CHALMERS

Discrete-event simulation of conveyor systems

- Providing decision support for Saab Automobile AB

Master of Science Thesis in the Master Degree Programme, Production Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2012

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Acknowledgement

This study represents a closing work of our Master degree in Production Engineering. The study was conducted in spring 2011 at the Department of Product and Production Development at Chalmers University of technology, Sweden. The work has been carried out at Saab Automobile AB (Saab) in Trollhättan, Sweden, with focus on discrete-event simulation and manufacturing logistics.

We would like to express our gratitude to all of you who have contributed to this work! Especially for you Andreas Ardhus, Project Engineer as well as our tutor at Saab, for your supervision and guidance; Johan Nordling, Consultant at Siemens Industry Software AB, for your assistance in Technomatix Plant Simulation; and Hans Sjöberg, for letting us use all the computers in the Product and Production Development laboratory when running the experiments. Nevertheless, we would like to thank all of You employees at Saab who have supported us with necessary information and data. Without you, this work had never been accomplished!

A great thank to all of you!

At last we would like to take the opportunity to encourage engineering students to take advantage of computerized simulation when providing evidence and support for important decisions. Simulation is a powerful problem solving tool for many real-world problems. This is something that we came to realize during the work at Saab.

Gothenburg, November 2011

Peter Nilsson Gustaf Nordberg

Abstract

Background & Problem: This study represents a closing work of our Master degree in Production Engineering and has been carried out at Saab Automobile AB (Saab) in Trollhättan, Sweden. Today, a critical activity in Saab´s body plant is the logistics of Side Panels Outer (SPO) and Side Panels Inner (SPI). These panels are transported with so-called carriers and it happens too often that car bodies on the production main line have to wait on these carriers (including panels). Thus, the productivity is suffering. In addition, Saab will start producing an all-new 9-3 model in year 2012. The introduction of model 540 will put new requirements on the Future Production System (FPS) and an identification whether the system will manage these is of necessity. For this purpose, Saab wants to use a tool to produce objective decision support. One such a tool is discrete-event simulation (DES).

Objectives: The study is based on three objectives. Objective one (1) involves developing a DES model of the FPS and thereafter to specify the maximum throughput rate out of the system without any disturbances. Objective two (2) involves identifying the relationship between the number of carriers in each subsystem (FCSSPO and FCSSPI) and the throughput rate out of the FPS. Objective three (3) involves identifying all potential bottlenecks that prevent the system to reach its maximum throughput rate specified in objective one and thereafter identify the relationship as in objective two.

Purpose: The overall purpose of this Master thesis is to provide Saab with reliable decision support, based on data produced by a computerized simulation model, for the company's future investments. The purpose of this Master thesis is also to give rise to fruitful discussions among concerned decision-makers, all leading to a more productive FPS.

Methodology: The study procedure was based on an adapted version of the so-called Banks model. It included three phases: pre-study, model development and experimental analysis.

Results & Conclusions: In line with the first objective, a computerized simulation model was developed in order to analyze the FPS and its behavior. The development involved a few, but necessary, pre-specifications of the layout, the control logic and the throughput rate. Furthermore, a successful simulation run resulted in an identification of the relationship between the number of carriers in each subsystem (FCSSPO and FCSSPI) and the throughput rate out of the FPS. The optimal numbers of SPO and SPI carriers (in each right and left system) were determined to 31 and 26, respectively. It means that a reorganization of carriers is needed in order to increase the throughput rate, rather than further investments in carriers. At last, two bottlenecks – number of operators and capacity of the FCSSPI - confined the FPS to achieve its maximal throughput rate at 36.1 JPH. The maximal throughput rate required 36 SPO and 34 SPI carriers.

Key words: Discrete-event simulation, manufacturing logistics, theory of constraints

Nomenclature

Throughout this Master thesis several project specific terms and concepts have been used. The most crucial of them are listed below. Terms defined in the thesis for the first time are boldfaced.

Term/Abbreviation	Description [unit]
Carrier	The device which transport side panels from up- to unloading
CCS	Current Conveyor System
CCSSPO	Current Conveyor System for Side Panel(s) Outer
CCSSPI	Current Conveyor System for Side Panel(s) Inner
CPML	Current Production Main Line
CPS	Current Production System
DES	Discrete-Event Simulation
FCS	Future Conveyor System
FCSSPI	Future Conveyor System for Side Panel(s) Inner
FCSSPO	Future Conveyor System for Side Panel(s) Outer
FPML	Future Production Main Line
FPS	Future Production System
SPO	Side Panel(s) Outer
SPOL	Side Panel(s) Outer Left
SPOR	Side Panel(s) Outer Right
SPI	Side Panel(s) Inner
SPIL	Side Panel(s) Inner Left
SPIR	Side Panel(s) Inner Right
Model 440	Saab 9-3 Sedan
Model 444	Saab 9-3 Combi
Model 540	Saab 9-3 Sedan – [New model planned in year 2012]
Model 650	Saab 9-5 Sedan
Model 651	Saab 9-5 Combi

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Chapter One
–
INTRODUCTION

The following chapter serves as an introduction to the study. The chapter begins with a brief description of both the background as well as the problems related to the study. The chapter continues with specifying the objectives and purpose of study. The study is based on three objectives, of which the second and third objective is dependent on the first one. At last, the chapter examines an overview of the scientific procedure (methodology) of study as well as the thesis outline.

1.1 Background

"In March last year, I could not imagine what the world would look like today."

(Victor R. Muller, CEO Saab Automobile, April 7 -2010)

1.1.1 Simulation – a tool for developing decision support

In the beginning of fall 2008 a global-scale economic downturn hit hard against the world economy. The downturn, which also became known afterwards as the great recession, affected several industries highly adversely. The impact of the economic downturn became much greater in the automotive industry than in many other industries. This was due to several interacting reasons including, for instance, that several automakers already were in a dire situation as well as the high cost that a car purchase involves (Evenett, Hoekman & Cattaneo 2009, p.294). One year later, in 2009, the global automotive industry continued to suffer very hard from the economic downturn. Actions such as governmental bail outs, liquidations and scrap car measures were common practice in many automotive companies around the world. The suffering was also the case for Saab Automobile AB (Saab) which at that time was owned by General Motors. The statement above by Viktor Muller, contemporary CEO of Saab, conveys the chaos that reined the automotive industry in that time.

In times of economic downturn, such as the great recession, increasing costs and time pressures in manufacturing production is, more than usually, a common notion. The high pressure often implies that money can be lost quickly through mishaps such as inefficient schedules and resource allocations as well as poor productivity. In order to not run into this fate, the fulfillment of profitable investments, just-in-time deliveries and well managed production lines are very important. This has proven to be true especially in the automobile industry. A fundamental requirement to the fulfillments above is that the management has access to objective decision support in order to evaluate and compare alternative approaches correctly. Today, there are variety of different types of tools and techniques for decision support available for decision makers. Among others are various optimization methods, cost models, and simulation techniques (Semini, Fauske & Strandhagen 2006, p.1947). The latter one has gained much attention in the past.

