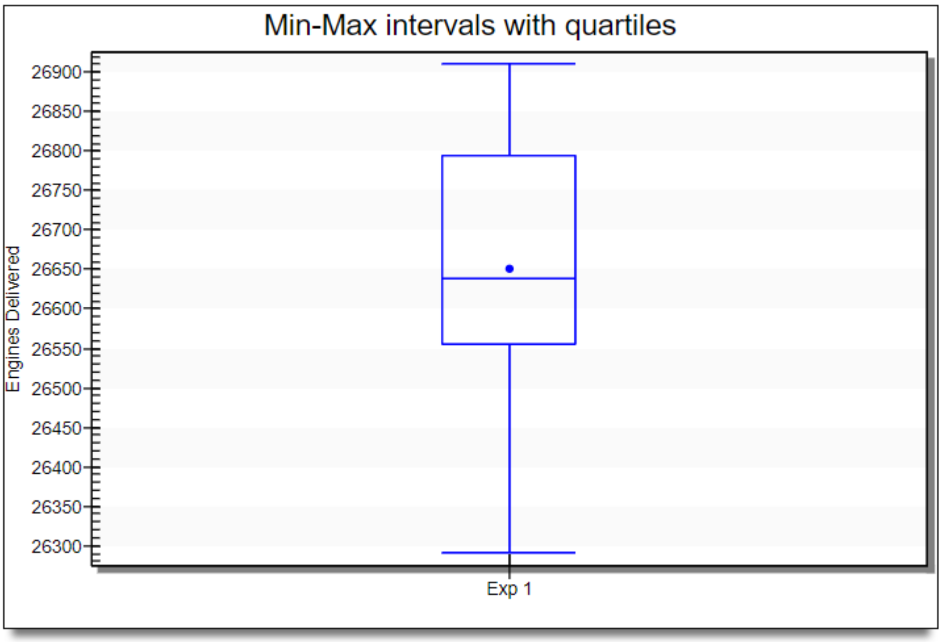
Evaluations of the output value 'Leadtime'



Experiment	Leadtime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	4:49:32.9202	7:20.5476	4:35:21.0809	5:08:16.4352	4:46:06.6675	4:52:59.1729

Figure 56. Avg. Lead-time. 10% modified.

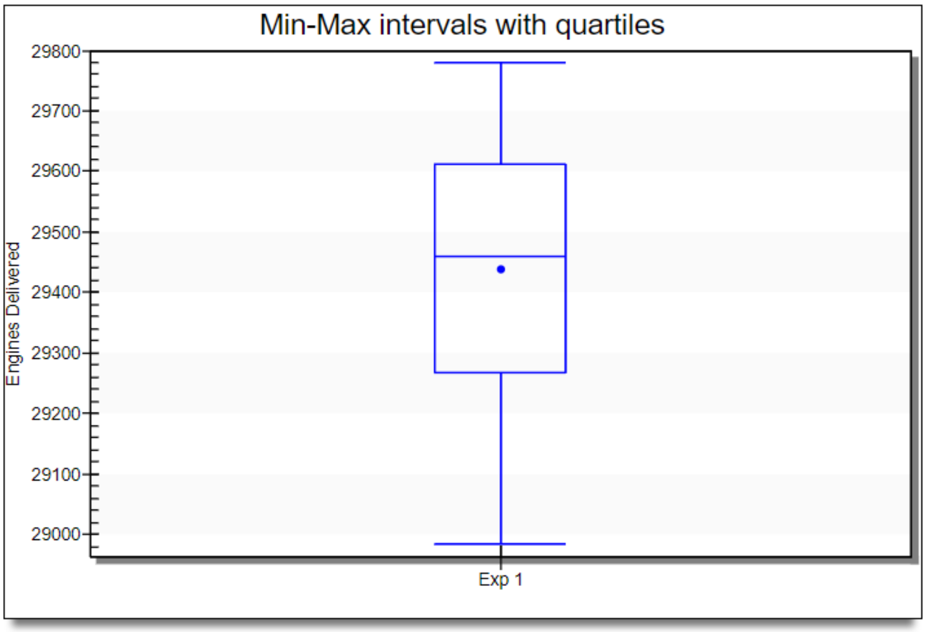
Evaluations of the output value 'Engines Delivered'



Experiment	Engines Delivered	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	26651.4	171.916564830495	26291	26911	26570.9132371599	26731.8867628401

Figure 57. Delivered Engines. 10% volume increase.

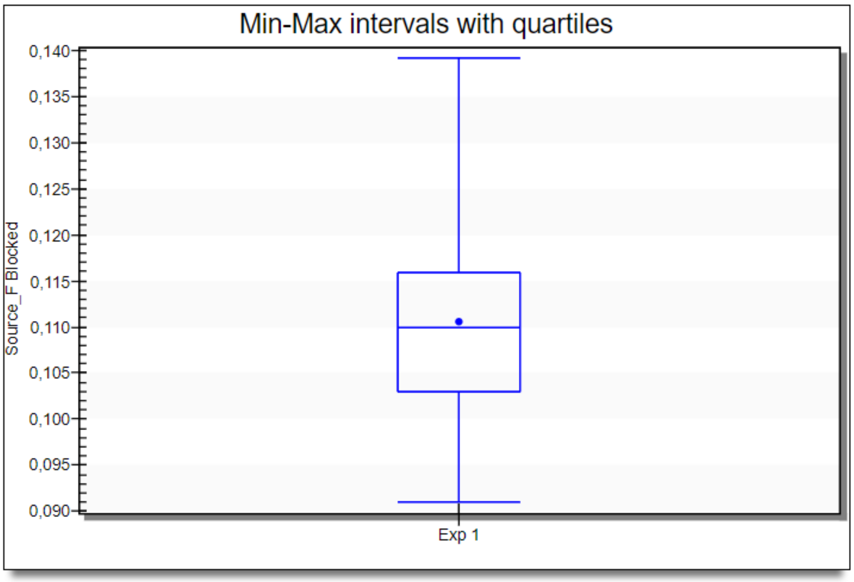
Evaluations of the output value 'Engines Delivered'



