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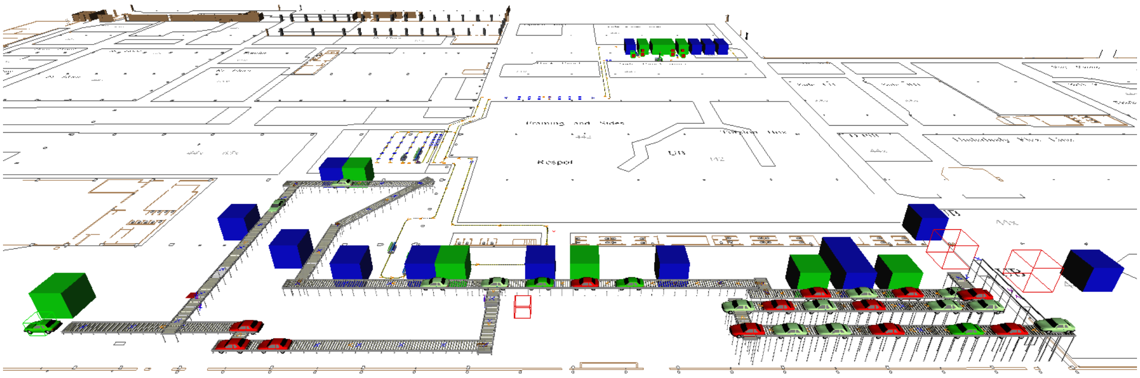

# AGV Transportation System for Internal Material Supply

## In collaboration with future production equipment using Discrete Event Simulation as decision support

Master's Thesis in the Master Degree Programme, Production Engineering

JOHAN BLIDSTEDT
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# Preface

This report is the result of a Master's Thesis in Production Engineering. The thesis is supervised by the Department of Product and Production Development at Chalmers University of Technology and performed at Saab Automobile AB situated in Trollhättan, Sweden.

We would like to thank all people who have contributed to this thesis. Especially our supervisor at Saab Automobile Tommy Christensen who have contributed with a lot of guidance and support throughout the process. The many discussions held with Tommy have not just led to increased knowledge about Saab's philosophy and their perspective of production, but also assisted in problem formulations and solutions.

We are also very thankful towards Anders Ode and Tommy Egelström at Saab Automobile who have provided a lot of important inputs.

Finally we wish to thank our supervisor at the Department of Product and Production Development, Tommy Fässberg for assisting in many different levels throughout the process of this thesis.

# Abstract

The introduction of a new car model in an existing production line results in a many complex challenges. Saab Automobile in Trollhättan, Sweden has realized that a new flexible Framing line is needed in their body shop in order to overcome these challenges.

This master thesis work aims to support the production engineering department at Saab with inputs in their work of implementing a new Framing line into their existing production line in the body shop. In addition, the thesis points to specify an internal AGV supply system to meet future demands. In order to fulfill these aims and to act as a decision making tool, a Discrete Even Simulation model has been created over both the future Framing line and the AGV system.

The methodology followed in the simulation part of the thesis is a customized version of Banks Methodology. In addition have methods based on Lean Production theories been used throughout the project.

The thesis has resulted in

- A validated simulation model.
- Volume and product flexible layout recommendation of the Framing line.
- Specifications of an internal AGV supply system, which is able to handle the demands at the Framing line.

*Keywords:* Discrete Even Simulation, Automated Guided Vehicle, Lean Production, Lean Automated Robotic Cell, LARC, Banks Methodology, AGV, Material supply

# Nomenclature

**AGV** - Automated Guided vehicle

**PLC** - Programmable Logic Controller

**DES** - Discrete Event Simulation

**AutoMod** - Discrete event simulation software

**WIP** - Work In Progress

**MTTF** - Mean Time To Failure

**MTTR** - Mean Time To Repair

**LARC** - Lean Automation Robotic Cell

**44x** - Old 9-3 car model

**54x** - New 9-3 car model

**65x** - 9-5 car model

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# Chapter 1

# Introduction

Saab Automobile AB, in this report referred to as Saab, is Sweden's second largest car producer. Saab is a small player in the highly competitive premium car segment, with worldwide representation in around 60 countries. After years of being a part of General Motors, Saab is once again an independent car brand. With the independence comes also new demands and obstacles which Saab needs to fast and effective overcome.

## 1.1 Background

To introduce a new car model into production leads to many complex challenges. Saab has realized that a part of their existing production line is not flexible enough to handle the future demands. The insight forces Saab to make major investments in order to strive against implementing more flexible and sustainable production equipment throughout their facilities. By striving towards a more flexible production, Saab hopes to gain position as an independent competitive car manufacturer.

One of Saab's first challenges as independent car manufacturer is the introduction of a new 9-3 car model. This model differs from previous models to the extent that it is not possible to use all the existing production equipment. An example of where the production equipment cannot handle an additional car model is the Framing line in the body shop. This means that it is necessary for Saab to invest in new equipment to handle this. Before ordering any new equipment Saab wants to be sure that not just the equipment is flexible enough to handle future models, but also compatible with the existing equipment.

Further, Saab has come to understand that the limited amount of space in the body shop requires a new system for internal supply in order to keep the size of the material facade limited. It has therefore been decided that a simple AGV system should be implemented in order to supply the new part of the line with smaller in-house sub-assembled parts. The implementation of the new AGV system is planned to be executed simultaneously as the new Framing line and should initially supply this new line.

## 1.2 Purpose

The purpose of this thesis is to investigate different layout proposals for the new Framing line to study how it collaborates with existing production equipment. The task of supplying the new Framing line with an internal AGV transportation system will be investigated simultaneously.

## 1.3 Aim and Objective

This master thesis work aims to support the production engineering department at Saab with inputs in their work of implementing new production equipment into their existing production line. In addition, the thesis points to specify an internal AGV transportation system to meet future demands of variance. The thesis should result in a decision basis for how to design the new production line and how an AGV system could be used to supply it with details. To fulfill the aims, a simulation model over both the new Framing line and AGV system will be created to act as a decision making tool.

- Design a discrete event simulation model including the new production line with a supplying AGV system.
- Evaluate layout and production parameters for the new part of the production line.
- Specifying a flexible internal AGV supply system for the new part of the production line.

## 1.4 Delimitations

To narrow the scope and prevent getting stuck in issues not important for the objectives, some delimitations have been made.

- Two different layout proposals associated with given characteristics, for the new Framing line will be analyzed.
- The study will cover future production scheduling.
- Forklift and conveyor transports will not be modeled.
- The outgoing flow will not be limited by production stops later on in the process.
- No non existing technical solutions for AGV systems will be developed.
- The possibility of an AGV being blocked by for instance a forklift is disregarded
- No consideration about economic consequences is taken between different layout proposals.
- The AGV system will be designed to meet the demand in a 20 - 15 car mix.
- Battery capacity and charging of the AGVs will not be included in the model

# Chapter 2

# Theory

Different concept and principles that are used throughout the thesis are described in this chapter. Most theories are gathered from scientific research regarding simulation model building and production efficiency. Some specific production concepts are also presented to increase the understanding of this thesis.

## 2.1 Flexibility at Saab

Flexibility is a wide concept and can be defined in numerous ways. In the production at Saab, flexibility mainly refers to production equipment ability to handle reconfigurations, future products, and volume fluctuations. Product flexibility is a factor that defines a system ability to handle product variants without major configuration. Volume flexibility can be defined as the production equipments ability to avoid bottle necks when increasing the volume while it refers to keeping high resource utilization when decreasing the volume. At Saab, flexible equipment is divided in the different categories depending on setup time, see Figure 2.1. (Christensen, 2011)

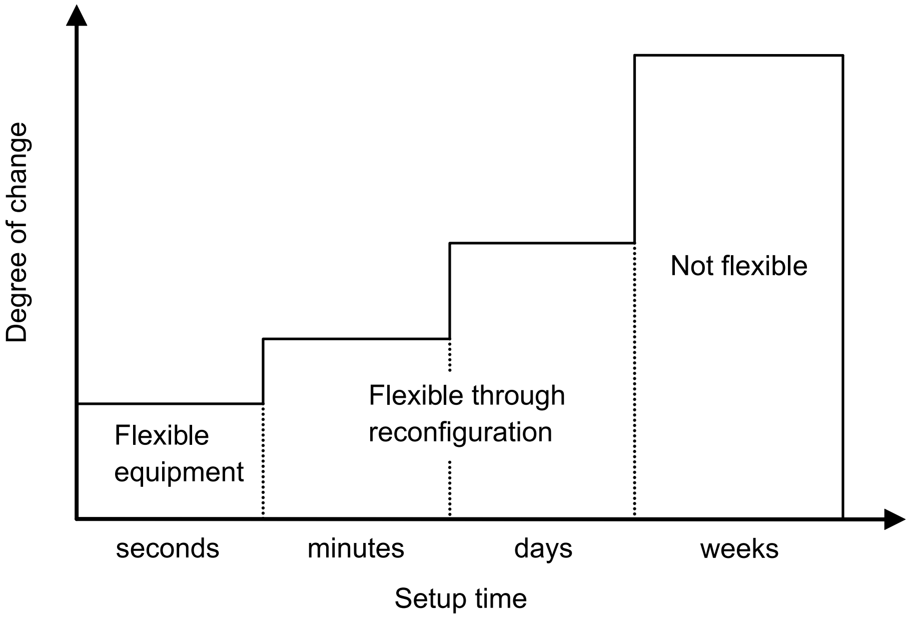
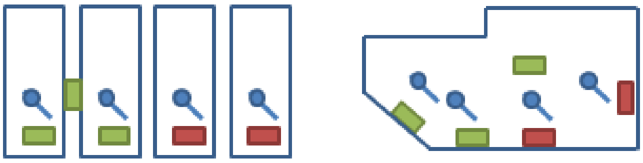


Figure 2.1: Flexible equipment categories at Saab

## 2.2 Lean Automated Robotic Cells

Lean Automated Robotic Cells are robot production cells, which are examples of production equipment in the “Flexible through reconfiguration” category as seen in Figure 2.1 (Christensen, 2011, Danielsson and Svensson, 2011). The following characteristics define LARCs

- The cell consists of standard components as far as possible.
- The cell can be reused in other applications, and is equipped with reconfigurable fixtures.
- Easy to move around entire cells due to the design.
- Possible to change takt time in an easy way, scalable production.
- The robot controls the entire cell. (for instance no overall controlling PLC is needed)



(a) LARCs (b) Typical robotic cell

Figure 2.2: Difference between LARCs and a typical robotic cell

As can be seen in Figure 2.2 (Christensen, 2011) the LARCs differ quite a lot from regular robotic cells. The main difference is that the LARCs are not mastered by any overall control unit, normally done by a PLC. This means that they all are run independently and does not take each other into consideration, and makes them a lot more flexible since it is possible to vary the number of LARCs when modifying capacity. Further, the task for a LARC can easily be changed by reprogramming the robot, and if necessary change the interior (Danielsson and Svensson, 2011). A great advantage with the LARCs is this independence that allows major changes without taking other robots, or an overall control system into consideration (Christensen, 2011). Replacing typical robotic cells with LARCs could lead to increased external transportation of material between the cells, due to the fact that the material need to be transported between the cells if processed in multiple steps. However, it is possible to transfer material directly between the LARCs, if the layout is well planned. The LARCs are not suited for producing large batches over long periods of time, since they are not optimized for one specific product. Further, the LARCs should preferably be balanced with teams, much like the teams used in final assembly lines.

## 2.3 Kanban Systems

Kanban is the Japanese word for “card” or “sign”, and is a scheduling system for determining when a specific detail should be started in production (Jonsson and Mattson, 2009). In its simplest form it consists of a card that is moved to the producing unit when it is time to start production. Kanban is in other words a trigger signal to start the production, which converts a pull system, into a push system (Liker, 2004). This eliminates scheduling and production planning when using a kanban system, it is sufficient with capacity planning (Jonsson and Mattson, 2009). Kanban systems are used to minimize the number of WIP by reassuring no overproduction, as no production is started before it is needed (Liker, 2004).

Kanbans can also be used to order movements or transports, called move kanbans (Jonsson and Mattson, 2009). Move kanbans can preferably be used as a bin-system where every kanban card is a bin, and when the producing unit gets an empty bin this trigger the production to start. To achieve an effective pull system the six requirements specified in Table 2.1 should be met (Wänström, 2010).

Table 2.1: Requirements for a successful pull system

| | |
|---|---|
| 1. | Short set up times |
| 2. | Flow oriented layout |
| 3. | Relatively high and smooth takt |
| 4. | Production smothering |
| 5. | Not to many product variants |
| 6. | Stable processes |

To get the most out of a kanban card system the number of kanbans should be minimized, because every card is indirect associated with a certain amount of WIP. To determine the number of kanbans needed equation 2.1 can be used (Wänström, 2010).

$$n = \frac{D \cdot L \cdot (1 + \alpha)}{a} \tag{2.1}$$

where

$n$ = $Number\,of\,kanban\,cards\,needed$
$D$ = $Demand\,per\,time\,unit$
$L$ = $Lead\,time$
$\alpha$ = $Safety\,factor$
$a$ = $Capacity,\,number\,of\,details\,per\,delivery$

The uncertainty in demand during lead time is illustrated by the safety factor. This factor could be set to one-fifth of a day's consumption or just be used as a safety constant. The safety factor should be kept to a minimum, because more kanbans leads to more WIP. For example is the goal at Toyota to keep the safety factor below 0.1 when designing kanban systems (Jonsson and Mattson, 2009). The calculated number of kanbans is then rounded up to nearest integer.

## 2.4 Kaizen

Kaizen is a Japanese word that can be translated as continuous improvements. The basic concept of kaizen is to continuously improve and update the process towards a more efficient way of doing it (Liker, 2004). The concept and philosophy of kaizen is that every member in the organization shall participate in the continuous improvement process and together work towards a better process and workplace (Liker and Hoseus, 2008). It is only possible to implement kaizen when the processes are stable and standardized, otherwise it is not possible to validate that an improvement is better than the current state (Liker, 2004).

## 2.5 Kaikaku

In Japanese kaikaku means radical change or breakthrough improvement. Kaikaku is not as well known as kaizen, but is considered as an extension of kaizen and whereas kaizen is to continuously improve bit by bit, kaikaku is a more radical approach of improving (Yamamoto, 2010). Kaikaku is generally used when kaizen is not considered to be sufficient (McAdam et al., 2000, Yamamoto, 2010). There could be a number of different reasons for using kaikaku, to mention a few:

- If the used processes are not right from the beginning, there is no idea to improve them.
- A breakthrough in a manufacturing technique. Because no matter how much you improve your process, you will never keep up with the alternative one.

## 2.6 Supermarket

A buffer or a storage area at the end of a production process can be called a supermarket (Rother and Shook, 2003). A supermarket can be used between two production processes where the supermarket consists of finished details from the supplying process. When a product is taken from the supermarket it triggers the production for a replacing product. This means that there is one kanban system controlling the customer process ("withdrawal" kanban) and another one the supplying ("production" kanban) (Rother and Shook, 2003). In Figure 2.3 the supermarket functionality is illustrated as an AGV system.