Simulation is one of the most powerful and efficient tools available for decision makers. The tool can be applied in conjunction with complex process and system analysis to find and solve problems. The tool is also associated with a number of advantages as well as disadvantages, but where the former usually outweigh the latter. There are several definitions of simulation given in the research field. A general one is that simulation is "*the use of a model to represent over time essential characteristics of a system under study*" (El Sheikh, Al Ajeeli & Abu-Taieh 2008, p.3). Moreover, simulation can be classified into different categories depending on what type of computerized model the simulation is based on. A known such type is discrete-event simulation (**DES**) which is characterized by the fact that the model is updated every time a specific event occurs in the system (Banks, Carson, Nelson & Nicol 2005, p.13). This study is based on DES, with specific focus on manufacturing logistics.

1.1.2 Client profile – Saab Automobile AB

This study has been carried out at Saab Automobile AB (Saab) in Trollhättan, Sweden. The company is a Swedish car manufacturer owned by the Dutch company Swedish Automobile NV. Saab started to produce cars in 1949, under the name Svenska Aeroplan AB, and has since then introduced several inventions (e.g. the dual break circuit, electrical heated seats and the turbo engine adaptable for cars) to the market. In 1990 Saab got its present name, Saab Automobile AB. At the end of 2010, Saab consisted of 3840 employees, generated a turnover of 6 301 MSEK (121.nu, 2011) and sold cars in more than 50 countries around the world through a network of around 900 sales representatives. (Spyker Cars N.V. 2011, p.12)

Saab´s current model range comprises of three series: Saab 9-3, Saab 9-4 and Saab 9-5. While the Saab 9-4 series is manufactured in a facility in Ramos Arizpe (Mexico), all operational activities related to the Saab 9-3 and Saab 9-5 series are centralized in Trollhättan (Sweden). It means that activities such as design, development, planning and manufacturing of these two models takes place here. Furthermore, the Saab 9-3 series is manufactured in three versions (models). These are the 9-3 Sedan (**440**), 9-3 Combi (**444**) and 9-3 Cabriolet. The slightly more luxurious and larger Saab 9-5 model is manufactured in only two models which are the 9-5 Sedan (**650**) and 9-5 Combi (**651**). While the model 650 is in full production, the model 651 is produced only occasionally for testing purposes. Today, all these models are built on a single adaptable production line in the assembly plant. (Spyker Cars N.V. 2011, p.12-13)

1.2 Problem description

The manufacturing activities of Saab cars in Trollhättan take mainly place in three facilities sequentially – the refinement starts in the body plant, continues into the painting and ends up in the assembly plant. In the body plant, all operational activities prior painting take place. These activities include in general complex manufacturing processes such as sheet metal forming, welding and various machining operations such as bending, punching (drilling) and cutting. Between the processes material components is transported with various means such as forklifts, automatic guided vehicles and different conveyors.

Today, a critical activity in Saab´s body plant is the logistics of Side Panels Outer (**SPO**) and Side Panels Inner (**SPI**). Together, these two components, and only these two, form the final side of the body frame. The critical point of view is in that both SPO and SPI have to travel long distances in order to get to the Current Production Main Line (**CPML**). More specifically, SPI has to travel from its production cell to its framing station, while SPO has to be transported from its mono uploading station, through a production cell, to its framing station. All the framing stations (also called unloading stations) are located at the CPML, where the side panel is fitted to the body. The transportation of SPO and SPI is today realized with the help of two extensive conveyor systems – the Current Conveyor System for Side Panels Outer (**CCSSPO**) and the Current Conveyor System for Side Panel Inner (**CCSSPI**) – which both extend across the body plant at ceiling level. Both CCSSPI and CCSSPO also houses buffers in between their respective uploading and unloading station in order to reduce material shortage at the framing stations when unexpected incidents occur.

Moreover, both CCSSPI and CCSSPO are today controlled by logic operations which further make the logistics even more complex. These operations are present in order to meet two requirements. First, the control logic ensures that right type of side panel is assembled to the right type of car body staying in the position at the production line. In other words, the logic operations control the panels into correct sequence. Second, the control logic also allocates the limited number of carriers to the four models. The reason for this is to obtain a consistent ordering of side panels that match the sequence on the production main line as well as to avoid so-called lock-outs in the system. In other words the control logic is a key factor in the work to get a well-functioning system. Further on, along the whole conveyor track so-called cutters are placed. These are present, especially in all curves, in order to keep the distance between the carriers and thus preventing collisions between them.

Both SPO and SPI are transported through the systems with **carriers**. Today, the CCSSPI and CCSSPO consist of 25 and 36 (excluding so-called 'mono carriers') carriers, respectively. Each carrier has an electric engine and the entire carrier equipment, including the engine, is expensive both to buy but also to maintain. Thus it is very important for Saab´s decision-makers to evaluate what a potential investment in a carrier can bring in return to the company´s productivity. If the company purchases too many of them than needed, the productivity can drop drastically due to over capacity and high expenses. If Saab purchase too few of them, the productivity can also drop drastically due to lack of carriers to deliver the needed material. It is therefore highly essential to balance the number of carriers with the given throughput rate. Otherwise, it can endanger the whole production flow. In conclusion, the transportation system of both SPO and SPI is today highly complex including long distances, control logics and a number of expensive carries.

In a near future (in year 2012) Saab plans to release an all-new 9-3 model (**540**) in production. It means that a total of five models (model 440, 444, 540, 650 and 651), instead of four models, will be manufactured at the concerned production line. In conjunction with the introduction the company also plans to redesign the current production system (**CPS**) as well as both CCSSPO and CCSSPI in order to meet the new requirements. Another conversion is that the new production system – in this thesis called the Future Production System (**FPS**) – is expected to manage a higher throughput rate than the rate of today. The future throughput rate out of the FPS is today not known or set. The increased pace, along with the redesign of the CPS, will impose additional and stricter requirements on both Future Conveyor System for Side Panels Outer (**FCSSPO**) and Future Conveyor System for Side Panels Inner (**FCSSPI**). Together, these two systems constitute the Future Conveyor System (**FCS**).

In summary, the logistics of SPO and SPI with help of the Current Conveyor System **(CCS)** and its carriers is anything but a simple process. Even today significant knowledge is missing about various relationships between the characteristics of the conveyor system and throughput rate. Especially knowledge is missing about the so important relationship, from a productivity point of view, between the number of carriers in each system and the throughput rate. This relationship will become even more uncertain when the all-new Saab 9-3 model is introduced in 2012. Therefore, questions such as – How can we increase the productivity in the FPS? What will the relationship be between the number of carriers and the throughput rate? What will the relationship be between number of carriers and waiting time for material shortage at respective unloading station? Will the FCSSPO and FCSSPI handle the new throughput rate requirements? Are there any potential bottlenecks in the FCSSPI and FCSSPO when speeding up the throughput rate and in case what are these? – concerning the FPS are all questions of interest to answer in this study.

In order to answer questions such as those listed above, it is highly appropriate to use a simulation model. Saab has also expressed a desire to base the analysis on a simulation model which also gives them the opportunity to evaluate further logistics ideas before implementation.