Experiment	Engines Delivered	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	29437.15	216.328764177319	28984	29779	29335.8706267471	29538.4293732529

Figure 58. Delivered engines. 10% modified.

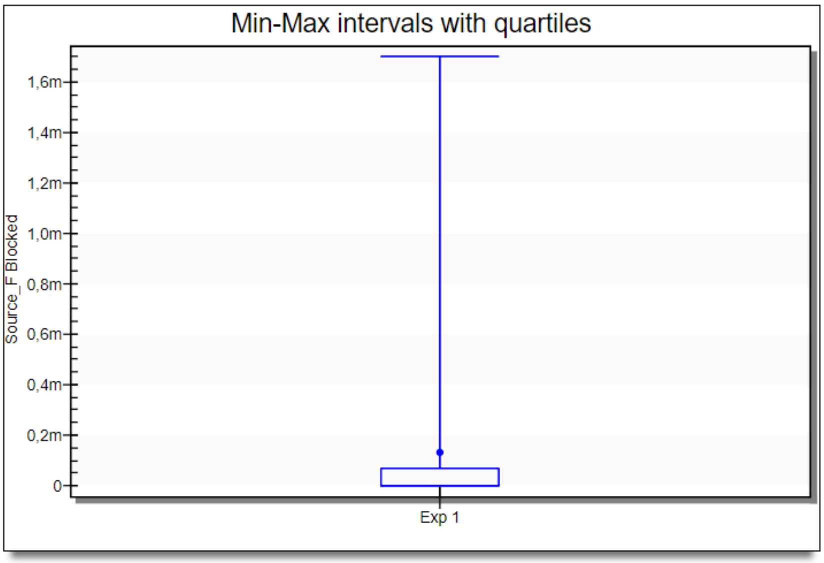
Evaluations of the output value 'Source_F Blocked'



Experiment	Source_F Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.110640734767929	0.0122077460353017	0.0910148529884363	0.139181430817959	0.104925392788383	0.116356076747474

Figure 59. Blocking portion of Source. 10% volume increase.

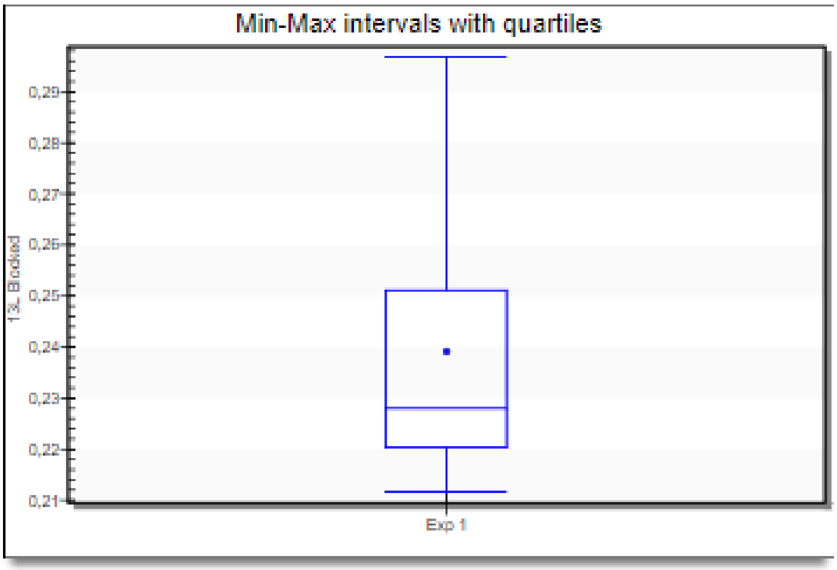
Evaluations of the output value 'Source_F Blocked'



Experiment	Source_F Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.000129709370639599	0.000382237686485983	0	0.00170183298115911	-4.92441470220748e-05	0.000308662888301273

Figure 60. Blocking portion of Source. 10% modified.