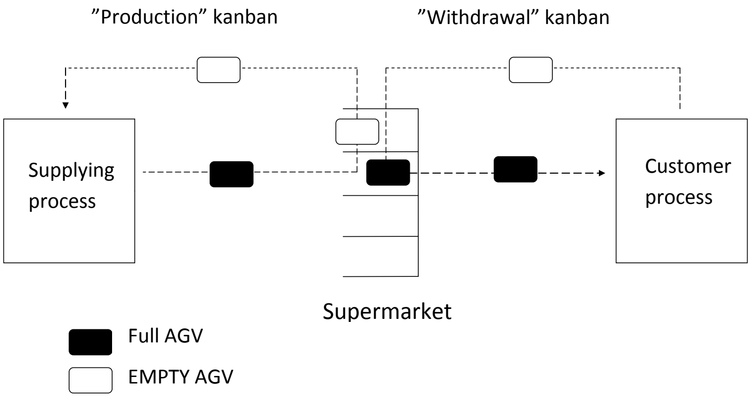


Figure 2.3: Supermarket concept

## 2.7 AGV Technologies

An Automated Guided Vehicle is a vehicle of some sort that operates without any operator. AGVs may have different type of work tasks, but primarily they are used in industry to transport goods and details. Most of the used AGVs are electrically powered with batteries and they can be used to transport anything from a few kilograms to several tons. The appearance of different AGVs varies depending on application. Some AGVs service the purpose of a forklift, whereas others are custom built for its intended application. (AGV-Electronics, 2011)

An AGV consist of two parts, the driving unit and the cart or fixture. With this in mind, two main controlling principles for AGV systems can be distinguished:

- **Custom Built AGV**

  All AGVs in the system are custom built for the intended purpose. That means all carts in the system has its own driving unit mounted on to it as well as a fixed fixture. The driving unit and cart can be seen as one since they are mounted to each other.

- **Tugger and Cart AGV**

  In difference from the custom built AGVs the tugger and cart are not mounted to each other using this technique. The tugger dock a cart and travel to a predetermined location where it lets go of the cart. That means the number of tuggers and carts are not necessarily the same in this type of system.

Several different alternative techniques to guide the AGVs are available on the market. The different techniques work in different ways and they are more or less suitable in different area of application. Five of the most commonly used techniques in industry today are presented below.

**Magnet Gyro Guidance:** A Magnet-Gyro Guidance system navigates with the help from small magnets that are put in the floor. A pair of magnets are typically placed within a distance of five to ten meters and installed in a drilled hole. A Gyroscope technology is used to keep the AGVs in the right direction between the magnets. (AGV-Electronics, 2011)

**Magnetic Guidance:** Operate in a similar way as the magnet gyro guidance system. The major difference is that the AGVs follow a continuous magnetic path instead of just placed magnets. The path may consist of a magnetic tape put directly on the floor, or of a machined down magnetic material in the floor. These two alternatives could with advantage be combined so where there is a lot of wear, the magnetic tape could be machined down and elsewhere taped on the floor to achieve a flexible system. (Trilogiq, 2011)

**Inductive Guidance:** A technology very similar to the magnetic guidance. But instead of machining down a permanent magnet tape, a wire is machined down that creates an electromagnetic field when a voltage is put through it that guides the AGVs. (AGV-Electronics, 2011)

**Optic Guidance:** Navigates by following a reflective tape put on the floor similar to the magnetic guidance, but without the possibility to machine down the tape (Helge-Nyberg, 2011).

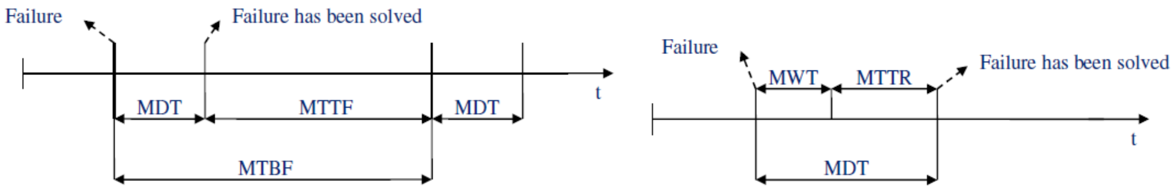
**Laser Guidance:** A laser guided AGV navigates using fixed points in the environment. The positions of the AGVs are determined by a laser scanner that is mounted on the AGVs. By measuring the distance and angle to each target it is possible to determine the AGVs exact position. A major difference from the other techniques is that it is not possible to foresee the exact path of the AGVs, since they do not follow a predetermined path exactly. (AGV-Electronics, 2011)

## 2.8 Breakdowns and Service Stops

Breakdown definitions and explanations can be seen in Table 2.2 and clarifying images in Figure 2.4 (Johansson, 2009a).

Table 2.2: Definitions of breakdowns and service stops

| | | |
|---|---|---|
| MTTF | - | Mean Time To Failure |
| MTBF | - | Mean Time Between Failure |
| MTTR | - | Mean Time To Repair |
| MWT | - | Mean Waiting Time |
| MDT | - | Mean Down Time |



(a) MTBF (b) MTTR

Figure 2.4: Breakdown defenitions

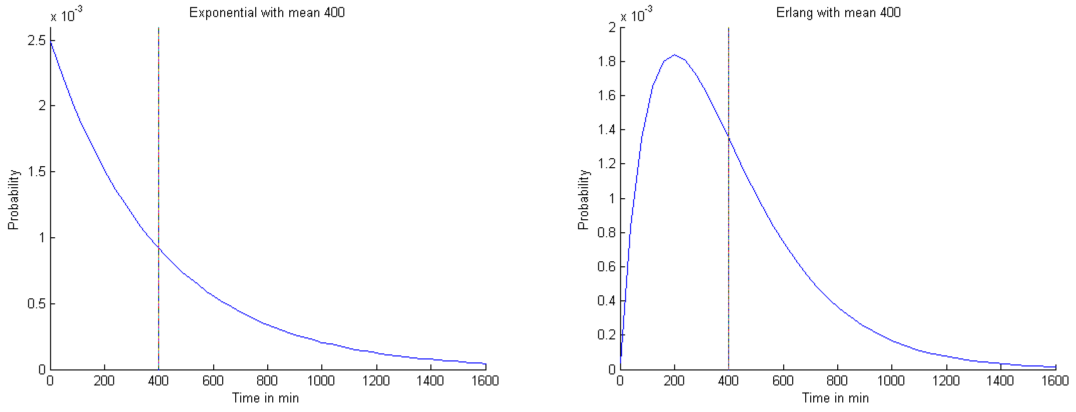
By studying Figure 2.4(b) it holds that MWT + MTTR = MDT. For simplicity MWT are included in the MTTR and it by that holds that MDT = MTTR. From here on the term MTTR is used for the entire repair time. The only definitions used from here on are therefore MTBF and MTTR.

A breakdown is stops that halts or hinder the production in an unforeseen way for example malfunction of a machine or similar. Whereas a service stop for instance caused by the refill of a barrel containing glue or joint sealer. This type of service stop can be foreseen since it is possible to calculate for how long a barrel of glue will last.

## 2.9 Probability Density Functions

A Probability density function is a function determining the likelihood for a value to be picked at a specific time. The interval from where it is picked is specified by the shape of a specific distribution. The probability density function is always non negative and the integral of its entire space is always equal to one (Råde and Westergren, 2004).

Two types of density functions, often used in simulation projects, are the Erlang and Exponential distributions. Both can be expressed as a probability density functions from which random variables are picked. These two among others can be a good estimate when illustrating for example MTBF and MTTR (Johansson, 2009a). A comparison between the functions can be seen in Figure 2.5.



(a) Exponential (b) Erlang

Figure 2.5: Comparison between Exponential and Erlang probability density functions

The main difference between the two distributions is that there are few short events in the Erlang distribution unlike the Exponential distribution. This makes the Erlang distribution more suitable when illustrating an automated station where very few stops happen directly after start up (Egelström, 2011). Further, in a manual station many stops often occurs after one another.

Both probability density functions can be generated from a mean value (Råde and Westergren, 2004). Equation 2.2 is describing the Exponential and Equation 2.3 the Erlang probability density function.

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x} & , x \geq 0 \\ 0 & , x \leq 0 \end{cases} \quad where\ Mean = \frac{1}{\lambda} \tag{2.2}$$

$$f(x;k,\mu) = \frac{\lambda^k x^{k-1} e^{-\lambda x}}{(k-1)!}\ for\ x,\lambda \geq 0 \quad where\ k = 2\ and\ Mean = \frac{k}{\lambda} \tag{2.3}$$

## 2.10 Discrete Event Simulation

Discrete Event Simulation is used to describe and analyze the behavior of a real-world system using a sequence of events. The sector of application for DES is massive and some suggestions where simulation comes in handy are presented by Adam et al. (Adams et al., 1999, Standridge and Marvel, 2006).

**Identifying problems in manufacturing or other processes**
- Possibility of identifying bottlenecks.

**Training operations personnel in the way the process operates**
- Train operators in how to preform a task, maybe even before the real equipment exists.
- Teach personal in how the process works to increase their knowledge of the process.

**Ranking various opportunities for process improvement**
- Evaluate different solutions to be sure of choosing the best alternative.

**Documenting the process**
- Document how the process operate, to gain better knowledge of your system.

**Predicting the impact of accepted improvements before implementation**
- Dealing with complex tasks where it is difficult to predict what will happen when one or several parameter is changed in your system, simulation can easily visualize this.

In order to perform a successful simulation it is recommended to follow a number of steps throughout the simulation project. A well proven work methodology for successful simulation project is Banks Methodology (Banks, 1998). A modified version of Banks Methodology can be seen in Chapter 3.

## 2.11 Elimination Matrix

To assist in decision making, an elimination matrix can be used. When having multiple concepts to choose from, the alternatives can be put into an elimination matrix to make comparison more obvious. An elimination matrix can be designed as suggested in Table 2.3. (Pahl and Beitz, 1995)

Table 2.3: Elimination Matrix

| | Concept 1 | Concept 2 | Concept 3 | Concept 4 |
|---|---|---|---|---|
| Compatibility assured | | | | |
| Fulfills demands of requirements list | | | | |
| Realizable in principle | | | | |
| Within permissible costs | | | | |
| Introduce favorable ergonomic conditions | | | | |
| Preferred by designer's company | | | | |
| Adequate information | | | | |
| Sum | | | | |

Different elimination criteria can then be used to classify the different concepts. A suggestion for of elimination criteria are presented below (Johannesson et al., 2004):

**(+)** Continue with the solution

**(-)** Eliminate solution

**(?)** Collect more information

**(!)** Control the specifications

# Chapter 3

# Method

In this chapter is the used methods described together with the overall methodology. Some of the most critical steps of the overall methodology are closer explained in order to declare the principles further.

Banks Methodology is a well proven and recognized method when performing simulation projects (Skoogh and Johansson, 2008). Banks method is used to control the overall structure of a project and can be used in the standard appearance or act as an inspiration when performing a simulation project. To fit the problems in the thesis, a customized version of this methodology have been developed, which can be seen in Figure 3.1.

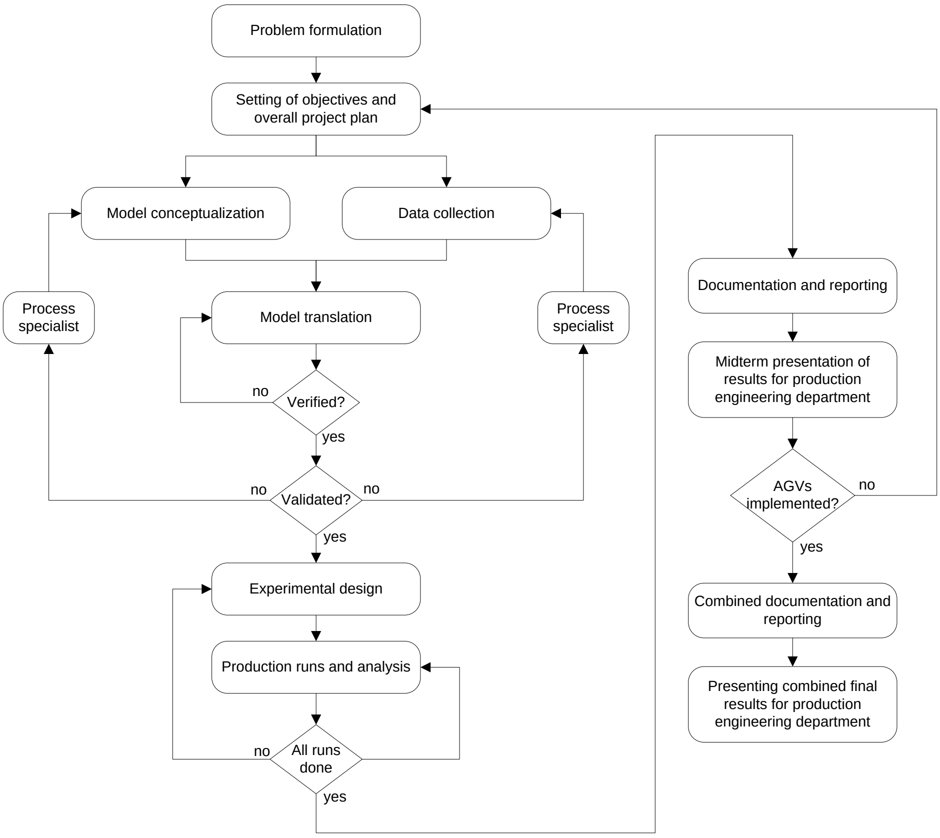


Figure 3.1: Customized Banks Methodology

As can be seen in Figure 3.1 the simulation model is built in two steps. Initially will the new Framing line be modeled, analyzed and documented and subsequently is the AGV system treated. This split is made due to the fact that the AGV system cannot improve the Framing line in any way and to be able to know the requirements on the AGV system, the capacity at Framing line must be known. In order to implement the customized Banks Methodology in a structured way, some critical steps in Figure 3.1 is further explained in this chapter.

## 3.1 Input Data Collection

The input data collection is one of the most time consuming tasks in a simulation study, up to 50% of the total time is usually spent on input data gathering (Robertson and Perera, 2002). It is also one of the most important tasks to get right. The challenge to overcome is to collect data of sufficient quality, quantity, and variety so that a simulation can be performed (Banks, 1998).

The data needed for a simulation can be categorized into three different groups depending on how hard the data is to obtain according to Table 3.1 (Robinson and Bhatia, 1995). Category A contains data that already is available, for instance data recorded in automatic logs. The second, category B contains data that is not available but can be collected. The data needs in other words to be collected during the study. The third, category C, contains data that neither is available nor can be collected. Input data in this category needs to be estimated in order to be able to preform the study (Robinson and Bhatia, 1995).

Table 3.1: Input data categorization

| |
|---|
| Cat A: available |
| Cat B: not available but collectable |
| Cat C: not available and not collectable |

Input data comes in many different variations and types. To achieve as correct illustration of the reality as possible, as many different sources on the same input data as possible should be used, to assure that the data is correct. Examples of data categorization can be seen in Figure 3.2.

Table 3.2: Input data types

| | |
|---|---|
| Cat A | Data Logs |
| | CAD-drawings |
| Cat B | Interviews |
| | Time Studies |
| | Contact with Suppliers |
| | Measurements |
| | Legislation |
| | Studying existing equipment |
| Cat C | Estimations |

Some specific input parameters to take into consideration when including AGVs in a simulation model can be seen in Table 3.3 (Banks, 1998).