1.3 Study objectives

In all projects, the objectives are of great importance in order to succeed. According to Robinson and Bhatia (1995, p.62) the objectives set the direction for the project and demonstrate an understanding of the problem to be tackled. In the start-up of the project, Saab identified and formulated several problems. These formulations were then, through discussions among involved parties, formed to specific objectives. Even these were modified later on. The final objectives, and thus deliverables, of this Master thesis are:

Objective 1: *To develop, with necessary and reasonable assumptions, a discrete-event simulation (DES) model of the future production system (FPS) and thereafter to specify the maximum throughput rate out of the system without any disturbances.*

Objective 2: *To identify, by using the developed DES model, the relationship between the number of carriers in each subsystem (FCSSPO[1] and FCSSPI) and the throughput rate out of the FPS.*

Objective 3: *To identify, by using the developed DES model, all potential bottlenecks that prevent the system to reach its maximum throughput rate specified in objective one. Thereafter, identify the relationship between the number of carriers in each subsystem and the throughput rate out of the FPS.*

To clarify once again, all the objectives above concern the FPS which is supposed to be implemented by Saab in year 2012. The FPS is described more in detail in chapter three. Moreover, many of the critical factors examined by Shannon (1998, p.10) were considered when planning the objectives above. Among these were factors such as adequate time frame, competence of project management and team members as well as availability of computer hardware and software.

1.4 Purpose

The overall purpose of this Master thesis is to provide Saab with reliable decision support, based on data produced by a computerized simulation model, for the company's future investments. It includes building up a simulation model as well as analyzing the same. The purpose of this Master thesis is also to give rise to fruitful discussions among concerned decision-makers, all leading to a more productive FPS.

[1] Excluding so-called 'mono-carriers' (see Chapter 3)

1.5 Delimitations

From the beginning, Saab and the analysts discussed various objectives. One desirable objective was to analyze the CPS and FPS as well as a number of various influencing factors such as control logic, carrier speed, conveyor path design and cost analysis. It was realized fairly quickly that these analyzes would not be possible to carry out within set time frame.

To clarify once again, the study focuses on the FPS when all five car models (model 440, 444, 540, 650 and 651) are in production. This scenario is also the most critical one since that is a period of time when all five models are in production at the same time. This is also agreed with project management. Furthermore, a number of analyses have not been carried out particularly due to the limited time frame of the study. Such analyses are:

Real Cost Analysis:

No cost analysis has been carried out. By analyzing the cost of various solutions a more credible, in an economic point of view, analysis can be delivered to Saab.

Conveyor Path Redesign Analysis:

No conveyor path redesign analysis has been carried out. By redesigning the layout of the conveyor systems – CCSSPO and/or CCSSPI - a more efficient system can be developed. A redesign is costly though.

Production Forecast Analysis:

No analysis of production forecast per model has been carried out. The analysis is based on the production forecast of each model for year 2012.

Carrier Speed Analysis:

The study has not been focused on to analyze various conveyor speeds. By analyzing different carrier speeds in the conveyor systems, the delivery of side panels can be much faster and thus more productive.

Control Logic Analysis:

No in-depth analysis concerning the control logic parameters has been carried out. Even though these parameters control the entire production system, the parameter values of today has been used.

1.6 Study procedure

DES is today a relatively well established tool in major production and logistic analyses. This is especially true for large manufacturing companies where relatively complex and costly investments are evaluated frequently. Despite the establishment, various analysis techniques and approaches are widely used in simulation studies. Several of them are examined in the literature and one of the most applied analysis approach in the field is the one developed by Jerry Banks (see e.g. Banks *et al.* 2005, p.13-18).

In order to identify the relationship between the number of carriers in respective future conveyor system (FCSSPO and FCSSPI) and the throughput rate of the FPS, a slightly adapted version of the analysis approach as defined by Banks *et al.* (2005, p.14) was applied. Initially, all focus was on developing a valid simulation model which corresponded to objective one. Key activities such as setting of objectives, data collection and model translation, including validation, were all undertaken in this part. Thereafter, several extensive production runs and analysis were carried out in order to identify variable interactions of the system. These analyses were based on a simple experimental plan. Furthermore, the phases of data collection, model translation as well as production runs and analyses were the steps that were most time consuming. This was in line with previous studies (see e.g. Robinson *et al.* 1995, p.62).

Quantitative data concerning FPS, including both FCSSPO and FCSSPI, were mainly collected through measurement- and time studies. Data concerning operating machines were, most of it, already documented. Furthermore, the step of model translation implied that the collected data was gradually transformed to a computerized model. Saab has in previous production and logistics analysis used the software package Technomatix Plant Simulation which, on request, also was used in this simulation study. Technomatix Plant Simulation is a DES tool offered by Siemens Industry Software AB. The tool is particular useful when analyzing various complex production systems, such as assembly plants and material logistics. It provides the information needed to make reliable decisions in the early stages of production planning. (Siemens PLM Software Inc., 2011)

At last, the entire study is mainly based on previous research in the field of production analysis and discrete-event simulation. During the project, literary information was mainly obtained from scientific articles, published in various journals such as 'Winter Simulation Conference' and 'Simulation Practice and Theory'. General keywords such as 'discrete-event simulation', 'theory of constraint's' and 'manufacturing logistics' were all applied in the information search.

1.7 Thesis outline

The thesis is divided into a number of chapters. Chapter one, this chapter, is an introduction to the study. The following chapters in the thesis are outlined as follows:

Chapter 2: Theoretical framework

Presents a theoretical overview of the field. Among other things, fundamentals of DES, theory of constraints as well as advantages and disadvantages with computerized simulation studies is examined.

Chapter 3: System description: The Future Production System

Gives a profound description of the FPS which will be implemented at Saab in a near future (in year 2012). The FPS represents the modeling system of study.

Chapter 4: Methodology

Describes in detail the procedure of study. The chapter is structured in the same manner as the applied procedure.

Chapter 5: Results and analysis

Presents the results of the simulation runs and analysis carried out during the study. The chapter also examines the simulation model and its development.

Chapter 6: Conclusions and recommendations on further studies

Summarizes the outcomes (results and key analysis) of the study. The chapter also examines recommendations on further studies.

Chapter Two
–
THEORETHICAL FRAMEWORK

The aim of this chapter is to serve as a theoretical platform to the study. The chapter starts with a brief introduction to the field of manufacturing logistics where three theories suitable for this study are described. Thereafter, a description of DES and its application areas is examined. At last, as a separate section, a brief description of programmable logic controller (PLC) is examined.

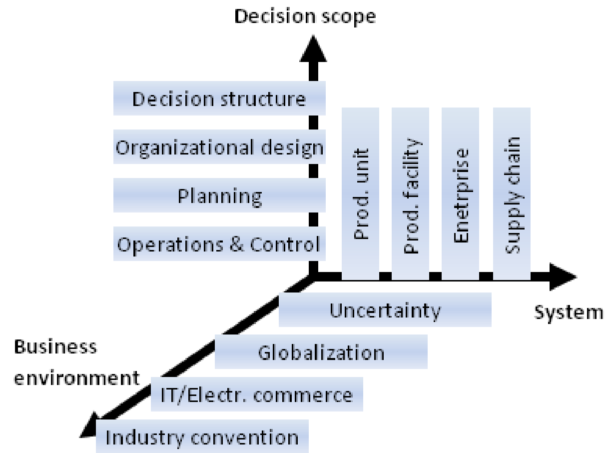
2.1 Manufacturing logistics

Manufacturing logistics is a broad term covering aspects of several overlapping fields. According to Chan (2005, p.21) the term refers to all functions that are required to carry out manufacturing activities based on the field of operation and supply chain management. Examples of concerned functions are planning, organization, coordination and controlling.