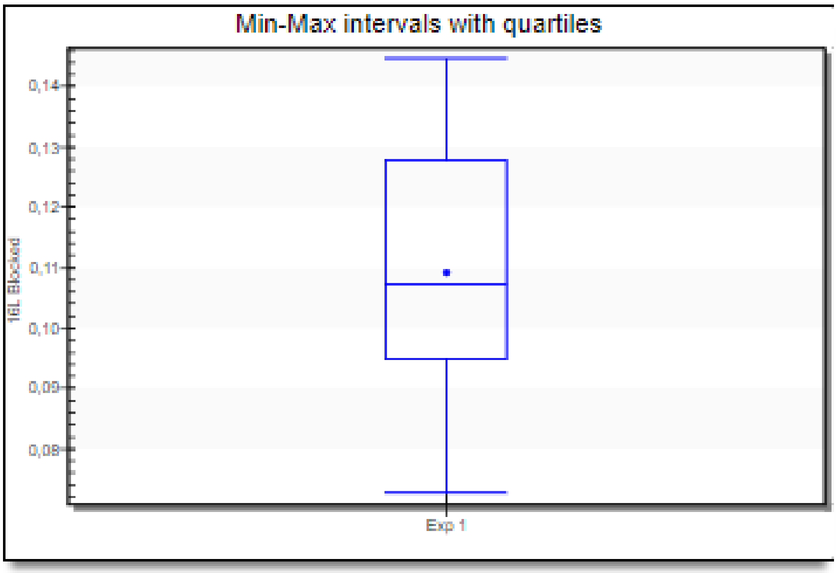
Evaluations of the output value '13L Blocked'



Experiment	13L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.239029644567691	0.0260560255583258	0.211575655642814	0.296807958871098	0.226830906466245	0.251228382669136

The analysis of variance is impossible.
At least two experiments with random output for '13L Blocked' are needed.

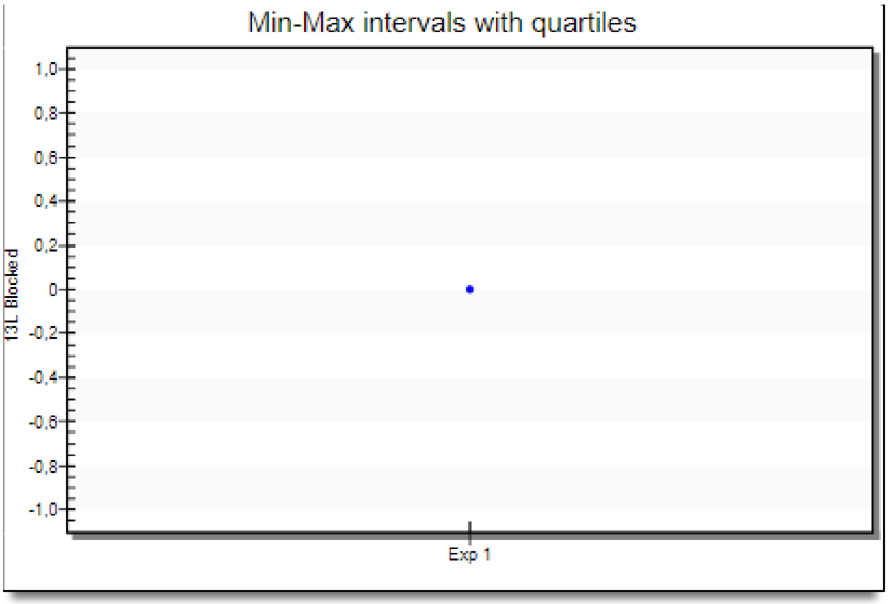
Evaluations of the output value '16L Blocked'



Experiment	16L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.109144897763712	0.0212320726699775	0.0727151183308706	0.144691306500913	0.0992046060921318	0.119085189435293

Figure 61. Blocking portion of Konpack buffers. 10% volume increase.

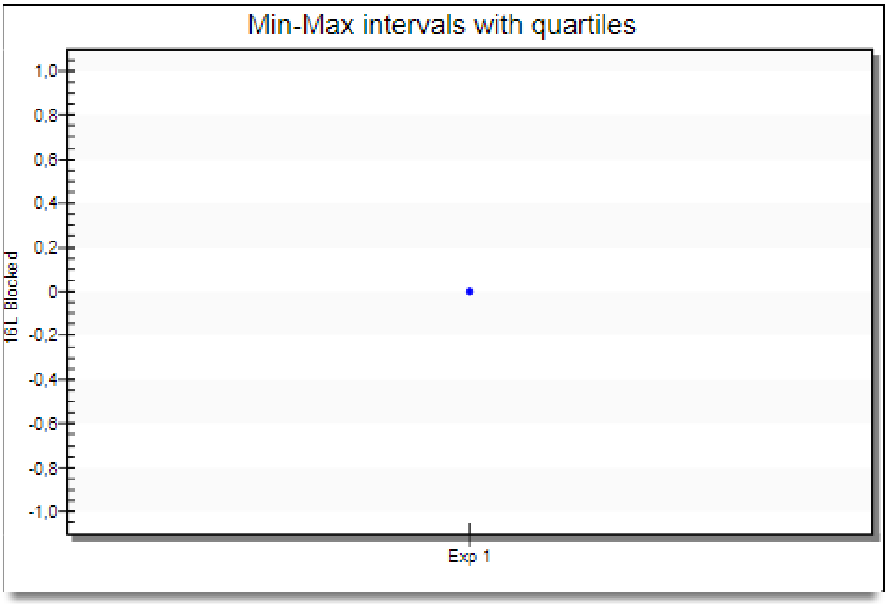
Evaluations of the output value '13L Blocked'



Experiment	13L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0	0				

The analysis of variance is impossible.
At least two experiments with random output for '13L Blocked' are needed.