Table 3.3: Important AGV input parameters

| |
|---|
| - Guide-path layout |
| - Control point location |
| - Horizontal and vertical speeds |
| - Acceleration and deceleration rates |
| - Load and unload times |
| - Vehicle blocking rules |
| - Empty vehicle management rules |
| - Battery charging rules |
| - Area counters and anti deadlock prevention |

## 3.2 Verification and Validation

Verification and validation of the model is essential when performing a discrete event simulation. For the model to gain sufficient credibility it must be shown that it is verified and validated. A model should be designed and developed for a specific purpose, otherwise it is not possible to use it on the intended problem. So it is of greatest importance that the model is verified and validated with respect to the sector of application. (Sargent, 2005)

- **Verification**: By verifying means to assure the correct behavior of each part in the model. Verification is about looking at smaller parts of the model, to see that they behaves correctly and that the model answers to different inputs in a desirable way, this is preferably done during and after the model building. All smaller parts should not just work as planned for themselves, they should also collaborate in a correct way. (Johansson, 2009b)
- **Validation**: Is performed to guarantee a correct behavior of the entire model. Validating a model implies to compare it to the real world system it represent, this could be done by comparing output data (Banks, 1998). Validation can with advantage be applied on subsystems during the model building process and on the entire model when the modeling phase is considered done. (Johansson, 2009b)

There exist many different techniques of how to verify and validate a model. Different methods can be more or less suitable depending on situation. The different verification and validation techniques can be classified according to Table 3.4 (Sargent, 2005).

Table 3.4: Classification of verification and validation techniques

| | Observable system | Non-Observable system |
|---|---|---|
| Subjective approach | • Comparison using graphical displays<br>• Explore model behavior | • Explore model behavior<br>• Comparison to other models |
| Objective Approach | • Comparison using statistical tests and procedures | • Comparison to other models using statistical tests |

Table 3.4 distinguish clearly between a subjective and objective approach. With an objective approach it means that the use of some mathematical procedure or statistical test is applied in the verification and validation evaluation. Whereas a subjective approach is more arbitrary, and could be to view the model visually to make sure the logic behaves as planned.

Different verification and validation techniques can also be categorized depending on the possibility to observe the model or not. If a model is observable it means that it is possible to obtain data that can be used in a for example comparison. Verification and validation of a model are in general more tricky when the created model does not exist in reality. There are for starters no existing data to be compared with simulated data, or any possibility to study the behavior of the model and compare it with the reality. (Sargent, 2005)

A model is said to be valid and approved for further analysis when the models accuracy is within acceptable range. The acceptable range is however depending on the models intended purpose and is not a fixed value. A typical variable to study is the output of the model that should match the reality (or planned reality) within a feasible region. (Sargent, 2005)

#### Visual examination

An easy but very useful validation method is to study the model visually when it is simulated to see if it behaves as desired. This should preferable be done by letting persons with great knowledge of the system look at it and ask them if the part of the model look realistic. A great drawback with this method is that it puts high requirements on the graphic appearance of the model. (Sargent, 2005, Johansson, 2009b)

#### Extreme mix validation

This technique tests the model in the most extreme cases. Different extreme inputs are used to investigate how the model behaves. This could be very useful when for examples many different types of product variants are simulated in the standard case. When letting one type of product into the model it gets a different characteristics than if several are used. As it often also is possible to calculate a theoretical maximum for example output when producing one type of product this could be a good indicator, when the calculated theoretical maximum are compared to the simulated value. This comparison can be done with and without for example any disturbances or breakdowns to see if the model behaves as it should. For instance it is natural to assume that the output will be reduced when breakdowns are included in the simulation. (Johansson, 2009b)

# Chapter 4

# The Model

In order to reach the objectives of this thesis, a simulation model has been created. Even though the creation of a simulation model is very time consuming it comes with many advantages. The model is used to analyze and illustrate the problems and solutions. The simulation model is created in the AutoMod software and the final model can be studied in Figure 4.1.

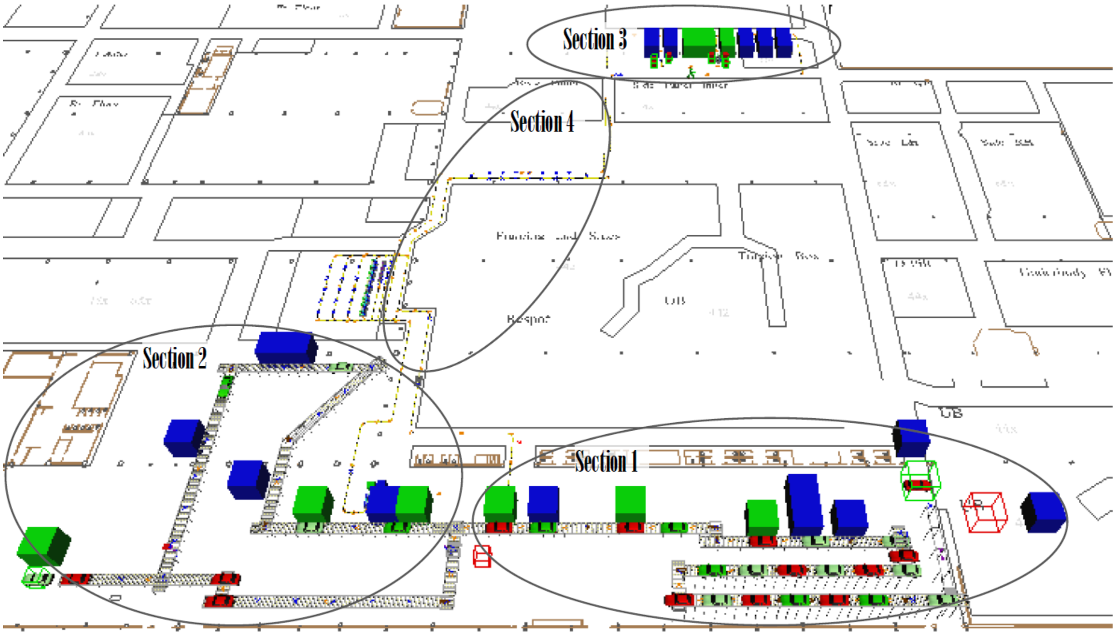


Figure 4.1: The simulation Model

A small part of Saab's body shop facilities in Trollhättan is represented in the simulation model. In the body shop, the car bodies are assembled before they are sent to the paint shop, which is the next step in the car building process. Pressed parts and sub-assemblies are mounted together in multiple steps resulting in a complete car body frame. The modeled part can be divided into four sections, seen in Figure 4.1, section 1 is an existing part of the line where the car sides of 65x models is mounted onto the undercarriage; section 2 is a future part of the line where the car sides of 54x models is mounted onto the undercarriage; section 3 consists of LARCs producing roof beams which are mounted on the undercarriage in section 2; section 4 is the AGV transport system, supplying section 2 with parts produced in section 3.

## 4.1 Model Description and Functionality

*The model have been created by studying layouts of existing equipment, future planned layouts provided by Saab and by studying existing equipment on location.*

The first part, section 1, seen in Figure 4.2, consists of existing production equipment and are the initiating part of the model. In this section the 54x and 65x undercarriages are let into the model and put into an inlet buffer which has room for 16 undercarriages. The inner parts of the car sides are attached to the 65x undercarriages in this section, often referred to as Framing inner (Framing outer for 65x is not included in the model). As can be seen in Table 4.1, mainly the 65x models are processed in this section and the 54x passes by all the stations except for the first, station 10 where all models are processed. The mix of models is also set in this section and the cars bodies must leave the last section in the same sequence as they arrive in this section.

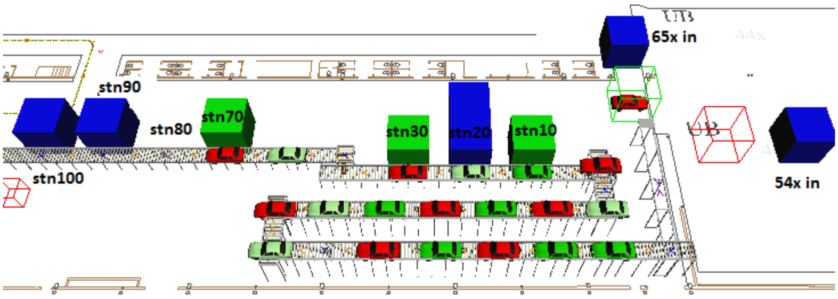


Figure 4.2: Section 1 - Inlet buffer and 65x Framing

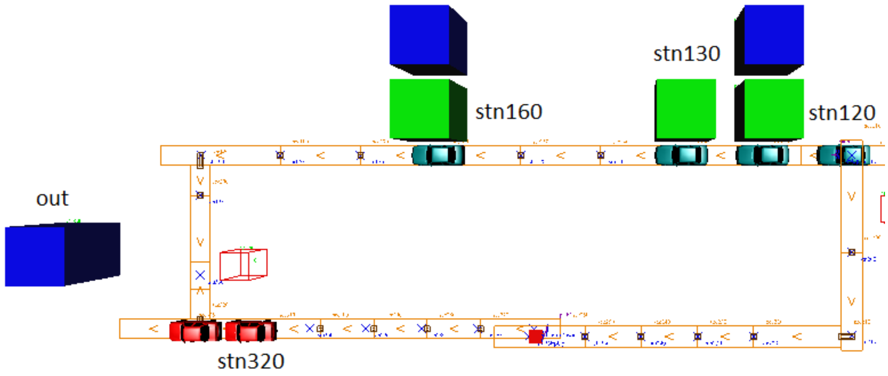
Table 4.1: Operation description for Section 1

| Station | Processed undercarriages | Type | Functionality |
|---|---|---|---|
| 10 | 54x and 65x | Automated | Stud welding |
| 20 | 65x | Automated | Spot welding |
| 30 | 65x | Manual | Place of beams |
| 70 | 65x | Automated | Spot welding |
| 90 | 65x | Automated | Spot welding |
| 100 | 65x | Automated | Spot welding |

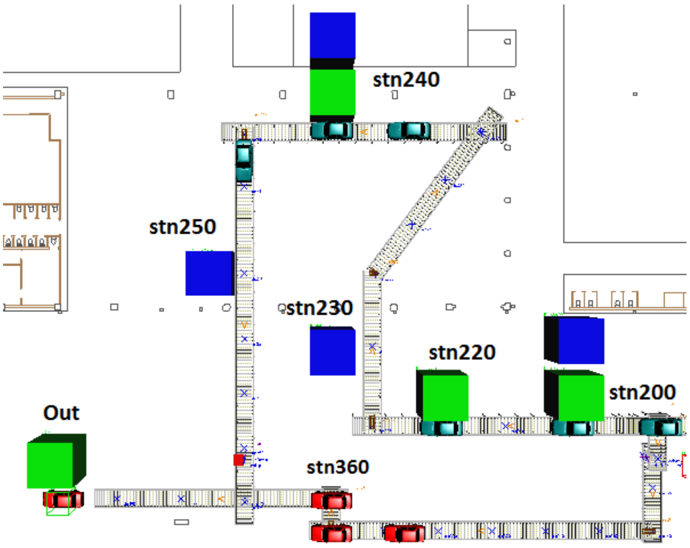
Unlike the first section, section 2, 3 and 4 does not exist in reality and are the ones being analyzed. Section 2 is currently used to manufacture the 44x model (old 9-3). This existing equipment will however be removed to allow room for the new Framing line. Section 3 is currently used as a storage place and Section 4 is a forklift path.

In section 2 are only the 54x undercarriages processed and the 65x car bodies just passes by. Furthermore is the layout not fully determined for this section and as one task of the thesis is to evaluate different layout proposals for the new 54x Framing line, two different models have been created to enable comparison between the two alternatives. The different layout proposals, called LP1 and LP2, can be studied in Figure 4.3. The processing in this section is also called Framing like in section 1, but unlike in section 1 both Framing inner and outer of 54x models are performed in this section. Specifications of the stations in this section can be seen in Table 4.2.

Regardless of which layout proposal that is used, the undercarriages are divided into two different flows in section 2. The 65x undercarriages travel on the bottom conveyor and goes through this part of the system without any processing. The 54x takes the top route and is processed in three or four stations depending on which scenario that is used. The major difference between the two proposals is that there are two buffer places between Framing inner and outer in LP1, while in LP2 there is room for six cars between the two Framing stations. Additionally in LP2, after Framing outer there is room for an extra station that could be used for tolerance measuring together with additional buffer space of five cars while in LP1 there is buffer space for four cars after Framing outer. Layout Proposal One (LP1) can be seen in Figure 4.3(a) and Layout Proposal Two (LP2) can be studied in Figure 4.3(b).



(a) Layout Proposal One



(b) Layout Proposal Two

Figure 4.3: Section 2 Framing 54x

Table 4.2: Operation description for Section 2

| **Station** | **Processed undercarriages** | **Type** | **Functionality** |
|---|---|---|---|
| 120 / 200 | 54x | Automated | Spot welding |
| 130 / 220 | 54x | Automated | Spot welding |
| 160 / 240 | 54x | Automated | Spot welding |
| 230 | Used when reduced takt time | Automated | Spot welding |
| 250 | Not in use | Automated | Measurement |

Section 3 is placed approximately 200 meters from section 2, and consists of the LARCs seen in Figure 4.4. Only LARC 4,5 and 6 are used in the model. These LARCs are used for manufacturing roof beams that are mounted on the 54x undercarriages in the 54x Framing line (station 120/200 in Section 2, see Figure 4.3). Three different beams, according to Table 4.3, are produced in section 3, also referred to as the LARCs. One operator is manning the LARCs supplying them with parts that are processed into sub-assemblies. However there are three additional pressed articles placed here for mutual transportation to the 54x Framing line. All six articles can be studied in Figure 4.5.

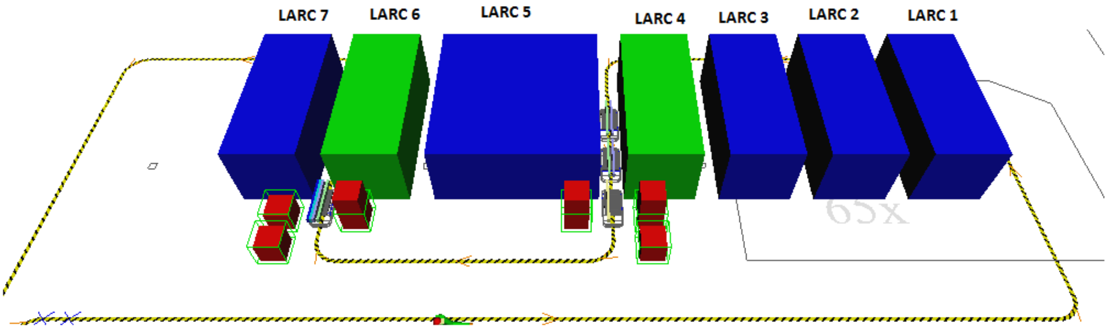


Figure 4.4: Section 3 - LARCs

Table 4.3: Operation description for Section 3

| **Part** | **LARC** |
|---|---|
| Roof Front Header | 4 |
| Roof Rear Header | 5 |
| Rear End Lower | 6 |

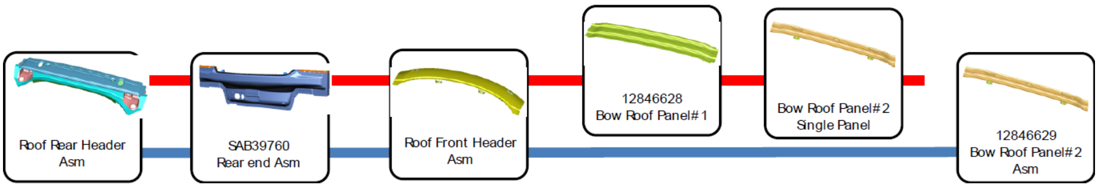


Figure 4.5: Parts loaded at the LARCs

To supply the 54x Framing line with the details seen in Figure 4.5 an AGV transportation system is designed, referred to as section 4. All six articles are loaded manually onto AGVs at the LARCS and transported mutually to the 54x Framing line. This means that every AGV holds all the necessary details for processing one undercarriage at the 54x Framing line.