Several taxonomies of manufacturing logistics research have been developed in order to clarify the extent of this field. One of these is examined by Wu, Roundy, Storer and Martin-Vega (1999). This taxonomy is based on three main dimensions and provides a basis for how one may categorize manufacturing logistics research, or study. The dimensions are; system, decision scope and business environment. While the 'system' "*specifies different levels of physical entities in a manufacturing environment*", the dimension of 'decision scope' "*distinguishes different levels of abstraction and focus for decision making*". Basically, both dimensions consist of four components each, ranging from a smaller scale to a larger. The third dimension, 'business environment', "*identifies the broader business context of manufacturing logistics research*" and consists of components that drive the business environment (Wu *et al.* 1999, p.7). Wu *et al.* (1999, p.7) points out that the status of this dimension sets the level of the problems identified in the other two dimensions (system and decision scope). Figure 2a summarizes the taxonomy and its components.

However, this study is best described by the system level of production facility and the decision scope level of planning. A study at the production facility level focuses on the manufacturing system, and its production units interplay with each other. Related problems concern units such as people, product and information. A study at the planning level concerns medium to long term decisions in order to affect the overall design of the operations. Decisions at the planning level include facility planning, production planning and capacity management (Wu *et al.* 1999, p.6-7).

Figure 2a: Dimensions and components of manufacturing logistics study (Source: modified picture, Wu, Roundy, Storer & Martin-Vega 1999, p.18)



Further on, Saab's business environment can be described with help of several components. For example, the degree of uncertainty is described as high considering Saab´s financial situation. The business environment can also be described as global with fierce competition.

Three different theories (concepts or philosophies), connected to the field of manufacturing logistics, have more than other theories served as a basis in this study. These are the theory of constraints, just-in-time and time studies which are presented, in brief, below.

2.1.1 Theory of time study

Time study is a theory as well as a practice to determine the input time for a production process in order to improve, control and follow up operations. A fundamental approach in the theory is that time is a resource like machines and humans and is therefore used to calculate the productivity ratio for a given production system. Productivity could here be defined as the number of products out of the system divided by the total amount of input resources (including time spent) on those products (Björheden 1991, p.34). Thus, time is a highly influential factor when calculating productivity and hence also influential on the cost.

Time study is one of the most common practices in manufacturing logistics (Björheden 1991, p.33). The practice is based on several standardized time concepts which all facilitates the work with the time study. A central concept is *lead time* which refers to the average time it takes to go through an entire process (Systems2win, 2011). Two other commonly practiced concepts are 'cycle time' and 'takt time' (throughput rate). These two are defined as (Systems2win, 2011):

- **Cycle time:** The average time between completed units in a process. The cycle time measures a whole "cycle" (e.g. from that a machine grips a part to that it grips next part).

- **Takt time:** The rate at which completed product needs to be finished in order to meet customer demand. A common applied unit is jobs per hour (JPH).

There are also some concepts associated with break downs. Three of them, commonly practiced, are Mean Down Time (MDT), Mean Time To Failure (MTTF) and Mean Time Between Failures (MTBF). The sum of the MDT and the MTTF is equal to the MTBF. Figure 2b defines the three time concepts and shows their relationship to each other.

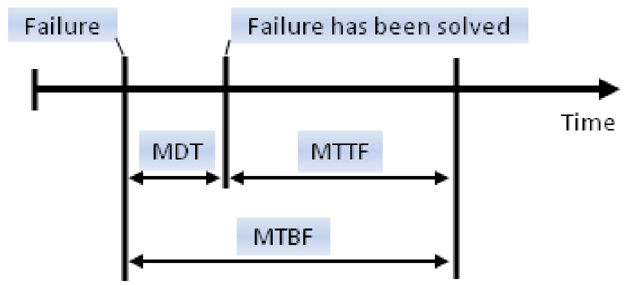


Figure 2b: The relationship between MDT, MTTF and MTBF

At last, there are several ways to carry out a time study. If the studied cycle time is less than a few seconds (e.g. less than five seconds) it is appropriate to use some kind of video recording equipment. The use of such equipment makes it possible to slow down as well as rewind the real time very easy. However, if the studied cycle time is relative long a stopwatch should be sufficient in order to reach an accurate result. (Freivalds and Niebel 2004, p.377-379)

2.1.2 Theory of constraints

The theory of constraints is a problem-solving methodology which seeks to determine the underlying causes of a problem in purpose of finding the best solutions (Stein 1997, p.1). The theory was developed by the Israeli physicist Eliyahu Goldratt in the late 1970´s and has since then produced important results in the manufacturing industries. An evidence of its importance can be taken from a study conducted by Balderstone and Mabin (1998). In their study they identify the actual performance of the theory and collect quantitative data, concerning the throughput, from more than seventy different companies. Based on the data they conclude that the theory of constraints is a philosophy that leads to success as well as that it works very well, even with only partial application of the methodology (Balderstone *et al.* 1998, p.210).

A central assumption in the theory is that every system must have at least one constraint, also known as the bottleneck or the weakest link, which dominates the entire system. In general, a constraint can be categorized as behavioral, managerial, capacity, market and logistical (Stein 1997, p.13). Constraints belonging to the capacity and logistical category are the one of interest in this thesis. While a capacity constraint involves limitations in resources such as machines and people, a logistical constraint involves limitations attributed to the planning and control systems. From another perspective, the constraint also determines the throughput of the system and thus, roughly speaking, the pace of revenues. Therefore, the secret to success is to managing these constraints to get the best out of the system (Balderstone *et al.* 1998, p.205).

A fundamental technique of theory of constraints is the one developed by Goldratt (Gupta, Bhardwaj & Kanda 2010, p.688-689). The technique (or process) improves the throughput and consists of five sequential steps. In the first step, the *constraint (*or the bottleneck) is identified. Several methodologies for this purpose are described in the literature and three of these are known as the 'average waiting time method', the 'utilization method' and the 'shifting bottleneck method'.

- **Average waiting method:** The method implies, firstly, to determine the average time that a product has to wait in each resource involved in the system and, secondly, to compare these times with each other. The buffer (or station) that has the highest average waiting time is considered to be the bottleneck of the system. One weakness of this method is that it is not applicable if concerned buffers have limited capacity. (Faget, Eriksson & Herrmann 2005, p.1401-1402)

- **Shifting bottleneck method:** The method is based on the approach that a resource can either be active or inactive. A resource which is in an active state is in a process mode (e.g. welding). By contrast, when a resource is in an inactive state it is waiting for input (e.g. material components). From this, the resource that possesses the longest aggregated active time is then considered to be the true bottleneck. The method is easy to use and no additional information about the system structure is needed. (Roser, Nakano & Tekana 2001, p.950-951)

- **Utilization method:** Like the shifting bottleneck method, the utilization method is also based on the approach of active (working and repair) time versus inactive (waiting) time. But instead of comparing active times in order to find the longest one, the utilization method measures the percentage of time a station is in its active state. The station with the highest active percentage is considered to be the bottleneck. (Faget *et al.* 2005, p.1401-1402)

A fourth method is to study by just watching the amount of work in front of concerned resources. Obviously, this method requires that the simulation model exists in a visual form. The method is very simple and no in-depth analyses are required.