Evaluations of the output value '16L Blocked'



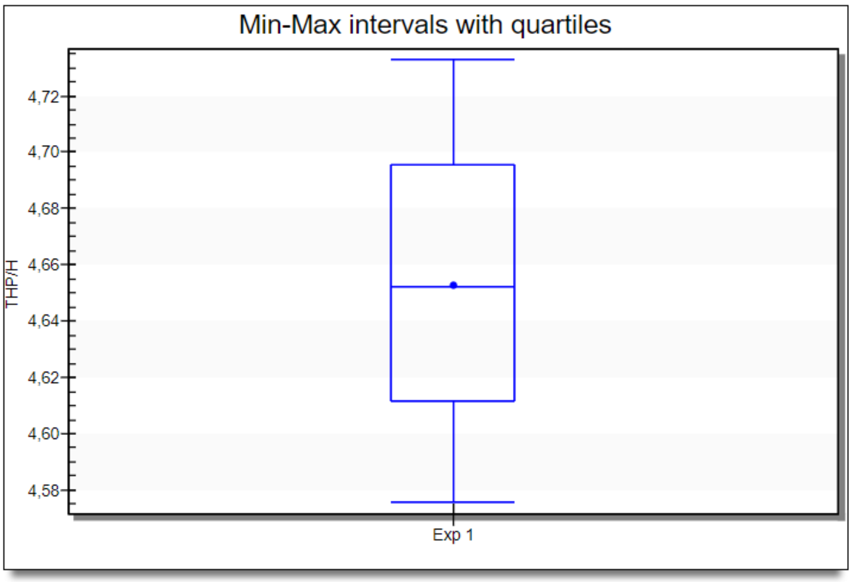
Experiment	16L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0	0				

Figure 62. Blocking portion of Konpack buffers. 10% modified.

APPENDIX 6

Experiment 2. Overestimated cycle times

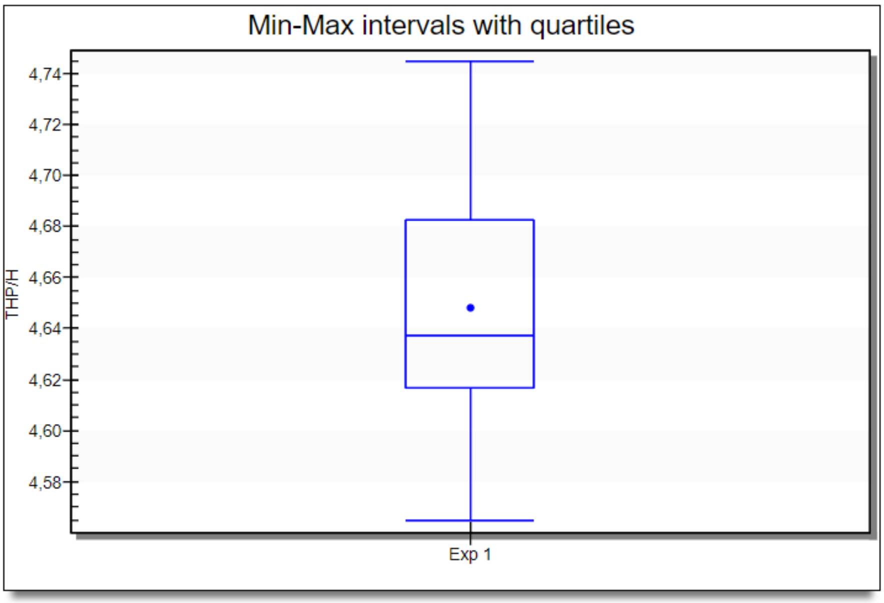
Evaluations of the output value 'THP/H'



Experiment	THP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	4.65255319148936	0.0456477657715269	4.57570921985816	4.73297872340426	4.63118212174135	4.67392426123737

Figure 63. Throughput/Hour. Default cycle times (0% in table 5).

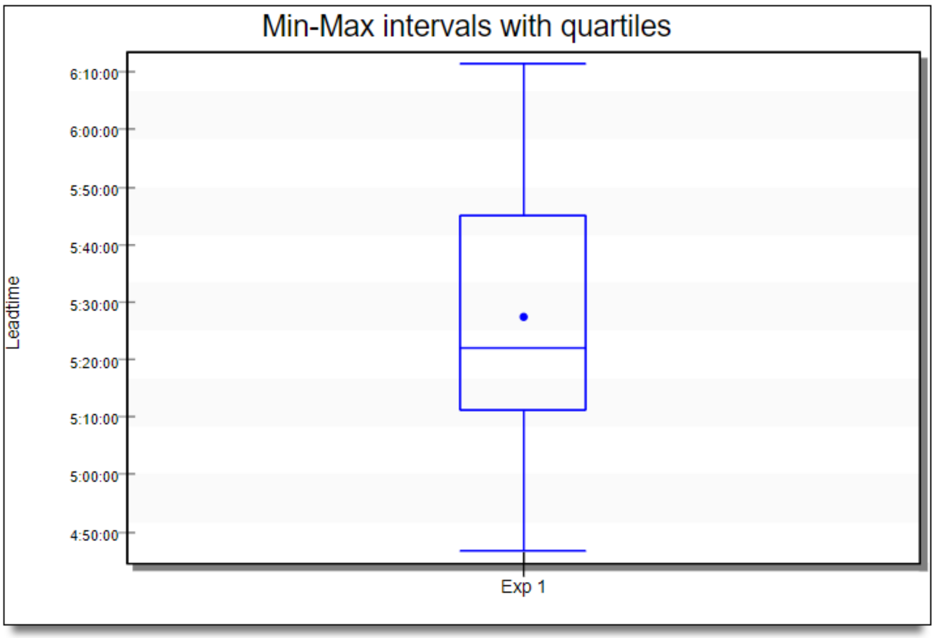
Evaluations of the output value 'THP/H'



Experiment	THP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	4.64809397163121	0.0481002508617742	4.56471631205674	4.74485815602837	4.62557471359766	4.67061322966475

Figure 64.Throughput/Hour. 5% increased cycle times (5% in table 5).