At the 54x Framing line a robot picks the articles needed to process the current undercarriage. This means that not all the articles on board the AGVs will be picked every time. This is due to two different roof types processed in the 54x Framing line:

- Normal roof
- Sunroof

A normal roof requires the five articles illustrated by the top line Figure 4.5 and consequently a sunroof requires the four articles illustrated by the bottom line in Figure 4.5. As can be noticed in Figure 4.5 the first three articles are used in both alternatives. These three parts are the ones produced in the LARCs according to the schedule in Table 4.3.

The AGV system can be called *non controlled* or *dumb*, since the AGVs does not care about which articles that are picked from them and at all time one or two articles will travel back on the AGVs. This means that no overall control is used to control the AGVs and they shall always arrive at the 54x Framing line with parts able to supply material for both a sunroof and a normal roof. The operator manning the LARCs is also responsible for filling up the AGVs with the parts that have been picked by the robot at the 54x Framing line. It should be noticed that there exist a possibility of loading the articles in two layers, obtaining a batch size of two.

This principle regarding the functionality of the AGVs are developed, and approved in collaboration with the supplier of the LARCs as well as the supplier of the 54x Framing line and is therefore the only one investigated.

## 4.2 Input Data

Gathering input data for a simulation model is a time consuming and very essential activity in order to achieve a correct model. The necessary input data required, for section 1 and 2, can be seen in Table 4.4 and 4.5. The data have been categorized according to Table 3.1 and the different techniques for collecting the data is also presented, when possible multiple sources are used in order to ensure the accuracy of the data.

Table 4.4: Framing specific input data required

| **Variable** | **Category** | **Source** | **Comment** |
|---|---|---|---|
| Shifts | Cat B | Interviews | What shift type is planned for the future |
| Cycle times | Cat B | Interviews / Time studies | Time in stations (constant) |
| Transportation times | Cat B | Interviews / Time studies | Between stations (constant) |
| Rotation times | Cat B | Time studies | Rotation time in turntables (constant) |
| Breakdowns / service stops | Cat A, B and C | Data logs / Interviews / Estimations | Disturbances in the stations |
| Car mix | Cat B | Interviews | Plausible future demands |
| Sunroof mix | Cat B | Interviews | Plausible future demand |
| Layouts | Cat A and B | Interviews / Data files / Suppliers / Existing equipment | Some layout exists, some is planned, some not defined |

In Table 4.5 the AGV input specific parameters are presented. This was done according to Table 3.3.

Table 4.5: AGV specific input data required

| **Variable** | **Category** | **Source** | **Comment** |
|---|---|---|---|
| - Guide-path layout | Cat A and B | CAD-drawings / Interviews | Cannot travel in highly traffic forklift paths. |
| - Control point location | Cat A, B and C | CAD-drawings / Interviews / Measurements / Estimations | The stations are placed to allow for easy access for the operator. |
| - Horizontal and vertical speeds | Cat B | AGV-suppliers / Legislation | Speed <= 30 meter /min need less safety equipment. |
| - Acceleration and deceleration rates | - | - | Not included in the simulation model. |
| - Load and unload times | Cat A | Documentation | Manually loaded so same handling time as in regular handling. |
| - Vehicle blocking rules | - | - | A stupid system should never be able to be blocked. |
| - Empty vehicle management rules | - | - | Always travels back to specified loading stations (or delivery stations). |
| - Battery charging rules | - | - | Not included in the simulation model. |
| - Area counters and anti deadlock prevention | - | - | A stupid system should never be able to be blocked. |

Some general assumptions have been made to simplify the model. All transportation and rotation times are set to a measured mean values and set to constants, even though the time could vary little depending on equipment. The speed of the AGVs are also set to a constant throughout the path, even though it would be normal to assume a slightly slower speed in narrow curves. The possibility of an AGV being blocked by a forklift or any other material placed in the route is also rejected and not included in the model. Specified input data can be seen in Appendix A together with variable inputs.

Worth noticing is the different Car mixes put as an input to the model. These mix alternatives is based on historical data and is probable alternatives to be produced in the future. All mixes are based on what should be produced in relation to each other and in all cases more 54x than 65x are predicted to be produced. If we for example study Car Mix 2 which is called 20-15, that means for every 20 cars of type 54x produced, there will also be 15 cars of type 65x produced. Historical data indicate that the mix will stabilize somewhere between Car mix 2 and 3 when no new types have been introduced recently.

| | | |
|---|---|---|
| **1.** | **16 - 15** | Considered to be the highest proportion of 65x that could occur. |
| **2.** | **20 - 15** | A likely future scenario when a new type of 65x is introduced |
| **3.** | **20 - 11** | A plausible scenario when a new type of 54x is introduced. |
| **4.** | **4 - 1** | A potential scenario when the 54x model are introduced and the demand for 54x are very high |

Further is the speed of the AGVs limited to two fixed alternatives, 30 and 50 [meters/min]. This is based on two facts:

- AGVs traveling faster than 30 [meters/min] needs additional security equipment in form of a laser scanner mounted on top. This means that an AGV allowed to travel faster than 30 [meter/min] gets more sophisticated and costs more, which explains why AGVs traveling no faster is commonly used within this sector of application.

- A maximum speed of 50 [meters/min] is also an industry standard for this type of simple AGVs. This means that there are developed AGVs traveling at 50 [meter/min], which makes this alternative realizable in practice. For this type of application is AGVs traveling any faster not recommended by the manufacturer due to safety reasons and battery capacity.

## 4.3 Verification and Validation

To ensure that the model is correct, different verification and validating tests have been performed to ensure the model's credibility. According to the modified Banks model from Figure 3.1 the Framing line where first modeled, hence also first verified and validated. Both the the Framing line and AGV system were continuously verified throughout the modeling phase, further were the Framing modeled exposed to a statistical test and the AGV system compared to theoretical assumptions.

### 4.3.1 New Framing Line

The input data such as cycle times and travel times have been verified and validated by studying existing production equipment. Since there have been limited opportunities to verify the breakdowns and service stops, these have been considered to be correct. This assumption have been made based on the fact that the designed probability density functions used to illustrate the breakdowns and service stops, are developed and approved in close collaboration with Saab employees. All production equipment simulated in the model does not yet exist in reality, which complicates things more since there is little or no data to compare the simulated values with. In cases where no such data exists the simulated values have been approved after clearance from Saab employees that have studied the values as well as the behavior of the model. Table 3.4 have been used when deciding verification and validation technique. A subjective approach has been used on the entire model, as well as an objective where it has been possible.

### Visual Examination

Visual examination has been carried out throughout the model building process. All new parts of the Framing line has thoroughly been reviewed graphically as well as logically before approved and let in to the final model. The final Framing model has also been rigorously studied and analyzed. The model seems to behave as planned, and as Saab personal have been studying the model and simulation without noticing any major inaccuracies, hence the model is approved at this level.

### Extreme Mix Validation

This method is realized by simulating the model with only one type of undercarriage. The simulated output is then studied and compared with a calculated theoretical maximum output.

**Theoretical Calculations** The maximum theoretical outputs are calculated by studying the takt time specified for the system. The maximum takt time for 65x is found in station 30 and is set to 102 seconds. For 54x the maximum takt times are found in stations 200, 220 and 240 which all have a takt time of 162 seconds.

The theoretical maximum output is calculated by dividing 3600 (seconds in one hour) with the takt time, according to Equation 4.1 and can be seen in Table 4.6

$$\frac{3600}{102} = 35,2941 \tag{4.1}$$

Table 4.6: Theoretical maximum calculated values

| Model (max takt) | 65x (102s) | 54x (162s) |
|---|---|---|
| Theoretical maximum | 35,29 | 22,22 |

**Simulation Tests** The model is simulated with four different preconditions and the simulated output can be studied in Table 4.7. The average output per hour for the different scenarios are also calculated to make comparison possible. All simulations are run to illustrate one days production when two shift is used according to Appendix A. A full days production according to Appendix A is 17.12 hours, and when excluding the breaks the efficient production time becomes 15 hour.

Table 4.7: Simulated output for extreme mixes

| Simulated Output (per hour) | | **65x (17.12h)** | **65x (15h)** | **54x (17.12h)** | **54x (15h)** |
|---|---|---|---|---|---|
| 1. | No breakdowns,<br>No breaks | 34,99 | - | 22,02 | - |
| 2. | No breakdowns,<br>With breaks | 30,49 | 34,80 | 22,02 | 25,132 |
| 3. | With breakdowns,<br>No breaks | 31,42 | - | 19,76 | - |
| 4. | With breakdowns,<br>With breaks | 27,45 | 31,33 | 19,75 | 22,55 |

As can be seen in the first row in Table 4.7 the simulated outputs are very close to the theoretical maximum when no breakdowns or breaks are used in the simulation model. In the best case scenario this number would be equal to the theoretical maximum. However as can be seen in Figure 4.8, the simulated value is extremely close to it and lies just below the theoretical maximum. This is explained by the transport times being slightly overestimated to avoid promising to much. Furthermore since the simulated value differs <1% than the theoretical, it is fair to say that the model is acceptable accurate for its intended purpose.

Table 4.8: Percentage of theoretical maximum output

| **Simulated output (%)** | | **65x (17.12h)** | **65x (15h)** | **54x (17.12h)** | **54x (15h)** |
|---|---|---|---|---|---|
| 1. | No breakdowns,<br>No breaks | **99,13%** | - | *99,10%* | - |
| 2. | No breakdowns,<br>With breaks | 86,39% | **98,60%** | *99,10%* | 113,10% |
| 3. | With breakdowns,<br>No breaks | 89,02% | - | 88,92% | - |
| 4. | With breakdowns,<br>With breaks | 77,78% | 88,76% | 88,90% | 101,46% |

As can be seen in Table 4.8 the simulated output gets lower as disturbances are put onto the model, which is in line with what could be assumed. Studying the 65x model it can be seen that the output are almost the same in row 1 and 2, marked bold in table 4.8. This is also a good indicator of that the model behaves in a desirable way. These numbers should be fairly equal because the production of 65x stops when there is break due to a manual station (station 30).

When studying the behavior of the 54x model it can instead be noticed that the numbers are almost equal when including breaks or not, marked italic in 4.8. This behavior occurs due to the fact that the 54x model is only processed in automated stations, and is produced as normal during a break. This leads to the somewhat confusing figures that are presented in lines 2 and 4, where the simulated output is higher than the theoretical maximum. This is however a desirable behavior of the model because the production time are approximately two hours longer than calculated.

In the normal case when a mix of cars are used there is at most two or three 54x that pass through the manual station before the production stops during a break. So this type of behavior occurs only in this extreme situation when just producing the 54x model.

### 4.3.2 AGV

Since the AGV system in the model does not exist any statistical comparisons have not been possible. Instead have this part of the model been verified and validated by studying the behavior of the model and in addition a theoretical comparison has been performed.

#### Visual Examination

Similarly as the Framing were examined, the AGV system has also been reviewed graphically. The AGV system seems to act and behave as planned, and is approved at this level.

#### Theoretical Comparison

Since it proved suitable with a pull system (see section 6.2), the kanban formula from Equation 2.1 can be used for estimating the number of AGVs needed. The calculated number of kanbans can then be compared with what the simulations results show. This will indicate if the modeled AGV system behaves as anticipated by the theory. To be able to use the kanban formula seen in Equation 2.1 the data in Table 4.9 were collected.

Table 4.9: Kanban variables

$$\begin{array}{rclc}
D & = & 18 & [deliveries/hour] \\
L & = & 0,170667 & [hour] \\
\alpha & = & 0,1 & [no\,unit] \\
a & = & 1 & [unit\,load]
\end{array}$$

Where $D$ is the demand at the Framing, $\alpha$ the approximated safety factor and $a$ the unit load of the AGVs (when set to one, six details are on board, enough to process one undercarriage). The value for $L$ can be determined by measuring the path of the AGV system, and by taking the times for loading and unloading into account. The length of the AGV system was determined to 462 meters, and the loading time to 35 seconds (7 seconds per part, at most 5 parts are put on) and the unloading time used is 25 seconds.

With these values it is possible to calculate the time for how long time it will take for one AGV to travel one lap according to Equation 4.2. These values put into Equation 4.3, with the speed set to 50 [m/min] and the unit load to one shows that four kanbans should be sufficient.

$$\frac{\frac{462}{(50/60)} + 35 + 25}{3600} = 0,170667 \tag{4.2}$$

$$\frac{18 \cdot 0,170667 \cdot (1 + 0,1)}{1} = 3,3792 \approx 4 \tag{4.3}$$

The same approach are used for calculating the number of AGVs needed when the unit load is set to two and the speed is set to 30 meter/min. It should though be noticed that the loading and unloading time are doubled when the unit load is set to two. A comparison between the calculated number of AGVs and and the simulated values from Tables 6.1 and 6.3 (the output must be larger than 18) can be seen in Table 4.10.

Table 4.10: Comparison between calculated numbers of AGVs and simulated values

| | Calculated | Simulated |
|---|---|---|
| Speed 30 unit load 1 | 6 | 6 |
| Speed 50 unit load 1 | 4 | 4 |
| Speed 30 unit load 2 | 3 | 4 |
| Speed 50 unit load 2 | 2 | 3 |

As can be seen in the table the calculated values corresponds quite well with the simulated. Worth noticing are that the calculated value are slightly smaller when the unit load is two. Since the calculated values are dynamic and do not take any unforeseen actions into consideration, these lower theoretical values are acceptable. The safety factor, which is set to 0.1 (which is the goal at Toyota) might also be a little low in this case. If for instance the safety factor is set to 0.2 all the values will match exactly.

# Chapter 5

# Framing - Execution and Results

According to the methodology used, the experimentation has been divided in two parts. In this chapter is the new Framing line analyzed and in Chapter 6 is the AGV system designed to be able to handle the characteristics of the entire system. Due to the fact that the AGV system cannot improve the Framing line in any way, it will only affect the Framing line in a limiting way. So knowing the Framing lines characteristics makes it possible to design an AGV system fulfilling the Framing requirements.

The main goal of the Framing analysis is to determine which layout proposal that are most suitable with respect to total output per hour. In addition the number of WIP will be studied and as well as the flow of the systems for the different layout proposals. The analysis of the Framing line was realized using three different experiments. These experiments are explained below

1. **The base design** - This experiment illustrates how the Framing line was planned from the beginning in two difference appearances. The both layout proposals differences can be seen in this experiment, as well as how the mix will affect the system.
2. **Material disturbances** - The influence of material disturbances will be investigated in this experiment. This means that the MTTF will be varied in stations 20, 120 and 160 for Layout Proposal One, and stations 20, 200 and 240 for Layout Proposal Two (those are the only stations that receives working material). To see any effect the MTTF will be decreased by 50% (that means a stop will occur twice as often). The MTTF will also be increased by 50% as well as 100% to see if it converges. Both layout proposals will be illustrated and the mix of cars will be constant 20-11 in this experiment to keep the number of combinations to a minimum.
3. **Reduced cycle time in Framing 54x** - Due to the high takt time in the Framing 54x it is likely that this will be the bottleneck of the system. This experiment investigates the effects of improving the takt time in the 54x Framing line. For Layout Proposal One this means a reduced cycle time in station 120, 130 and 160. For Layout Proposal Two it means a reduced cycle time in station 200, 220 and 240. To make this scenario more realistic an additional station has been added, as it most likely would have been in reality if this improvement were implemented. The additional station is also a spot welding station and will therefore have the same properties as such a station in the aspect of MTBF and MTTR. The mix will also vary in this experiment

It is possible to study a lot of different parameters in these experiments. In collaboration with Saab it was decided to study four parameters described below, in order to capture the dynamics of the system.