Once the bottleneck is identified the analyst must decide how to 'exploit' it. The aim is to maximize its capability and hence increase the throughput. When it is working at maximum capacity, the analyst must 'subordinate' all other resources to support the constraint. It may mean that some of the subordinated resources, especially those in front of the constraint, will sacrifice productivity for the benefit of the entire system. (Gupta *et al.* 2010, p.688-689; Stein 1997, p.12-14)

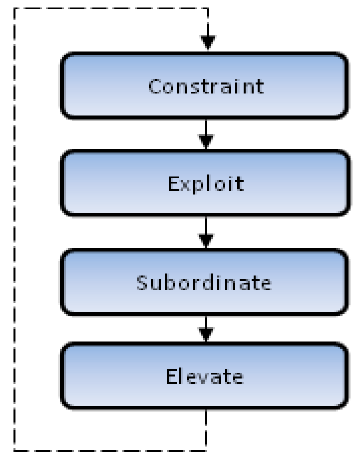


Figure 2c: The improvement process of throughput

Even though the capacity of the bottleneck is maximized, the throughput of the overall system might not be satisfactory. The analyst must in these cases even further strengthen the bottleneck in order to 'elevate' the capacity. Strengthening the system might require major expenditures of time or money. The last step, named 'repeat', means that the entire system is re-evaluated in order to identify as well as improve the new constraint of the system (Gupta *et al*. 2010, p.688-689). Figure 2c above summarizes the improvement process for throughput in which the dashed line represents the step of repeat.

2.1.3 Theory of just-in-time

The theory of just-in-time (JIT), also referred to as a philosophy, is about having "*the right items of the right quality and quantity in the right place at the right time*" (Podolsky & Cheng 1996, p.2). To achieve this purpose JIT involves a set of principles, tools and techniques. The theory was first developed by a Japanese, named Taicho Ohno, in the early 1970s and was on that time solely a method for reducing inventory levels. This is still a central part in the philosophy but today the philosophy is more comprehensive and includes specific goals such as to improve product quality and production efficiency as well as continuously eliminate waste in all forms (Podolsky *et al.* 1996, p.1-2). A common form of waste is waiting and it may arise out of several reasons. For example, it may arise if there is a lack of material in the system as well as if one of the resources is a bottleneck in the process. However, a reduction of waiting time for a component is directly a reduction of the lead time. Thus, JIT is a philosophy which partly aims to reduce the lead time.

An essential part in the work to achieve JIT is the process of improvement (Hutchins 1999, p.64). The process of improvement is based on a universal problem-solving sequence of events which are in order: symptom, cause and remedy. The symptom represents the problem concerned. An example could be late delivery of material to an assembly line. In order to solve the problem one have to brainstorm realistic and plausible theories of causes and then test the same. The brainstorming process can be carried out in many ways. An extremely effective approach is the so-called Ishikawa diagram, also known as fishbone diagram. This technique enables identification of specific causes which then can be broken down into their detail. Once the true cause or causes have been identified it is necessary to consider possible remedies. Only one of these possible remedies is then selected for test purpose. If the test shows to be successful, the remedy is thereafter fully implemented. (Hutchins 1999, p.49-64)

2.2 DES for decision support

As discussed in the introduction, simulation is one of the most powerful problem-solving tools available for decision-makers who are responsible for manufacturing logistics operations. According to Semini *et al.* (2006, p.1947) there are several reasons for this fact. Among others, a simulation facilitates both understanding of the real system and the communication among involved parties. A simulation study also allows concerned decision-makers to test different scenarios without disturbing the real system.

Focus of this study is on DES and its use to solve material logistic problems. DES is a specific type of simulation and is appropriate for those systems for which changes in system state occur only at a discrete set of points in time (Banks *et al.* 2005, p.13). DES and simulation in general has a lot of things in common. Therefore, many of the characteristics held by simulation in general are also applicable for DES, and vice versa.

2.2.1 Fundamentals of DES

“Simulation is both an art and a science”

(Shannon 1998, p.8.)

DES is not only a science, it is also an art. Researchers who claim this mean that simulation requires not only knowledge about programming and statistical components, but also several hours of specialized practical training. Thus, the art, in contrast to the science, can only be taught by simulating.

More specifically, DES modeling is a popular method for predicting the performance of complex systems. According to Shannon (1998, p.7) the method includes both the construction of the model and the experimental use of it in order to describe either a present or a future behavior of the system. A common analogy is the one with the black-box which transforms inputs to outputs (Sánchez 2007, p.59). Figure 2d shows the Black-box. The analogy highlights the model’s potential in transforming inputs to outputs. The following sections examine the definition, concepts and structures, and the application areas of DES.

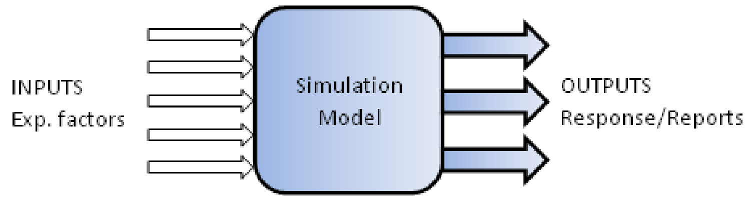


Figure 2d: DES as a black box (Source: Sánchez 2007, p.60)

2.2.1.1 Definition of DES

The term 'discrete-event simulation' refers to a specific type of simulation rather than one's own discipline. The main word in the term is 'simulation' and in general it is defined as "*the use of a model to represent over time essential characteristics of a system under study*" (El Sheikh *et al.* 2008, p.3). A more comprehensive and appropriate definition of simulation is given by Shannon (1998, p.7). Therefore, in this thesis, simulation is referred to as:

> *"…the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system."*
>
> (Shannon 2008, p.7)

Two central words in the definition above are model and system. 'Model' is defined as "*a representation of a group of objects or ideas in some form other than that of the entity itself*" while 'system' is defined as "*a group or collection of interrelated elements that cooperate to accomplish some stated objective*" (Shannon 2008, p.7). An example of a system could be a production system that manufactures automobiles.

It appears from the definition above that simulation is the process of designing a model of a real system. A real system, often referred to simply as a system, can be characterized as either continuous or discrete (Banks *et al.* 2005, p.11). In contrast to a continuous system, a discrete system consists of state variables that change at a discrete set of points in time. When this set of points in time corresponds to specific system events, the application is called discrete-event simulation (DES). Several researchers describe the meaning of a DES. For example Schriber and Brunner (1997, p.15) explains that DES is *"…the one in which the state of a model changes at only a discrete, but possibly random, set of simulated time points*". A slightly more descriptive definition, and therefore a more appropriate one to use in this thesis, is given by (Banks 1998, p.8). DES is referred to as the:

> *"…one in which the state variables change only at those discrete points in time at which events occur"*
>
> (Banks 1998, p.8)

The unique with DES seems to be that the system state variables are updated only when events occur. State variables can here be viewed as the set of all information needed in order to describe the real system at a given point in time. They change value only when specified events occur (Banks 1998, p.7).