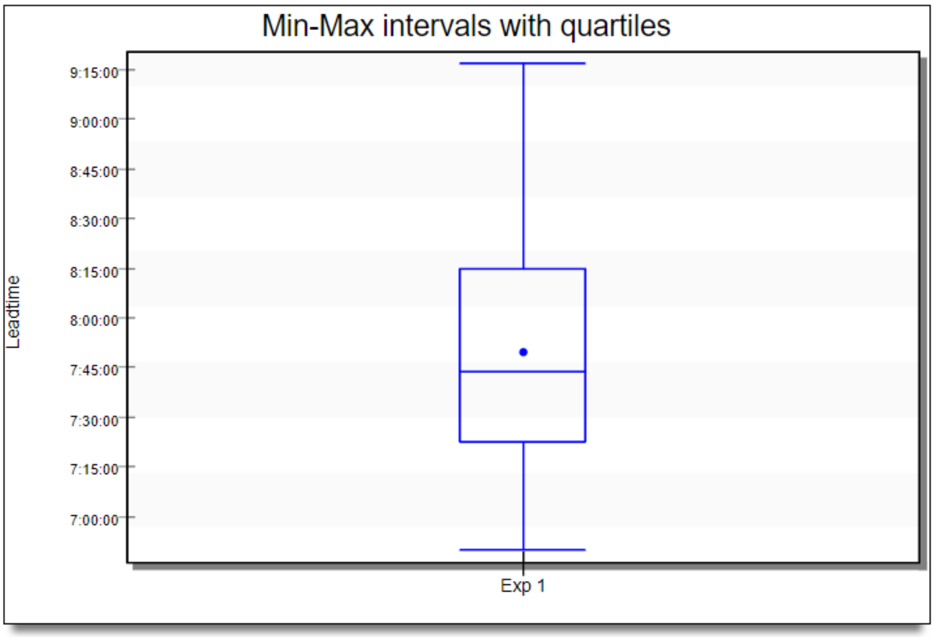
Evaluations of the output value 'Leadtime'



Experiment	Leadtime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	5:27:24.4429	24:46.7857	4:46:43.4855	6:11:30.4038	5:15:48.3694	5:39:00.5165

Figure 65. Avg. Lead-time. Default cycle times (0% in table 5).

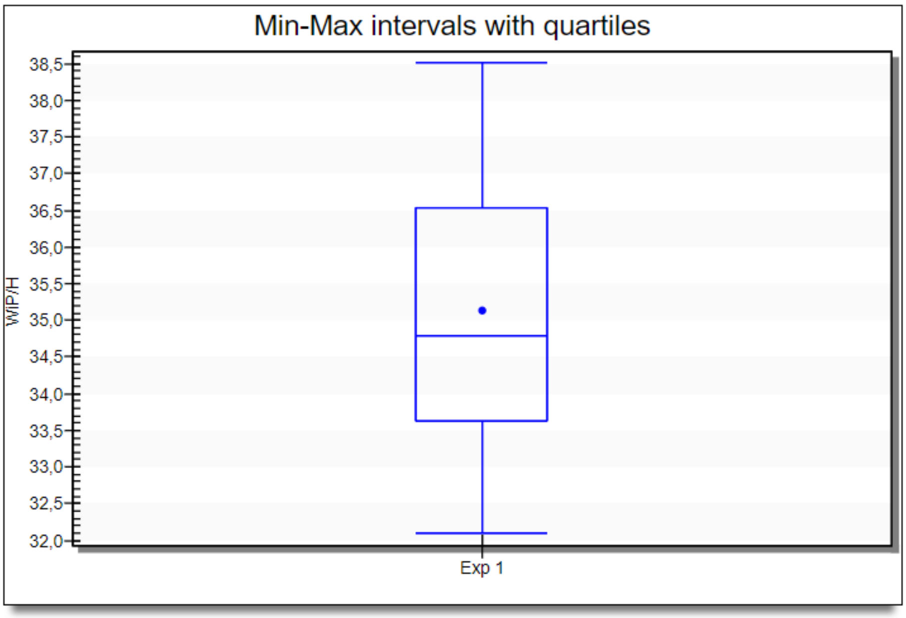
Evaluations of the output value 'Leadtime'



Experiment	Leadtime	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	7:49:39.0836	40:12.6223	6:49:51.6063	9:17:01.6600	7:30:49.5580	8:08:28.6091

Figure 66. Avg. Lead-time. 5% increased cycle times (5% in table 5).