**Total output per efficient hour:** The total output per production hour is an output used by Saab to illustrate how many cars that are produced per hour. In a two-shift day the production is manned for 17.2 hours, with the breaks taken into consideration this results in 15 production hours. As a comparison to the presented numbers, the modeled system has a planned output of 31 jobs per producing hour. This figure is valid for the mix 20-15 and for the other mixes slightly lower.

**Average number of Work in Progress in the entire model:** The number WIP is used to describe how many unfinished cars that are waiting or being processed at the same time. The optimal would be to minimize this figure even if is it not the main goal of the analysis.

**Average time in station 80:** Average time in station 80 is used to describe the flow of the system before the car models are separated into different lines. The point where the undercarriages are separated is an area where problems might occur when varying the cycle time of upcoming lines and when varying the mix. The location of station 80 can be seen in Figure 4.2.

**Average time in station 320 or 360 depending on layout proposal**: Average time in station 320 or 360 shows for how long time a 65x car body needs to wait for the 54x car bodies in order to leave the Framing in the same sequence as they entered. The location of station 320 and 360 can be seen in Figure 4.3.

The results from the simulations in this chapter are mean values based on 100 runs. Confidence intervals of 95% are in addition presented as a small line on each bar in the figures.

## 5.1 Experiment 1 - Base Design

In the first experiment are the two layout proposals studied in order to investigate what impact the different mix have. How the different inputs are handled in this experiment is described in Table 5.1.

Table 5.1: Input data Experiment 1

(a) Varied inputs

| Type | Unit |
|---|---|
| Car mix | (16-15) / (20-15) / (20-11) / (4-1) |
| Layout Proposals | LP1 / LP2 |

(b) Constant inputs

| Type | Unit |
|---|---|
| MTBF | 100% |
| 54x cycle time | 162 s |

The average output per production hour is presented in Figure 5.1. The graph shows that the average output per production hour will decrease as the mix of 54x increases. The total output is relatively similar for the first two mixes, then reduces slightly with the 20-11 mix and reduces even more for the 4-1 mix. The difference between the two layout proposals are quite small but layout proposal two handles a higher mix of 54x better than layout proposal one.

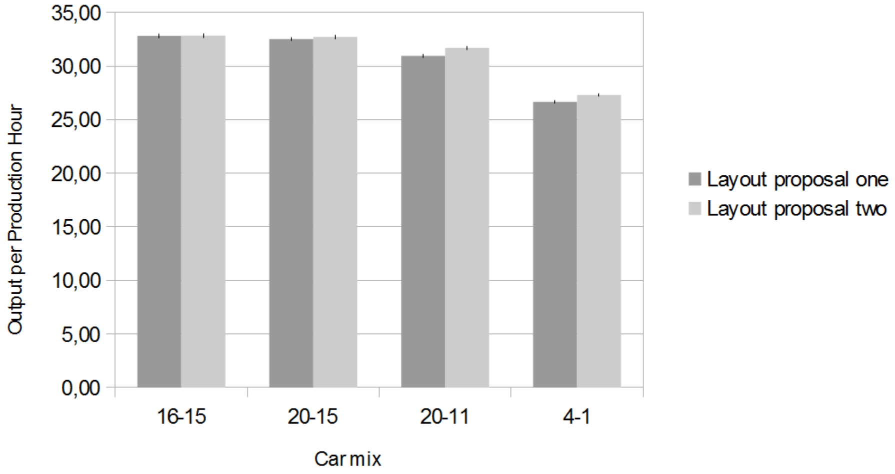


Figure 5.1: Output per production hour, comparison between the two layout proposals.

The average WIP is showed in Figure 5.2. The graph shows that a higher mix of 54x increases the WIP. The WIP is also slightly higher in LP2 due to more buffer places in the layout.

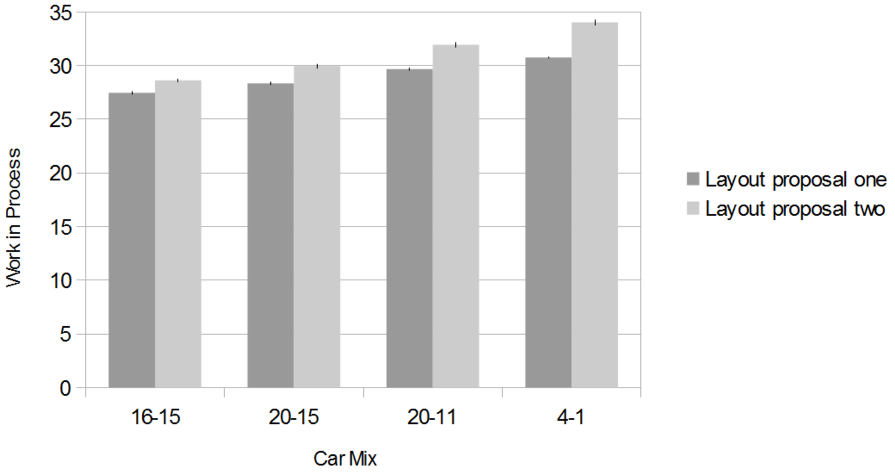


Figure 5.2: Average WIP, comparison between the two layout proposals.

The average wait time in stations is a measurement of how smooth the flow through the system is. Less waiting time means a better flow. The analysis of average wait times in station 80 and station 320/360 are presented (in seconds) in Table 5.2. Station 320 refers to the last station in the passby route of LP1 while station 360 is the corresponding station in LP2.

Table 5.2: Average wait times in seconds for stations

| Car mix | LP1, stn 80 | LP2, stn 80 | LP1, stn 320 | LP2, stn 360 |
|---|---|---|---|---|
| **16-15** | 72 | 67 | 218 | 214 |
| **20-15** | 82 | 75 | 253 | 251 |
| **20-11** | 106 | 100 | 335 | 330 |
| **4-1** | 140 | 135 | 576 | 684 |

As shown in Table 5.2, a smoother flow is acquired in LP2 with one exception for the extreme mix of 4-1 where the wait time in station 360 is considerably longer then the corresponding wait time in station 320.

**Analysis**

The first experiment was done to act as a reference for upcoming analysis when varying inputs of the model. The result from this analysis shows that LP1 is a more "Lean" layout, with less buffers in between the stations. The investments costs is also lower for LP1 compared to LP2, due to the fact that less conveyors is needed in the the compact layout. The advantages of LP2 are the higher capacity and the placement is better prepared for future development of the line.

## 5.2 Experiment 2 - Material Disturbances

In the second experiment the impact of material disturbances are studied. How inputs are handled in this experiment is described in Table 5.3.

Table 5.3: Input data Experiment 2

(a) Varies

| **Type** | **Unit** |
|---|---|
| MTBF | 50% / 100% / 150% / 200% |
| Layout Proposals | LP1 / LP2 |

(b) Constant

| **Type** | **Unit** |
|---|---|
| Car mix | (21 - 11) |
| Cycle times | 162 s |

The most notable in Figure 5.3 is that the output seems to flatten out when the MTBF is extended. The difference in total output between the base design and the 50 percent increase are small, and between the 50 and 100 percent improvement is it not possible to draw any conclusion of the changes in total output. The difference between the two layout proposals follows each other.

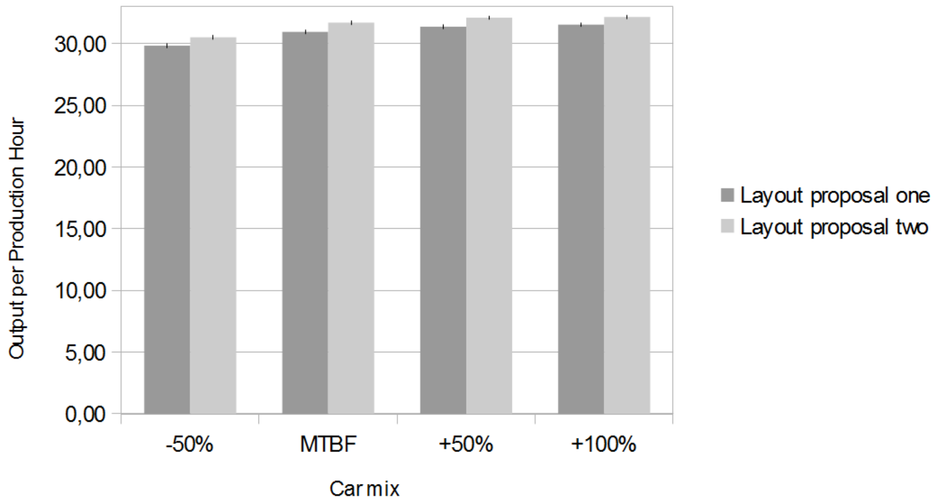


Figure 5.3: Output per production hour, varying material supply disturbances of car sides.

The WIP is almost constant when the MTBF is changed. It is reasonable to believe that the average WIP will be affected when varying the MTBF for the material distribution. But the fact that both the 65x Framing and 54x Framing lines are affected by the change in MTBF could explain why the average WIP does not vary that much.

When analyzing the flow of the system it shows that the average wait times increases considerably when the MTBF is decreased by half. While increasing the MTBF does not improve the flow of the system in the corresponding extent.

**Analysis**

The second experiment was performed in order to evaluate how the two layout proposals handled material disturbances. Both the layout proposals were influenced by the disturbances, and in the same way was the output and the flow of the system studied. Relatively large investments are needed in order lower the disturbances and there are only minor improvements to gain. On the other hand if the disturbances increase, this will result in significant negative effects in the system.

## 5.3 Experiment 3 - Reduced Cycle Time in Framing 54x

In the third experiment is the impact of reduced cycle time in the 54x Framing line studied. How inputs are handled in this experiment is described in Table 5.4.

Table 5.4: Input data Experiment 3

(a) Varies

| Type | Unit |
|---|---|
| Takt time | 162s / 130s |
| Layout Proposals | LP1 / LP2 |
| Car mix | (16-15) / (20-15) / (20-11) / (4-1) |

(b) Constant

| Type | Unit |
|---|---|
| MTBF | 100% |

The average output per production hour is shown in Figure 5.4. The results of the simulation shows that the decreased cycle time have large impact on a higher mix of 54x, while with a more balanced mix the increase is just marginal. The decreased cycle time have almost the same effect on both layout proposals.

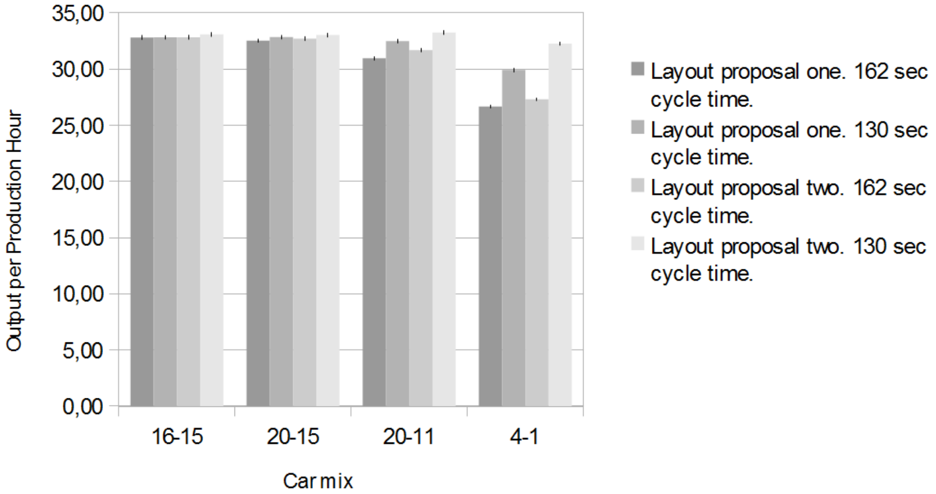


Figure 5.4: Total output, comparison between LP1 and LP2 with normal and decreased cycle time.

When studying the WIP, the clear trend is that the reduced cycle time also reduces the WIP with the largest effect on the 20-15 mix. The decreased cycle time have almost the same effect on both layout proposals.

The reduced cycle time has also a positive effect on the flow in both layout proposals. Here the effect tends to be greater when the mix of 54x increases.

### Analysis

In the third experiment the cycle time was lowered in the stations for the 54x Framing line. This was done in order to see the impact when investing in production equipment with higher capacity. The analysis showed a significant increase in output for higher mixes of 54x cars; the WIP was lowered; and the reduced cycle time also had a positive effect on the flow of the system. On the other hand, in order to increase the capacity relative large investments is needed. Further, there is no use in investing a in a higher capacity in the 54x Framing line without taking surrounding production equipment into consideration. The advantages of a shorter takt time in 54x Framing are only beneficial for shorter periods of time, since supplying and subsequent production equipment cannot handle such high takt time over time.

# Chapter 6

# AGV - Execution and Results

The purpose of the AGV analysis is to specify a functional internal transportation system without limiting the Framing line. The AGV supply system was analyzed using two different experiments, described below.

1. **Fixed drive on each AGV -** In this experiment, all AGVs have a fixed drive unit. The AGVs are running on one fixed route between the LARCs and the Framing station.
2. **Tugger AGVs using a supermarket buffer -** In this experiment, parts are transported on carts that are being tugged by AGVs. The tuggers run in two different routes, one for loading the carts and one for unloading the carts at the Framing line. The common supermarket for the two routes works as a buffer of full and empty carts.

Two different outputs have been studied when analyzing the AGV system.

**Total output per production hour:** The output must be the same as before the AGVs where introduced. If the total output is lower, the AGV system is limiting the whole Framing line. The results from the Framing analysis shows that the AGV system must manage an average of 18 jobs per production hour when producing according to 20-15 mix. Since there are disturbances in the LARCs it is decided that the entire system must provide an output of 18 54x models per efficient production hour, when the AGV system delivers material. If the output is lower than this the solution is rejected. In this analysis the average 54x output per efficient production hour is studied since this is the only relevant output in this case.

**Utilization of the unloading station buffer:** There is room for one batch of articles in the unloading station buffer. A new batch of articles can be handled by the unloading robot as soon as the processing in the Framing station starts. The utilization of this buffer is used as an indicator of robustness. To be sure that there always is at least one AGV ready to unload at all time this value should be close to one, but since there is a lot of variation in the model this is hard to achieve without over-dimension the AGV system.

According to the modified Banks (Figure 3.1) the Framing analysis have already been made at this stage. This allows for a simplified AGV analysis, where some conclusions drawn in Chapter 5 about the Framing line is applied. By this work methodology no irrelevant analysis are performed at this stage, and some variables are therefore set to constants in both AGV experiments, as can be seen in Table 6.1. The car mix 20 - 15 is used throughout the AGV analysis due to the fact that it is a likely mix when no new car model is introduced recently, and as it represents relatively high total output as can be seen in Chapter 5.