2.2.1.2 Modelling structures and concepts

A model structure, also called world view or simulation strategy, is defined as a "*structure of concepts and views under which the modeler is guided for the development of a simulation model*" (Balci 1988, p.287). There are several modelling structures used today by the simulation community. Some of these are process-interaction approach, three-phase approach, event-scheduling approach, scanning approach and transaction-flow approach.

According to Schriber *et al.* (1997, p.14) DES is often based on the transaction flow approach. This approach was developed in 1962 and is today primarily used for simulating detailed processes in activities such as manufacturing and material handling. A complete description of a transaction flow world is:

> *"In the transaction flow world view, a system is visualized as consisting of discrete units of traffic that move (flow) from point to point in the system while competing with each other for the use of scarce resources."*
>
> (Schriber and Brunner 1997, p.14)

A model which is based on the transaction-flow approach consists of modelling concepts such as entities, resources and control elements. Complementary concepts such as event, activity and attribute are also included in a model. It is necessary to understand these concepts in order to build a sufficiently good model of the real system (Banks *et al.* 2005, p.9).

2.2.1.3 Areas of application

DES is today applied to support decision-making in many areas. Examples of application areas are manufacturing, transportation, logistics, health care, military, and project management (Johansson 2002, p.38-40). However, when is DES applied to support manufacturing logistics decision-making? This issue is explored in a study carried out by Semini *et al.* (2006, p.1946-1953). In order to get an understanding of its affiliation, they survey more than 50 DES applications. Based on the survey they conclude that the majority of applications can be assigned to the production plant design and to the evaluation of production policies, lot sizes, work in progress levels and production schedules. In contrast, they find no applications in business process design.

Recently, a number of trends of simulation applications have been indentified (Banks *et al.* 2005, p.8). Simulation for risk analysis and call-center analysis are both examples of growing areas. Simulation models of automated material handling systems such as various conveyor systems and automated guided vehicles are another example of a growing area.

2.2.2 Steps in a DES study

One of the secrets to a successful simulation study is the application of an indicative project plan as well as the knowledge of how such a plan should be performed (Robinson *et al.* 1995, p.61). In the last decades, several methodologies and models have been developed. These approaches are similar in the way that they contain similar kind of steps in a similar order.

Perhaps one of the most frequently applied models of them all is the one developed by Jerry Banks (see e.g. Banks et al. 2005, p.13-18). The model consists of central steps such as problem formulation and setting of objectives, model building, experimental design as well as production runs and analysis. Figure 2e shows the so-called 'Banks model'. The following sections discuss the model steps.

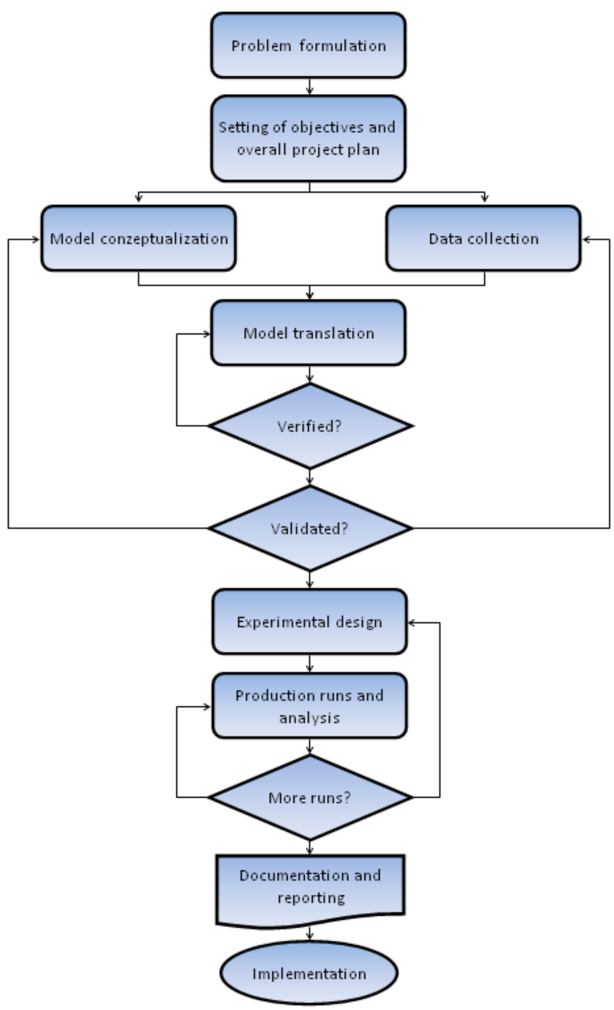


Figure 2e: Banks model (Source: Banks *et al.* 2005, p.14)

2.2.2.1 Problem formulation and setting of objectives

The step of problem formulation and setting of objectives constitutes a crucial part in a DES study. The step sets the direction of the project and it is therefore very important that the modeler initially identifies and understands the problem, or problems, of project. The problem may be identified and formulated by the modeler, but it can also be the client who communicates the problem. If the problem is formulated by the modeler, it is important that the client understands and agrees with the formulation. (Banks 1998, p.15)

Once the problem of system is identified feasible objectives are formulated. According to Robinson *et al.* (1995, p.62) the objectives set the direction for the project and demonstrate an understanding of the problem that are going to be tackled. The objectives also indicate the questions that are to be answered by the simulation study. Thus, it is important that these objectives are stated in such a way that they can be fulfilled within specified time frame.

Moreover, Robinson *et al.* (1995, p.63) stresses out that the step of problem definition and setting of objectives also should include identification of what they call 'experimental factors' and 'reports'. An experimental factor is defined here as an independent factor having an effect on the system (simulation model). In the same manner, a report refers to the response out of the system. Figure 2e shows the two concepts' relation to the simulation model. The identification of experimental factors and reports has to be realized in the beginning of the project. Otherwise it will be impossible to predict the future scope of the model and thus the resources needed to build it.

2.2.2.2 Data collection and model conceptualization

When the formulation of problems and objectives are accepted by all involved parties it is time to start modeling. First out, is the two activities of data collection and model conceptualization, which according to Banks model should be performed in parallel (see figure 2e).

A conceptual model is "*a series of mathematical and logical relationships concerning the components and the structure of the system*" (Banks 1998, p.15-16). A conceptual model can also be viewed as an abstracted model of the real system sufficient to support the stated objectives. An important aspect to take into account when building the conceptual model is the scope and level of the model (Robinson *et al.* 1995, p.63). Here, 'scope' refers to the breadth of the model while 'level' refers to the depth of detail. It is of great importance that both these magnitudes are well balanced so that they are neither under- or over-dimensioned. Otherwise, significant amount of time can be wasted as well as non-sufficiently accurate result can be jeopardized. The same magnitudes also define two very effective approaches to model building. These are breadth first and depth first (Sturrock 2009, p.37). In 'breadth first', the entire model or a major section of it is build with a minimal level of detail. In 'depth first', a small section of the system is modelled in the full detail required. The two approaches can also be combined by first adding some details to a subsection and then adding some details to the entire model level, or vice versa.