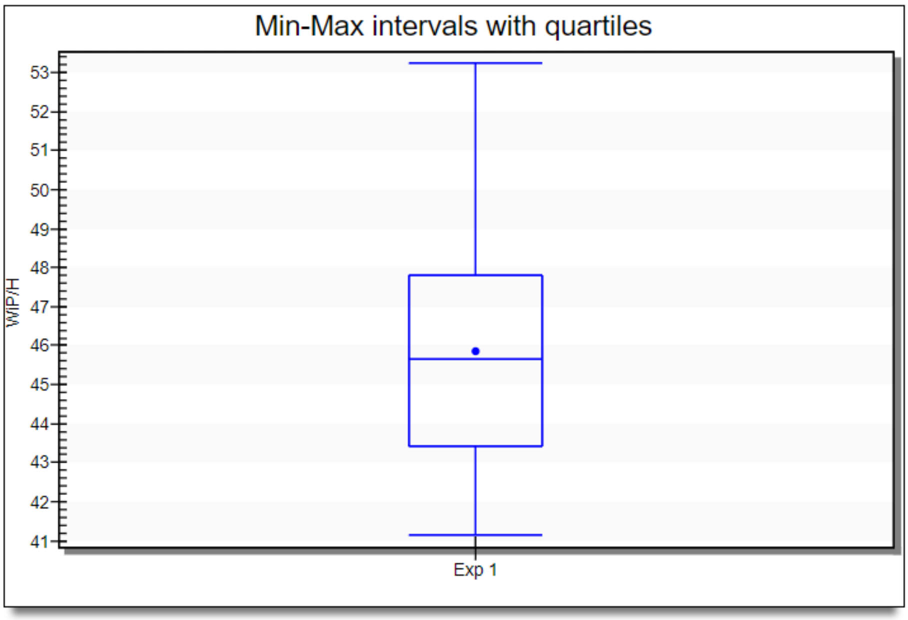
Evaluations of the output value 'WiP/H'



Experiment	WiP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	35.143773962327	1.96804300615815	32.0963493915653	38.5157526254376	34.2223885748755	36.0651593497786

Figure 67. WIP/Hour. Default cycle times (0% in table 5).

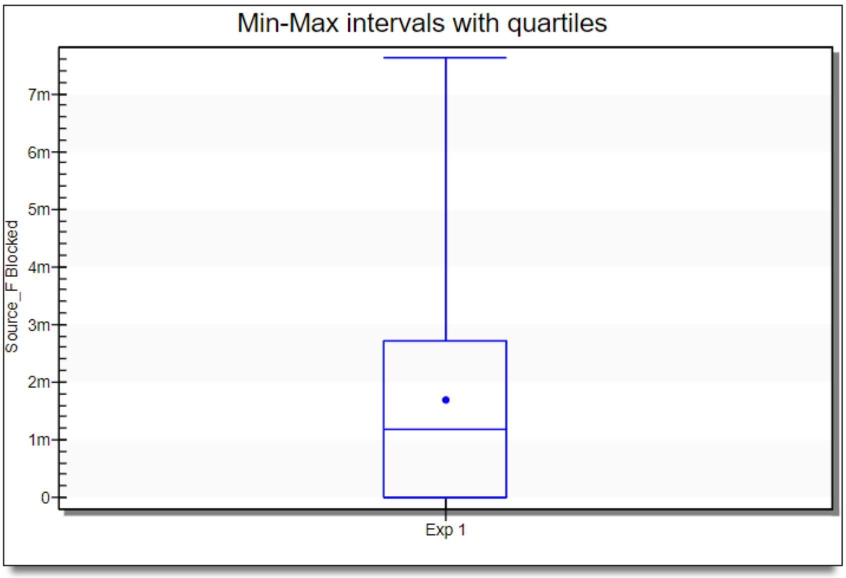
Evaluations of the output value 'WiP/H'



Experiment	WiP/H	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	45.858926487748	3.09985774257047	41.1450241706951	53.2478746457743	44.4076555458805	47.3101974296155

Figure 68. WIP/Hour. 5% increased cycle times (5% in table 5)

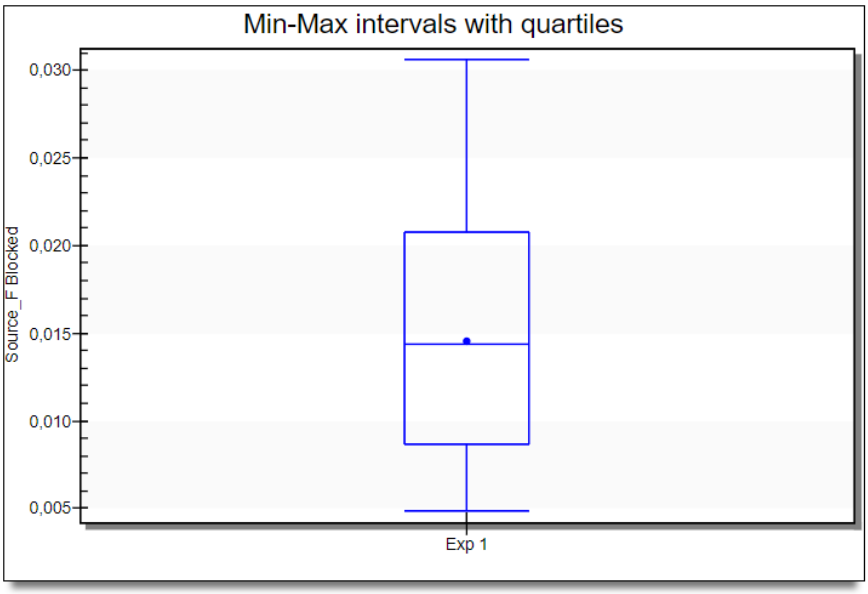
Evaluations of the output value 'Source_F Blocked'



Experiment	Source_F Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.00169414129531302	0.00205593460549238	0	0.00762938216099445	0.000731607398884369	0.00265667519174167

Figure 69. Blocking portion of the Source. Default cycle times (0% in table 5).