Table 6.1: Constant inputs in the AGV analysis

| **Type** | **Unit** |
|---|---|
| Layout proposal | LP2 |
| 54x cycle time | 162 sec |
| Car Mix | 20 - 15 |
| Sun roof | 50% |
| Material disturbance (MTBF) | 100% |

Some additional tests will also be made on interesting solutions to illustrate how the designed systems handles different situations. These tests could also provide important characteristic information about the designed systems. The variables used for these tests can be found in Table 6.2.

Table 6.2: Performance test variables for the AGV system

| **Type** | **Variable** |
|---|---|
| Car mix | 4 - 1 |
| Sun roof varied between | 30 - 70% |
| LARC operator take break | NO |

## 6.1 Elimination Matrix

A simple Elimination Matrix analysis has been implemented to study the possibilities of excluding some guiding technologies. This is done to be able to take specific guiding technology properties into account when designing the AGV transportation simulation model. The elimination matrix can be studied in Table 6.3 and the different guiding techniques are presented in Chapter 2. Even though there exists more guiding technologies than presented here, these are considered to be the most feasible for this application.

Table 6.3: Elimination Matrix of AGV Technology

| | Magnetic Gyro Guidance | Magnetic Guidance | Inductive Guidance | Optic Guidance | Laser Guidance |
|---|---|---|---|---|---|
| Compatibility assured | + | + | + | + | ? |
| Fulfills demands of requirements list | + | + | + | + | + |
| Realizable in principle | + | + | + | - | + |
| Within permissible costs | + | + | + | | - |
| Introduce favorable ergonomic conditions | + | + | + | | |
| Preferred by designer's company | - | + | - | | |
| Adequate information | | + | | | |
| Result | - | + | - | - | - |

As can be seen in Table 6.3 all guiding techniques are rejected but the Magnetic Guidance alternative. A Laser Guided System would mean a higher investment cost, due to higher complexity and both the Magnetic Gyro and Inductive Guidance are rejected because of the fact that a small change in the route will demand processing with machines in the floor. Optical Guidance has proven to work satisfactory in clean environments, this is not the case in a body shop and this alternative is therefore rejected. The Magnetic Guidance route is though simple to change with a piece of magnetic tape. And since the magnetic tape also can be milled down to the floor to achieve the same properties as the Magnetic Gyro and Inductive Guidance, this is considered to be the best alternative.

Consequently is the model designed with this in mind, which enables for some simplifications in the model. Since the route of the AGVs using the Magnetic Guidance technology easily can be altered without major rework at late stage in the process, the focus of the model is not to determine a definite path. Instead the focus is put on the functionality of the entire AGV system.

## 6.2 Pull Concept

By studying the requirements for a successful pull system in table 2.1 is it possible to assume that a pull system could be suitable in this situation. Consequently as can be seen in Table 6.4, this is a correct assumption.

Table 6.4: Are the requirements for a successful pull system fulfilled?

| | **Requirement** | **Comment** |
|---|---|---|
| 1. | Short set up times | Yes, no set up times |
| 2. | Flow oriented layout | Yes, LARCs placed in a straight line |
| 3. | Relatively high and smooth takt | Yes, the LARCs have the same takt time |
| 4. | Production smothering | Yes, dedicated production cells |
| 5. | Not to many product variants | Yes, only two |
| 6. | Stable processes | Yes |

This indicates that a pull system would probably work satisfactorily for the AGV transportation system. The AGVs can thus adopt the functionality of a kanban card in the system. In other words when an AGV arrives at the loading station it triggers production of new details. This helps keeping the amount of WIP to a minimum in the system, because no parts are produced in the LARCs if no AGVs are in place. This is however not fully true in this case because it is always allowed for the LARCs to produce one detail, even if no AGV are in place. It should also be noticed that there is a possibility of placing a buffer in front of the LARCs. The buffer is located there to cope with some fluctuations in the demand, and used as a safety buffer when there are problems with the LARCs. The buffer sizes should though be kept to a minimum, and there is no possibility of producing mode details in the LARCs than there is room for in the buffers.

## 6.3 Experiment 1 - Fixed Drive on Each AGV

The input data used in the first experiment is shown in Table 6.5.

Table 6.5: AGV - Input data Experiment 1

(a) Varied inputs

| **Type** | **Unit** |
|---|---|
| Number of AGVs | 2 - 12 |
| Speed of AGVs [m/min] | 30 - 50 |
| Buffer in front of LARCs | 1 - 5 |
| Unit Load on AGVs | 1 - 2 |

(b) Constant inputs

| **Type** | **Unit** |
|---|---|
| Car mix | 20 - 15 |
| Sunroof mix | 50% |
| LARC operator take break | Yes |

To investigate what effect the speed, of the AGVs, has on the system, the speed have been plotted against a varying number of AGVs as can be seen in Figure 6.1. In this experiment, the buffer size in front of the LARCs and the unit load is set to one. The speed is varied between 30 and 50 [m/min] and the number of AGVs from 2 to 12. With increased speed, the system converges towards the maximum output using fewer AGVs, than when the speed is set to 30 [m/min].

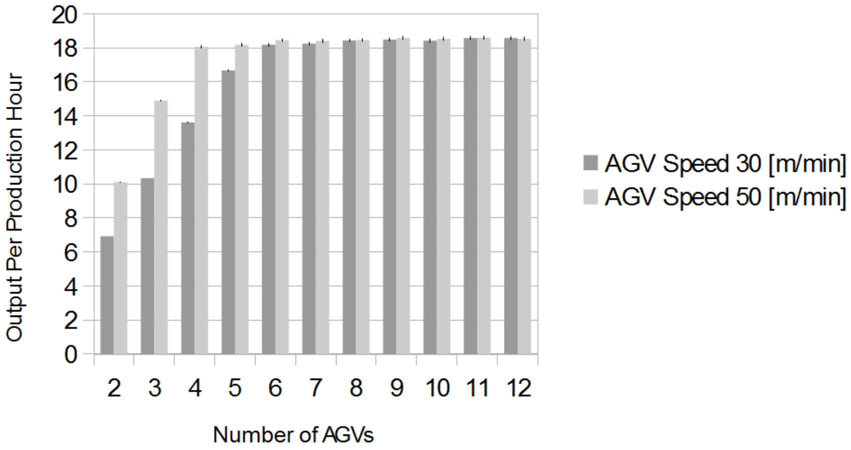


Figure 6.1: Output when varying the speed

Due to the result of the speed analysis is 50 [m/min] used as the constant speed in future AGV analysis.

In order to investigate the effects of a buffer in front of the LARCs, the size of the buffers have been varied between 1 and 5. In Figure 6.2 a buffer size of 3 is plotted against the base scenario of 1. The figure shows the utilization of the buffer placed in front of the Framing station when varying the number of AGVs. An increased buffer size by the LARCs leads to a higher utilization at the framing buffer, which means that the system can handle fluctuations in the production better.

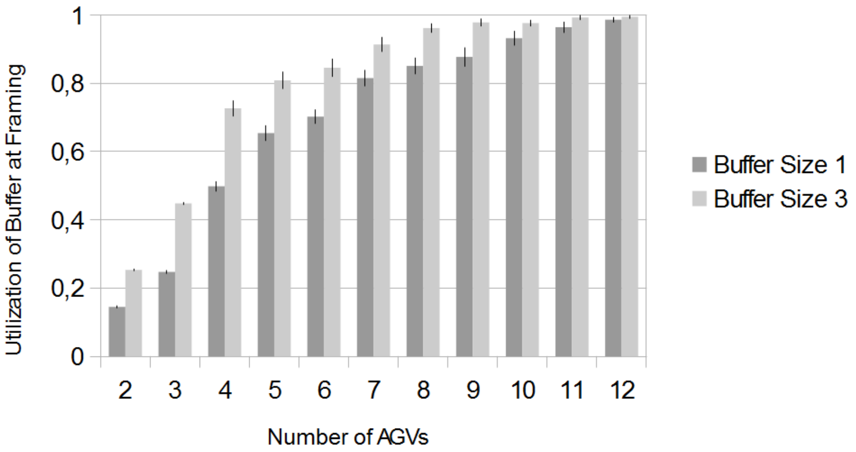


Figure 6.2: Utilization of buffer in Framing

Due to the result of the buffer analysis is a buffer size three used in future AGV analysis.

The effects of an increased unit load of the AGVs is illustrated in Figure 6.3. The graph shows that if the number of AGVs exceeds four, a double unit load has little or no effect.

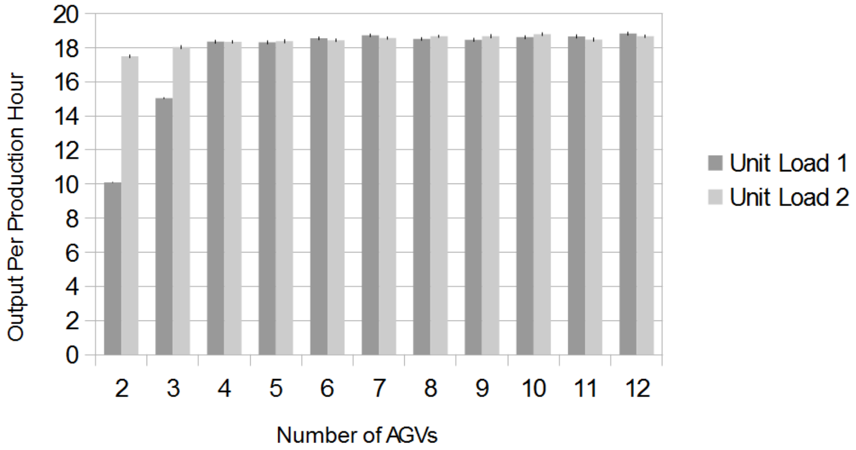


Figure 6.3: Output per production hour varying the unit load per AGV

Due to the result of the unit load analysis is a unit load of one used in future AGV analysis.

A final performance test is done on the extreme mix 4-1. Producing according to the 4-1 mix leads to a higher demand of the 54x output per production hour. Therefor is also an analysis when the LARCs are continuously manned illustrated as well in Figure 6.4.

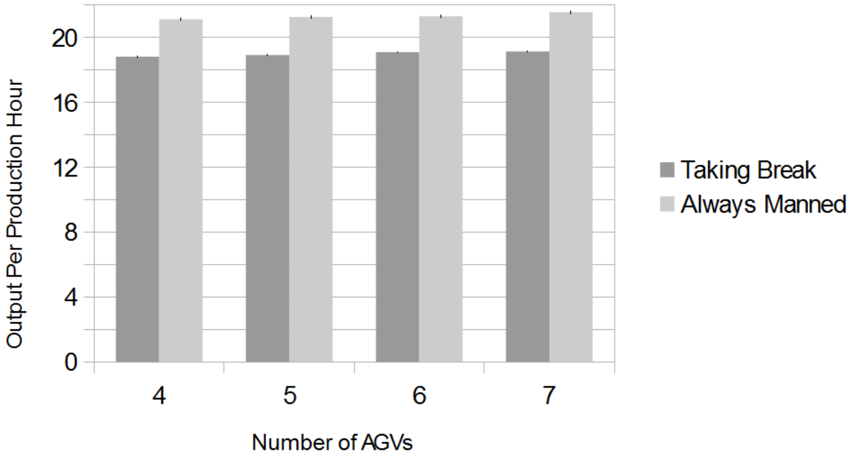


Figure 6.4: Performance test of experience one

**Analysis**

The experiments, on the AGV system, started with analyzing the effects of different speeds. An increased speed resulted in less AGVs needed in order to meet the demands at the Framing line. The increased speed of 50 [m/min] will require higher demands of the safety system on board the AGV. This is not a major investment and it has big advantages when it comes to safety of the operators. A higher speed will also results in less irritation among the forklift operators who is trafficking the same passage.

In order to better handle disturbances in the LARCs, an analysis determining the effect of a buffer between the LARCs and the AGV has been performed. The buffer result in less effect on the Framing line when a LARC break down. The buffer also gives the operators a freer work situation with the ability to build up a small buffer when the work situation allows this. On the other hand a buffer is waste and should be minimized.

A test with double unit load was performed to determine the effect on the AGV system. The advantage with a double unit load is that the number of AGV could be reduced from 5 to 4. On the other hand it would require more advanced programming of the picking robot at the Framing line as well as a more advanced fixture on the AGV carts.

Finally was a performance test done in order to evaluate how the AGV system handled a mix with tougher output demands. The test was realized with and without the LARCs manned continuously in order to see if the output demands could be met. This indicated that it is possible, when producing a high mix of 54x, to meet output demands by manning the LARCs during breaks.

The mix of different roof types have shown to have little effect on the system. Since the roof specific beams are not produced in the LARCs, they have been modeled as always available at the loading of the AGVs. The only difference between a normal roof and a sun roof is the operator loading time of seven seconds.

## 6.4 Experiment 2 - Tugger AGVs Using a Supermarket Buffer

In the second experiment the most beneficial speed and buffer size determined in the previous experiment are used. The input data used in this experiment can be seen in Table 6.6.

Table 6.6: AGV - Input data Experiment 2

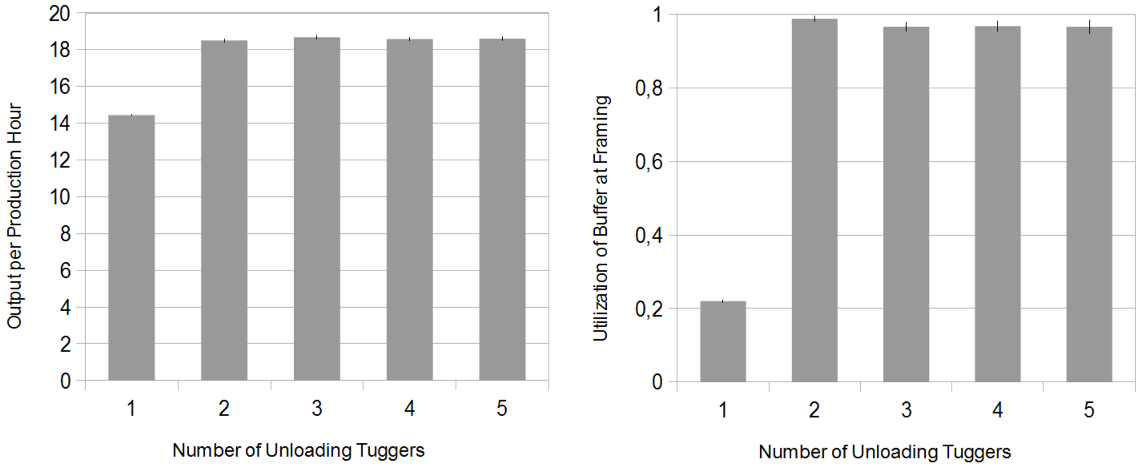
(a) Varied inputs

| Type | Unit |
|---|---|
| Number of Carts | 3 - 15 |
| Number of Loading Tuggers | 1 - 5 |
| Number of Unloading Tuggers | 1 - 5 |

(b) Constant inputs

| Type | Unit |
|---|---|
| Mix | 20 - 11 |
| Speed of AGVs [m/min] | 50 |
| Buffer in front of LARCs | 3 |
| Sunroof mix | 50% |
| Unit Load on AGVs | 1 |
| LARC operator take break | Yes |

To be able to determine the number of unloading tuggers required, the number carts and loading tuggers were set to a non limiting value. While the number of unloading tuggers where varied from 1 to 5, the results of this analysis is shown i Figure 6.5. The graph shows that when using only two unloading tuggers the output per production hour reaches the required level of 18 units and that there are parts in the buffer in front of the Framing station 90 percent of the time.