A DES study relies heavily on input data and its quality. According to Sargent (2005, p.135) data are needed for three purposes. Firstly data are needed to build the conceptual model, secondly data are needed for validation of the model, and thirdly for performing experiments with the same. Moreover, the data can roughly be divided into three categories depending on whether the data is available, as well as collectable, or not (Robinson *et al.* 1995, p.63). The three categories are:

- **Category A** – Data are available
- **Category B** – Data are not available but collectable
- **Category C** – Data are not available and not collectable

The first category, category A, consists of data that are available for the modeller. It means that the data in some form are documented and therefore relative easy to get. The collection of this kind of data is the least time-consuming one since the data already exists. In contrast, data belonging to either category B or category C are not available. This is true especially in scenarios when data are too expensive to gather or when the system being modeled is not in existence. Unlike the data in category B, data in category C is nor collectable. It complicates the situation significantly and a common solution of this problem is to just estimate the values. For these cases, it is also preferable to conduct sensitivity analysis on these data.

One major concern with the process of data collection is that it takes such a large portion of the total simulation time. According to a study, carried out by Perera and Liyanage (2000, p.645-651), poor availability is considered to be the main cause of long data collection time. Other major influencing causes, given in the study, are high level model details, difficulty in identifying available data sources as well as complexity of the system under investigation. Since the data collection is so time-demanding it is hence important that the modeler starts with this process as early as possible. Also, the importance of having a well designed conceptual model is significant. If the level of detail indicates exactly what data are required for each element, required data can more quickly be identified.

As a result of the concerned complexity above, Johansson and Skoogh (2008) study how to increase the precision and rapidity when managing the input data collection (also called input data management (IDM)). In their study, they develop a structured model by linking all IDM activities in an efficient way. Figure 2f shows the proposed methodology step by step.

The methodology includes a total of 13 activities where all, except ‘compile available data’ and ‘gather not available data’, are sequentially connected to each other. The methodology also provides a complete set of elements starting with ‘identification of relevant data’ and ending up with ‘finish final documentation’. Furthermore, Johansson *et al.* (2008, p.1729) point out that the methodology fits well into previous works, on how to perform a DES study. They also point out that the profit of using proposed methodology is largest in projects where the members do not work with DES on a daily basis.

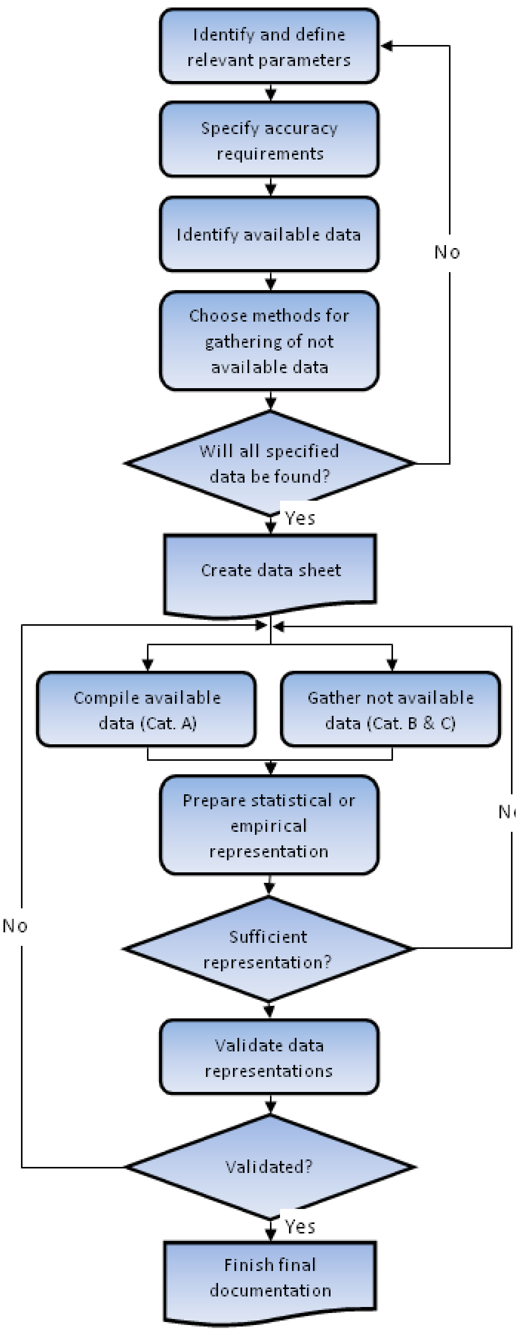


Figure 2f: Methodology for increased precision and rapidity in IDM (Source: Johansson & Skoogh 2008, p.1730)

2.2.2.3 Model translation

Model translation refers to the process where the conceptual model is transferred and coded to a computerized model. Maybe the most important aspect of this step, highlighted in the literature (see e.g. Robinson *et al.* 1995, p.64), is that the modeller should consider to add relatively small sections of model logic and then to verify each section before adding more. By doing so, major error coding is avoided.

In order to achieve an efficient and correct execution of model translation, the modeller has to possess knowledge within chosen simulation software. Today, in contrast for some decades ago, there are several simulation software used by the simulation community. Examples of simulation software packages are QUEST®, Automod, Arena, WITNESS, Flexsim and Technomatix Plant Simulation. These software have many similarities but also dissimilarities. Since the choice of simulation software package in this study was predetermined by Saab, no more discussion about these different software packages will be examined.

2.2.2.4 Verification and validation

Model verification and validation are two critical steps in the development of a simulation model. For instance, Balci (1995, p.147) claims that the probability of a successful simulation project increases significantly just by applying the right principles of model verification and validation. While 'model verification' refers here to "*the process of ensuring that the model design has been transformed by into a computer model with sufficient accuracy*", 'model validation' refers to "*the process of ensuring that the model is sufficiently accurate for the purpose at hand*" (Robinson 1997, p.53).

In Banks model (see figure 2e) the activities of verification and validation are both illustrated as two consecutive steps positioned after the step of model translation. This is somewhat misleading. In reality, these two should be conducted during all phases of the modelling process instead of a single time. Among others, Rabe, Spieckermann and Wenzel (2008, p.1720) argue that verification and validation have to accompany the simulation project from the start until the very end. They also point out that validation and verification should not only be applied at the end of each step. Instead the model should be verified and validated once a suitable result or intermediate status has been achieved.

Even though verification and validation should be conducted continuously during all phases of the modelling process four types are known as more subtle than others. These are 'conceptual model validation', 'data validation', 'verification and white-box validation', and 'black-box validation' (see e.g. Robinson 1997, p. 54-57; Sargent 2005, p.135-138). The four verification and validation types are explained in brief below.

- **Conceptual model validation:** Determination of that the scope and detail level of conceptual model is reasonable and sufficient for the intended purpose.

- **Data validation:** Determination of that input data are sufficiently accurate to develop the model as well as of how the applied software interprets the input data.

- **Verification and White-box validation:** refers to the determination of that subsets of the computer model correspond to the real world. Various aspects such as timing, control of flows, control of elements and control logic, are checked.

- **Black-box validation:** refers to the determination of that the overall model, and its output behaviour, reflects the real world with sufficient accuracy. This is where much of the validation evaluation takes place.