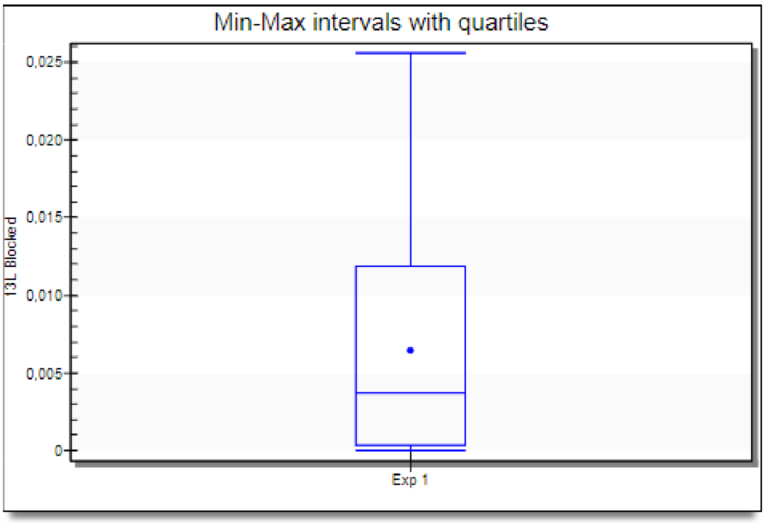
Evaluations of the output value 'Source_F Blocked'



Experiment	Source_F Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.0145404284094223	0.00712614997901169	0.00485862239343693	0.0306187284362953	0.0112041545379145	0.0178767022809302

Figure 70.Blocking portion of the Source. 5% increased cycle times (5% in table 5)

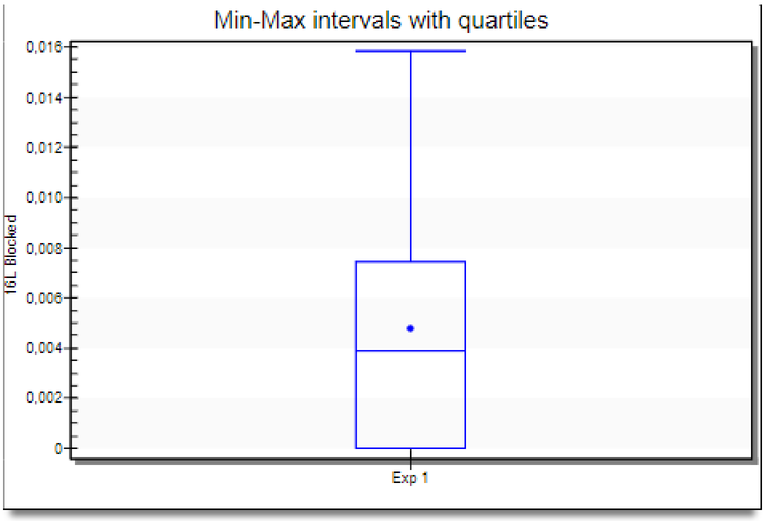
Evaluations of the output value '13L Blocked'



Experiment	13L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.00648181096402347	0.00766340801185195	0	0.0256168797168586	0.00289400717208143	0.0100696147559655

The analysis of variance is impossible.
At least two experiments with random output for '13L Blocked' are needed.

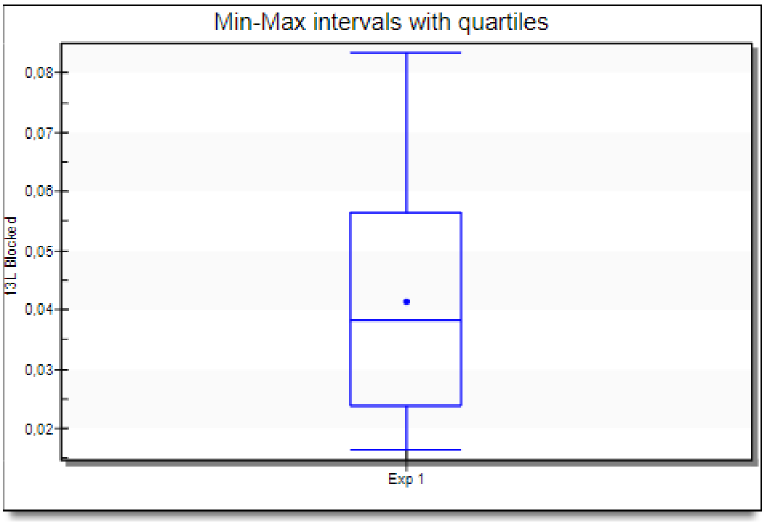
Evaluations of the output value '16L Blocked'



Experiment	16L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.00477391147348455	0.00499566601674316	0	0.0158468891111185	0.00243507352430746	0.00711274942266164

Figure 71. Blocking portion of Konpack buffers. Default cycle times (0% in table 4).