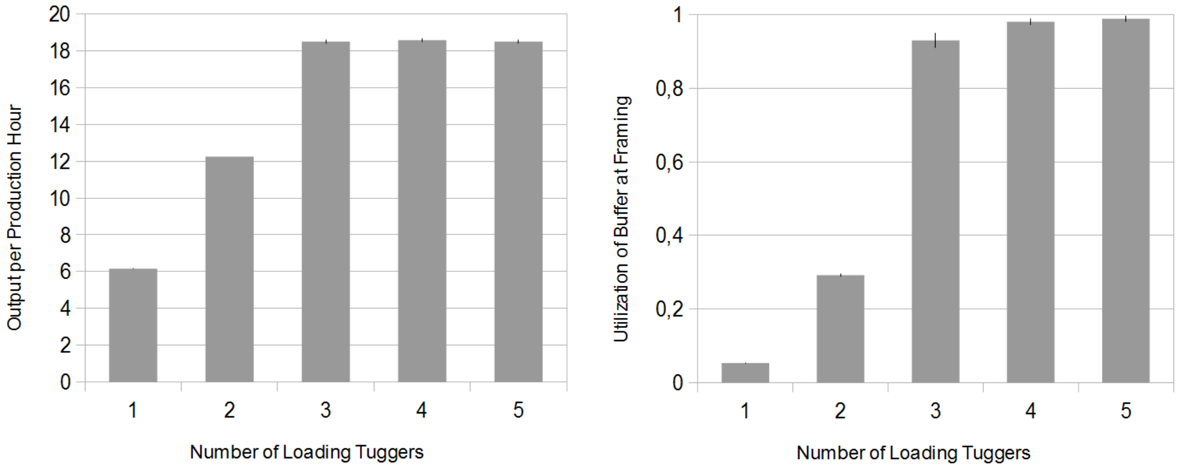


(a) Output per production hour

(b) Utilization of buffer at Framing

Figure 6.5: Results when varying number of unloading tuggers

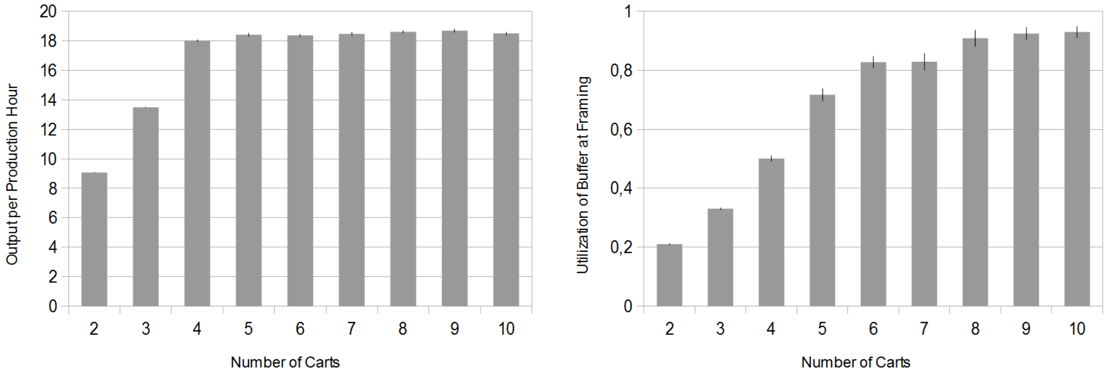
Next parameter to analyze is the number of loading tuggers. The number unloading tuggers were set to two and the number of carts was set to a non limiting value. Results from this analysis shows that three tuggers are enough to reach the demanding output. Three loading tuggers also keep a high utilization of the Framing buffer, see Figure 6.6.



(a) Output per production hour (b) Utilization of buffer at Framing

Figure 6.6: Results when varying number of loading tuggers

Finally the number of carts required is analyzed. Number of unloading and loading tuggers were kept to two respective three while the number of carts where varied between 2 and 10, showed in Figure 6.7. The graph shows that five carts are enough to cover the output demands. The buffer in front of the Framing station is in this case occupied by waiting parts just over 70 percent of the time.



(a) Output per production hour (b) Utilization of buffer at Framing

Figure 6.7: Results when varying number of carts

### Analysis

The alternative solution of using a supermarket buffer together with tuggers and carts have been shown to be realizable using two unloading tuggers; three loading tugger; and five carts. Advantages with this kind of system are the possibility of sequencing the supply of parts to the Framing line. This is something that is a necessary in the future when additional car models will be produced in the Framing line. The supermarket solution is technically more advanced and requires the AGVs to be able to communicate with the control system of the Framing line. A positive consequence of sequencing is that the waste of parts traveling back on the AGVs will be eliminated.

# Chapter 7

# Discussion

Production systems are indeed very complex systems and since there exists no such thing as a standard production equipment, they all have their own specific characteristics. This makes analysis of production systems to a difficult task, because there exist no general best solution. It is often hard to predict how a specific production system will behave when changing conditions, for example installation of new equipment into the existing system. In situations like this the many benefits of discrete event simulation really comes in handy. Even though the creation of a discrete event simulation model is a rather time consuming process, used in the right way it can be very valuable. Further, as another consequence of experimenting on a model, the ongoing production will not be disturbed.

The amount of different scenarios and parameters that can be varied are almost indefinite. It is therefore important to work in a structured way and to keep the number of options to a minimum when analyzing production equipment. It is not just the number of possible combinations that makes this complicated, the possibility of variables being interdependent is also evident.

It is also important that the intention of the simulation model is clear and to know what should be studied and analyzed. For instance is the solution that provides the highest output necessarily not the best alternative. It would be pure waste to invest in a capacity that not the rest of the system can handle, or a capacity higher then what is decided to be produced within the entire facilities. This puts consequently high pressure on the forecast that must be relatively precise in order to design a system with the correct capacity.

As Saab has introduced the flexibility aspect into their philosophy, it is important that all new installations are compatible with this. There are of course limitations in how flexible some parts of their production line can be. It is naive to believe that the main flow can be flexible enough to introduce a new car type in minutes. However many other parts of their production system could cope with that, if just some thinking is done before ordering new equipment.

This new way of thinking when introducing new production equipment could somewhat be called to take a Kaikaku leap. If for example the new 54x Framing line that is ordered is studied, it is designed so that when a new car model is introduced an additional fixture could easily be installed without disturbing the ongoing production and high installation cost. This is implementable because that a robot picks up, and holds the fixture instead of a fixture being mounted in the roof. This effect would never been achieved applying only Kaizen.

Even though an AGV system can never be as flexible as a forklift, the implementation of an AGV system could also somewhat be considered kaikaku. An AGV system comes with many benefits compared to using traditional forklift transportation. To mention a few:

- Forklifts are a major hazard in production facilities.
- No need of large batch transportation.
- Frees operators that can do value added work, instead of driving a truck.
- Smaller material facades near the main flow.

The possibility of something blocking the AGV route is foreseen in all analyzes. The probability of this occurring is however quite large initially, because operators is unaware of the consequences of blocking the route. Sometimes it might be necessary to block the route for shorter periods of time when replacing a pallet. Neither is any considerations taken to the battery capacity of the AGVs. If it is necessary to charge the AGVs during production, additional AGVs are required. A solution could be to charge the AGVs at the loading and unloading stations. However the time spent at these stations may not be enough to be able to run continuously. It is hard to predict how things like these will affect the system, but this must be considered when deciding the number of AGV to be ordered. It is possible that more AGVs are needed in reality than presented in this thesis.

## 7.1 Sustainable Production

In order to be a successful car manufacturer it is important to look at the sustainability aspect. Sustainability can be divided into the tree dimensions Environmental, Social and Economical (Jovane et al., 2008).

**Environmental** The historical way of producing cars have been to scrap old production equipment and completely build a new line when introducing a new car model. This thesis work presents a flexible part of the production line where future car models can be introduced without major investments in production equipment. Since it is natural to assume that all production equipment has an environmental effect, the more equipment that can be reused the better.

**Social** A social aspect of introducing an AGV system is the reduced number of forklift operators needed. There is a risk that the forklift operators sees AGVs as a threat to their jobs and try to oppose the implementation of such systems. However AGVs are quite appreciated among operators that work with them. This due to the high safety reliability of an AGV system compared to forklifts, which are a large source of injuries in production environments.

**Economical** There are of course economical consequences in installing new production equipment, like the Framing line and the AGV system. Since it is necessary to install a new Framing line in order to produce the new 54x model, this cost cannot be removed. It is though very important to make sure that the new Framing line is flexible enough to handle the introduction of new car models in the future, without major investments. The flexible aspect regarding the AGV system is also important. A car model is usually just produced for a couple of years, before it is abandoned to let future models in. Consequently, the AGVs must be able to adopt other tasks when this happens, in order to get the most out of them. Further, since the Framing line must be able to handle the introduction of a new car model, it is essential that the AGV system can manage that as well. There is a lot of economical benefits in using the same AGV transportation system to deal with these new models as well, instead of designing a new or using forklifts.

# Chapter 8

# Conclusions

This thesis first objective was to design a Discrete Event Simulation model. The objective have been realized without finding any major inaccuracies throughout the verification and validation process, hence the model was approved for experimentation. The first experiments concerned the layout of the new Framing line. A list of what have been concluded the best solution for Saab can be seen in Table 8.1. The solution specifies a reconfigurable, product and volume flexible Framing line ready for future model introductions.

Table 8.1: Framing Conclusions

- Layout Proposal two
- Material disturbances should be kept at present level
- Takt time of 162 seconds in the 54x Framing line

Further experiments concerning the specification of the internal AGV supply system have been performed. The choice have been made to recommend a simple initial AGV system that have the potential to be further develop in order to handle future demands. Concluded specifications of the initial and future AGV systems can be seen in Table 8.2. In the initial system the AGVs consist of two parts, a tugger and a cart. By this, future implementation towards a supermarket layout will be smother. In addition the equipment can be reused when implementing the supermarket system.

Table 8.2: AGV Conclusions

(a) Initial Scenario

- Pull system
- Magnetic guidance
- Manual loading
- Automatic unloading
- One tugger for each cart running on one route
- Five running vehicles in the system
- 50 [m/min]
- LARC buffer size of three
- Unit load one
- Unused parts travel back

(b) Future Scenario

- Implement a supermarket
- Sequencing parts
- Two unloading tuggers
- Three loading tuggers
- Number of Carts depending on mix and number of variants

With the supermarket solution it is possible to supply the production with large material variance, without increasing the size of the material facade. However in order to fully understand the consequences of a complex system like this, further investigation is advised.

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# Appendix A

# Input Data

## Simulation Inputs

The model is simulated to illustrate a full day production when two-shift production is applied. All figures presented in this report are in produced products per efficient producing hour. With an efficient producing hour it means the time when the equipment is running according to schedule, the breaks are not included in this figure. In the two-shift case this means 15 hours as can be seen in Figure A.1.

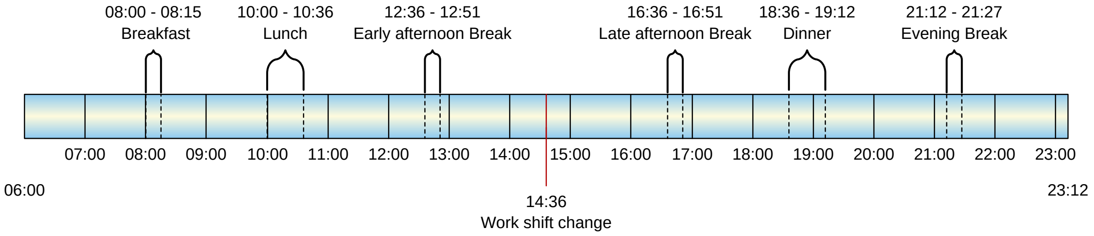


Figure A.1: A full day of production using two-shift

The reason for not simulate a full day's work and remove the time for the pauses are that some of the equipment still runs during that time. When there is a break the manual handling stops, whereas the automated equipment still runs as before. This will lead to that the production system does not fully stop when there is a break and will give the production system a somewhat different behavior than if this would not have been taken into consideration.

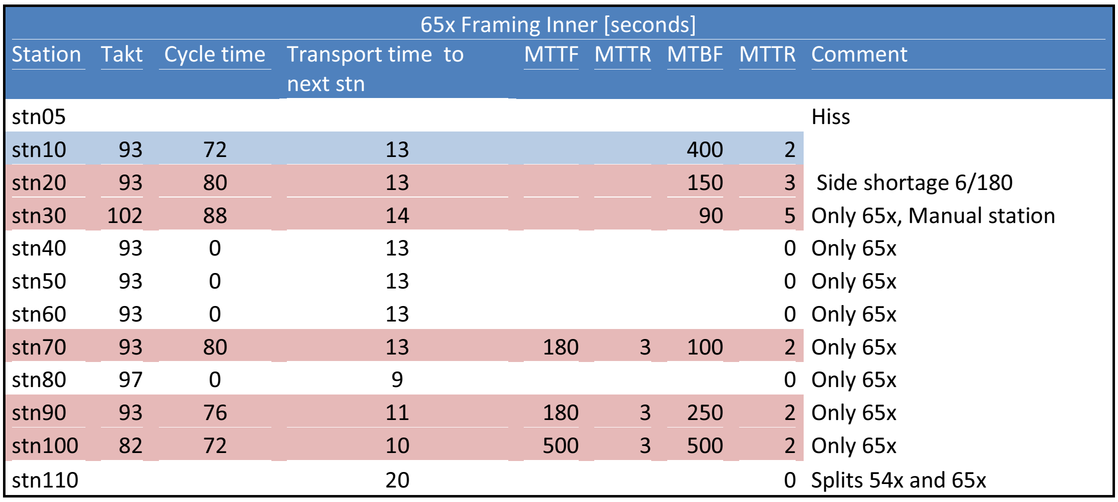
Before any analysis starts and data is gathered the model needs to get into a steady state, which means that the model runs for a specific period of time to assure there is always correct preconditions in the system. By warm up analysis the warm up time were determined to approximately three hours. A three hour warm up time would result in that the breaks starts at the wrong time. To avoid this, the setup time is set to one shift (516min) and all data gathering will therefore start after this time.

All analyzes are simulated 100 times, and all numbers presented are mean values based on these simulations.