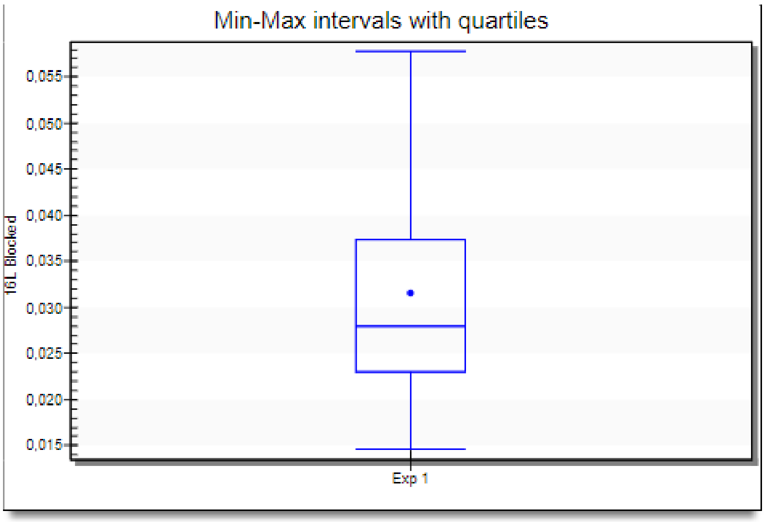
Evaluations of the output value '13L Blocked'



Experiment	13L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.0413223796010778	0.0192526898913126	0.0163985447904807	0.0834669715618056	0.0323087822968096	0.0503359769053459

The analysis of variance is impossible.
At least two experiments with random output for '13L Blocked' are needed.

Evaluations of the output value '16L Blocked'



Experiment	16L Blocked	Standard Deviation	Minimum	Maximum	Left interval bound	Right interval bound
Exp 1	0.0316283679503743	0.0133990880532559	0.0146123620715315	0.0577898304497459	0.025355271326563	0.0379014645741856

Figure 72. Blocking portion of Konpack Buffers. 5% increased cycle times (5% in table 5)

APPENDIX 7

Pareto front solutions from the optimisation.

Table 8. Pareto front solutions.

Total buffers	Motor_Buffer_130_131_Capacity	Motor_Buffer_160_Capacity	Return_Pos_Capacity	Seq_A17_Capacity	Seq_A19_Capacity	Seq_A14_Capacity	Seq_A18_Capacity	Seq_A29_Capacity	Seq_A14X_Capacity	Throughput	Produced Parts	ViP	Leadtime	Source_Factory_Blocked
2	1	1	1	3	4	1	1	1	1	3,965	22361	37,515	25170,416	0,204
3	2	1	1	4	2	2	1	1	1	4,114	23204	37,765	24544,008	0,167
4	3	1	1	3	1	4	1	1	1	4,262	24038	37,815	23701,873	0,125
5	2	3	1	2	2	4	1	1	1	4,266	24061	38,135	23943,635	0,117
6	3	3	1	2	1	5	1	1	1	4,376	24682	37,120	22543,100	0,090
7	4	3	1	2	2	4	1	1	1	4,412	24886	37,526	22712,674	0,091
8	5	3	1	2	1	5	1	1	1	4,462	25166	37,098	22120,562	0,073
9	4	5	1	1	1	6	1	1	1	4,497	25364	37,634	22470,042	0,067
10	5	5	1	1	3	4	1	1	1	4,510	25439	37,579	22224,826	0,069
11	5	6	1	1	1	6	1	1	1	4,541	25610	38,240	22597,583	0,057
13	6	7	1	1	2	5	1	1	1	4,543	25624	37,863	22257,707	0,049
14	7	7	1	1	2	5	1	1	1	4,557	25701	38,153	22448,365	0,046
15	8	7	1	1	1	4	1	2	1	4,575	25805	38,152	22415,121	0,048
16	8	8	1	1	1	6	1	1	1	4,576	25810	38,746	22889,402	0,038
17	8	9	2	1	1	5	1	1	1	4,579	25825	38,985	23048,280	0,039
18	10	8	1	1	2	5	1	1	1	4,591	25892	38,878	22913,123	0,039
20	10	10	1	1	2	5	1	1	1	4,593	25904	40,159	23894,964	0,036
22	10	12	1	1	1	6	1	1	1	4,608	25987	39,916	23657,784	0,027
23	11	12	1	1	1	5	1	1	1	4,617	26042	40,195	23743,651	0,027
27	13	14	2	1	1	5	1	1	1	4,623	26075	41,590	24893,582	0,025
28	13	15	2	1	1	5	1	1	1	4,634	26135	41,752	24987,626	0,024
35	17	18	1	3	4	1	1	1	1	4,642	26180	43,211	26068,745	0,022
40	17	23	1	1	1	5	1	2	1	4,649	26218	44,387	26972,712	0,015
42	21	21	1	1	2	5	1	1	1	4,654	26247	45,567	27982,133	0,018
43	21	22	1	2	2	4	1	1	1	4,660	26281	46,033	28241,607	0,018
49	22	27	2	1	1	1	1	1	1	4,666	26317	45,813	28243,146	0,015
51	25	26	1	3	1	4	1	1	1	4,668	26326	48,109	29847,476	0,013
54	23	31	2	2	1	1	1	1	1	4,674	26361	47,352	29181,170	0,013
65	33	32	1	3	4	1	1	1	1	4,678	26383	52,996	33666,927	0,013
66	34	32	1	1	1	6	1	1	1	4,684	26420	51,970	32858,076	0,010