# Model Inputs

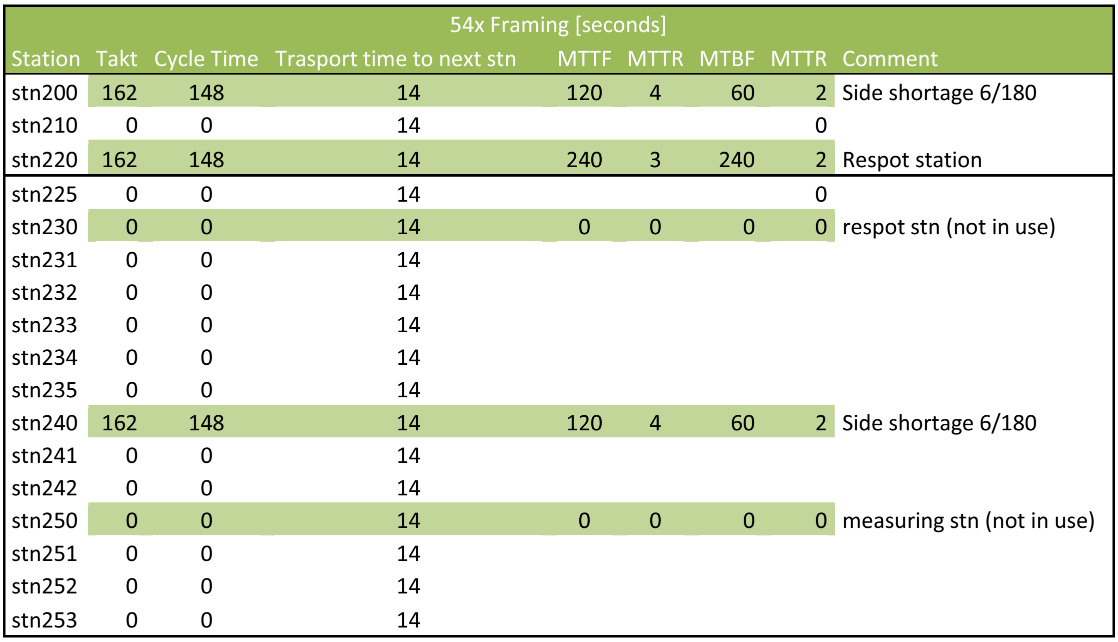
All the inputs to the model are presented categorized depending on what they affect as can be seen in the Tables below.

Table A.1: 65x Framing



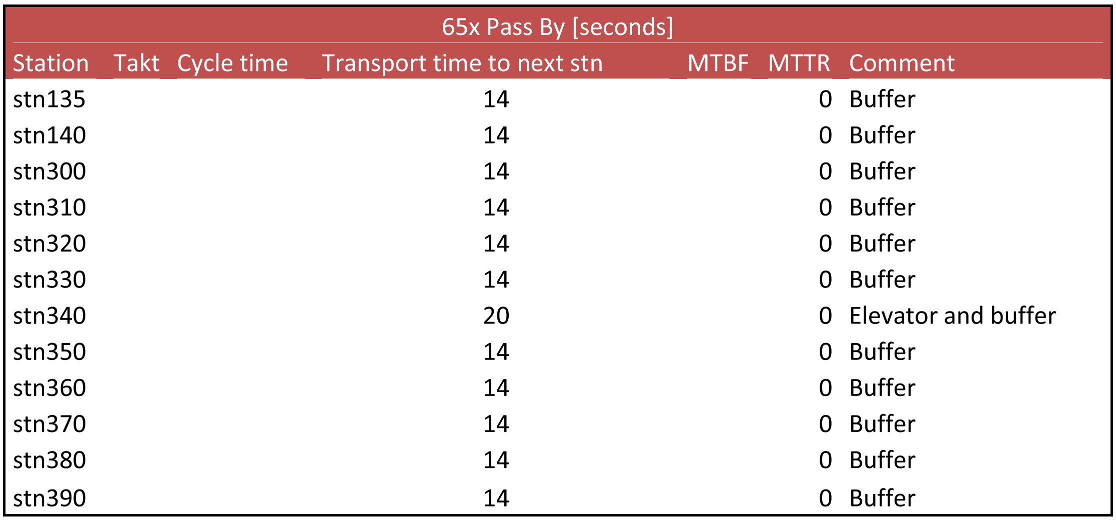
| 65x Framing Inner [seconds] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Station | Takt | Cycle time | Transport time to next stn | MTTF | MTTR | MTBF | MTTR | Comment |
| stn05 | | | | | | | | Hiss |
| stn10 | 93 | 72 | 13 | | | 400 | 2 | |
| stn20 | 93 | 80 | 13 | | | 150 | 3 | Side shortage 6/180 |
| stn30 | 102 | 88 | 14 | | | 90 | 5 | Only 65x, Manual station |
| stn40 | 93 | 0 | 13 | | | | 0 | Only 65x |
| stn50 | 93 | 0 | 13 | | | | 0 | Only 65x |
| stn60 | 93 | 0 | 13 | | | | 0 | Only 65x |
| stn70 | 93 | 80 | 13 | 180 | 3 | 100 | 2 | Only 65x |
| stn80 | 97 | 0 | 9 | | | | 0 | Only 65x |
| stn90 | 93 | 76 | 11 | 180 | 3 | 250 | 2 | Only 65x |
| stn100 | 82 | 72 | 10 | 500 | 3 | 500 | 2 | Only 65x |
| stn110 | | | 20 | | | | 0 | Splits 54x and 65x |

Table A.2: 54x Framing



| 54x Framing [seconds] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Station | Takt | Cycle Time | Trasport time to next stn | MTTF | MTTR | MTBF | MTTR | Comment |
| stn200 | 162 | 148 | 14 | 120 | 4 | 60 | 2 | Side shortage 6/180 |
| stn210 | 0 | 0 | 14 | | | | 0 | |
| stn220 | 162 | 148 | 14 | 240 | 3 | 240 | 2 | Respot station |
| stn225 | 0 | 0 | 14 | | | | 0 | |
| stn230 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | respot stn (not in use) |
| stn231 | 0 | 0 | 14 | | | | | |
| stn232 | 0 | 0 | 14 | | | | | |
| stn233 | 0 | 0 | 14 | | | | | |
| stn234 | 0 | 0 | 14 | | | | | |
| stn235 | 0 | 0 | 14 | | | | | |
| stn240 | 162 | 148 | 14 | 120 | 4 | 60 | 2 | Side shortage 6/180 |
| stn241 | 0 | 0 | 14 | | | | | |
| stn242 | 0 | 0 | 14 | | | | | |
| stn250 | 0 | 0 | 14 | 0 | 0 | 0 | 0 | measuring stn (not in use) |
| stn251 | 0 | 0 | 14 | | | | | |
| stn252 | 0 | 0 | 14 | | | | | |
| stn253 | 0 | 0 | 14 | | | | | |

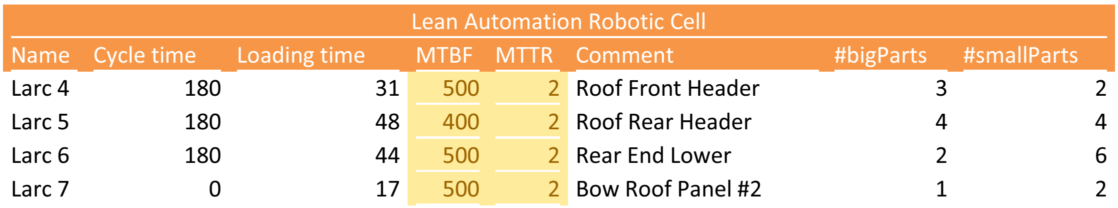
Table A.3: 65x Pass by



65x Pass By [seconds]

| Station | Takt | Cycle time | Transport time to next stn | MTBF | MTTR | Comment |
|---|---|---|---|---|---|---|
| stn135 | | | 14 | | 0 | Buffer |
| stn140 | | | 14 | | 0 | Buffer |
| stn300 | | | 14 | | 0 | Buffer |
| stn310 | | | 14 | | 0 | Buffer |
| stn320 | | | 14 | | 0 | Buffer |
| stn330 | | | 14 | | 0 | Buffer |
| stn340 | | | 20 | | 0 | Elevator and buffer |
| stn350 | | | 14 | | 0 | Buffer |
| stn360 | | | 14 | | 0 | Buffer |
| stn370 | | | 14 | | 0 | Buffer |
| stn380 | | | 14 | | 0 | Buffer |
| stn390 | | | 14 | | 0 | Buffer |

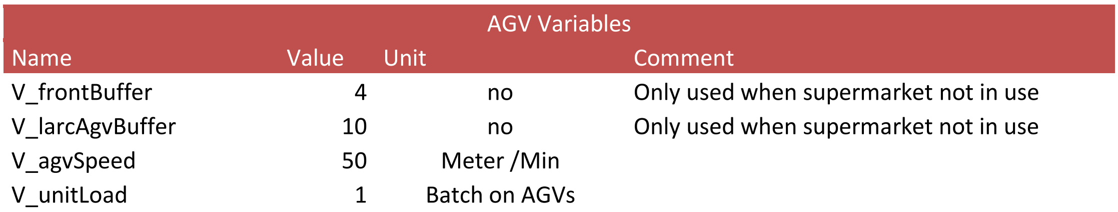
Table A.4: LARCs



Lean Automation Robotic Cell

| Name | Cycle time | Loading time | MTBF | MTTR | Comment | #bigParts | #smallParts |
|---|---|---|---|---|---|---|---|
| Larc 4 | 180 | 31 | 500 | 2 | Roof Front Header | 3 | 2 |
| Larc 5 | 180 | 48 | 400 | 2 | Roof Rear Header | 4 | 4 |
| Larc 6 | 180 | 44 | 500 | 2 | Rear End Lower | 2 | 6 |
| Larc 7 | 0 | 17 | 500 | 2 | Bow Roof Panel #2 | 1 | 2 |

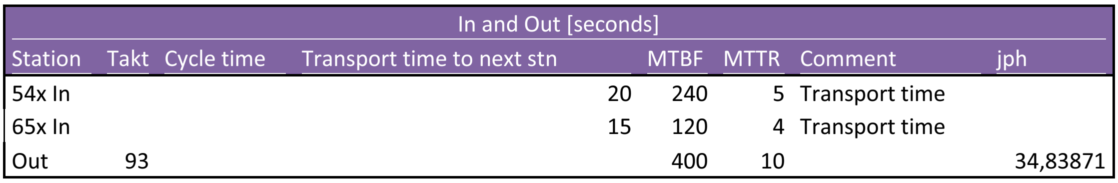
Table A.5: LARC variables



AGV Variables

| Name | Value | Unit | Comment |
|---|---|---|---|
| V_frontBuffer | 4 | no | Only used when supermarket not in use |
| V_larcAgvBuffer | 10 | no | Only used when supermarket not in use |
| V_agvSpeed | 50 | Meter /Min | |
| V_unitLoad | 1 | Batch on AGVs | |

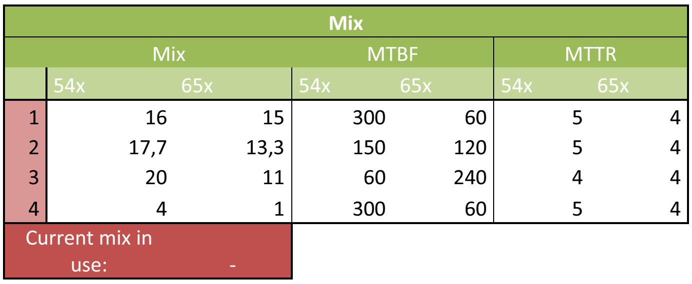
Table A.6: In and Out



In and Out [seconds]

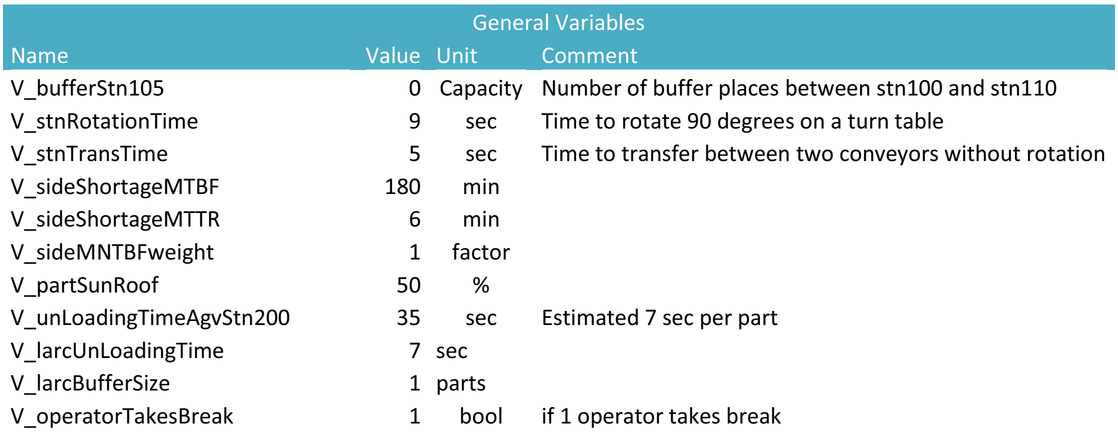
| Station | Takt | Cycle time | Transport time to next stn | MTBF | MTTR | Comment | jph |
|---|---|---|---|---|---|---|---|
| 54x In | | | 20 | 240 | 5 | Transport time | |
| 65x In | | | 15 | 120 | 4 | Transport time | |
| Out | 93 | | | 400 | 10 | | 34,83871 |

Table A.7: Car mixes



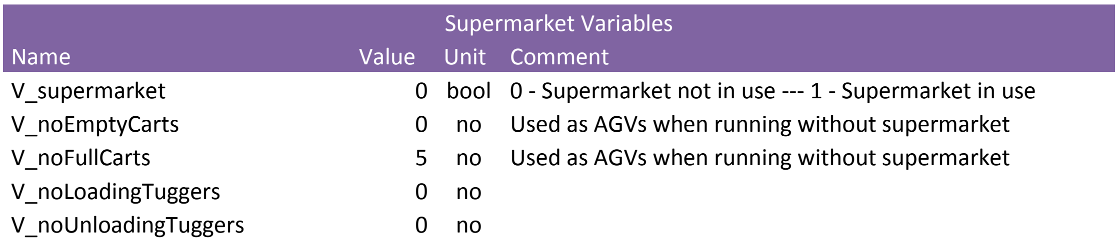
| | Mix | | MTBF | | MTTR | |
|---|---|---|---|---|---|---|
| | Mix | | MTBF | | MTTR | |
| | 54x | 65x | 54x | 65x | 54x | 65x |
| 1 | 16 | 15 | 300 | 60 | 5 | 4 |
| 2 | 17,7 | 13,3 | 150 | 120 | 5 | 4 |
| 3 | 20 | 11 | 60 | 240 | 4 | 4 |
| 4 | 4 | 1 | 300 | 60 | 5 | 4 |
| Current mix in use: | | - | | | | |

Table A.8: General variables



| General Variables | | | |
|---|---|---|---|
| Name | Value | Unit | Comment |
| V_bufferStn105 | 0 | Capacity | Number of buffer places between stn100 and stn110 |
| V_stnRotationTime | 9 | sec | Time to rotate 90 degrees on a turn table |
| V_stnTransTime | 5 | sec | Time to transfer between two conveyors without rotation |
| V_sideShortageMTBF | 180 | min | |
| V_sideShortageMTTR | 6 | min | |
| V_sideMNTBFweight | 1 | factor | |
| V_partSunRoof | 50 | % | |
| V_unLoadingTimeAgvStn200 | 35 | sec | Estimated 7 sec per part |
| V_larcUnLoadingTime | 7 | sec | |
| V_larcBufferSize | 1 | parts | |
| V_operatorTakesBreak | 1 | bool | if 1 operator takes break |

Table A.9: Supermarket variables



| Supermarket Variables | | | |
|---|---|---|---|
| Name | Value | Unit | Comment |
| V_supermarket | 0 | bool | 0 - Supermarket not in use --- 1 - Supermarket in use |
| V_noEmptyCarts | 0 | no | Used as AGVs when running without supermarket |
| V_noFullCarts | 5 | no | Used as AGVs when running without supermarket |
| V_noLoadingTuggers | 0 | no | |
| V_noUnloadingTuggers | 0 | no | |