2.2.2.5 Experimental design

Once the model is verified and validated it is time for the step of experimental design. In a broad sense, experimental design concerns the decisions how to experiment with a simulation model in order to learn about its behavior. More specifically, experimental design concerns decisions related to the model configuration, the length of the simulation run, the number of runs and the interpretation of the outputs (Kelton & Barton 2003, p.59).

Activities, considered as steps in the design of an experimental plan, are (A) state a hypothesis, (B) plan an experiment to test the hypothesis, (C) conduct the experiments and (D) analyze the data from the experiment (Barton 2004, p.73). This is not a one-time process but rather an iterative, cyclic process where the last step, analysis from experiment often leads to modifications of the original hypothesis. The activity, plan an experiment to test the hypothesis (step B), can further be divided into five sub-activities (Barton 2004, p.73). These are:

- B:1 - Define the goals of the experiments
- B:2 - Identify and classify the independent and dependent variables
- B:3 - Choose a probability model for the behavior of the simulation model
- B:4 - Select an experimental design
- B:5 - Validate the properties of the chosen design.

There are several beneficial tools and applications available for the purposes above. An application, intended for identifying independent and dependent factors (B:2), is the already discussed Ishikawa diagram, also known as fishbone diagram. Another approach for the same purpose is the so-called process analysis in which boxes are drawn on a flip-chart symbolizing all aspects from cause to symptom (Hutchins 1999, p.55-57). Furthermore, an useful experimental design (B:4) when searching for bottlenecks in a system is the so-called approach of 'one factor at a time analysis'. In contrast to the approach of design of experiments (DoE) in which multiple factors are varied at a time, only one factor is varied. Thus, no advanced and time-consuming planning (design) of experiment is required. Even though its superior advantage in planning, the approach is associated with disadvantages such as that it is usually impossible to keep all other factors constant, there is no way to account for interactive effects as well as experimental error including measurement variation (Faget *et al.* 2005, p.1402).

Further on, according to Donhue (1994, p.201) there are a number of specific experimental design issues that are unique to experimentation within a simulation environment. These issues are both on a tactical as well as strategic level and have to be treated in order to get reliable and valid output. Robinson *et al.* (1995, p.65) discuss the same kind of issues but highlight four of them as more central than others. These are:

- **Selecting warm-up time:** An important issue is to select the initial conditions, or more specific the duration of the warm-up period. By doing so, the modeler avoids biased results out of the model.

- **Deciding run time:** Instead of selecting initial conditions, a modeler has to choose the final conditions such as run time or number of events completed. For non-terminating simulation, such as a manufacturing process, the basic rule is the longer the run, the better.

- **Deciding number of replications:** Another issue is to deciding on an appropriate balance between run length and the number of replications (runs). There are many advanced techniques available for this purpose. At least three to five replications are in general recommended. The more number of runs, the better.

- **Selecting actual experiments:** The last issue to take into consideration is to select the actual experiments (scenarios) that need to be performed. It is a common case that the number of scenarios exceeds the maximum number that can be performed within set time frame. Therefore, it is essential that the actual scenarios are selected with care.

2.2.2.6 Production runs and analysis

When the experimental design (plan) is set, production runs are realized and results are analyzed in order to get the information needed. This step is often associated with great time consumption (see e.g. Robinson *et al.* 1995, p.62). However, the time consumption can greatly be reduced if the experiments are well planned.

Once the production runs are made the results are analyzed. According to Robinson *et al.* (1995, p.65) the purpose of analysing the results is "*to check the extent to which the objectives of the project have been achieved*". If the objectives are not fulfilled, additional runs have to be carried out until they are fully met (see figure 2e).

At last, even though the simulation model is a reflection of the real system it is important to note that the results are just estimates of the true values. The reason for this is that the model is built on data. Moreover, when drawing conclusions of production runs and its results one should consider wider influences from the organisational context as a whole. The simulation is just a decision support among others (Robinson *et al.* 1995, p.65).

2.2.2.7 Documentation and implementation

The final step of a simulation study is to present the results for the client as well as implement recommended solutions in system concerned. The presentation, or documentation, can be divided into two different types, namely program documentation and progress documentation (Banks *et al.* 2005, p.17). Program documentation refers to documentation of information concerning the software (computer model) which has been used. This type of documentation is necessary in order to create a thorough understanding of the program, so that model users can make decisions based on the analysis. Progress documentation, on the other hand, provides the client with information regarding the simulation project as a whole. Notably, the documentation is carried out entirely by the analyst.

In contrast to the documentation, implementation is an activity made by the client. It is therefore important that the client is involved throughout the study period as well as fully understands the outcomes of project. Since this activity is made by the client, and so also supposed to be in this project, no further discussions will be carried out here.

2.2.3 Advantages and disadvantages of DES

DES and its application in manufacturing logistics studies is characterized with a number of advantages as well as disadvantages. The literature examines several of them (see e.g. Bank *et al.* 2005, p.3-4; Shannon 1998, p.8; El Sheikh *et al.* 2008 p.4-6) and some of these are presented in the following two sections. In general, the advantages usually outweigh the disadvantages.

2.2.3.1 Advantages of DES

As mentioned above, there are several advantages associated with the application of DES in manufacturing logistics analysis. One of the greatest advantages, according to Banks *et al.* (2005, p.3), is that the real system does not need to be disrupted once a valid model has been developed. Thus, DES is a very cost efficient tool when used for exploring new scenarios and methods. Some additional advantages include:

- DES allows you to test different scenarios and designs without acquiring new assets for the intended purpose at hand.
- DES allows you to better understand the interaction of different variables in complex systems.
- DES allows you to control the time which in turn enables to simulate long periods of time in a fraction of the real time.
- DES allows you to visualize the objects of analysis so that different kinds of design flaws can be detected.

2.2.3.2 Disadvantages of DES

Even though DES is associated most times with beneficial characteristics, the technique is also associated with some disadvantages. Among these are:

- DES modelling associates with high time consumption.
- DES results rely heavily on and are thus very sensitive to the input data.
- DES results are very sensitive to the skills of whom is making the model.
- DES modelling requires specialized training and is learned over time.

2.3 Description of PLC

A Programmable Logic Controller (PLC) is a digital computer used for automation of electromechanical processes for control of various machines and transportation systems. The controller uses a programmable memory to store instructions and to implement functions such as logic, sequencing and timing (Bolton 2003, p.2).

The first PLC was developed in 1969 and is today a common tool in many manufacturing industries. One significant reason for PLCs commonality might be its simplicity. PLC is in fact designed to be operated by people with a relative limited knowledge of computers and computing. Thus, no additional training expenses are needed in order to manage or maintain the control system. Another reason, and maybe the greatest one of them all, is that the same basic controller can be used with a wide range of control systems. Thus, PLC is very flexible. (Bolton 2003, p. 3)

Chapter Three
–
SYSTEM DISCRIPTION:
THE FUTURE PRODUCTION SYSTEM

The aim of the chapter is to present, and thus deliver, a thorough description of the modelling system – the Future Production System (FPS). Important to note is that the future production system is solely based on the Current Production System. But in order to clarify the differences between the current production system and the future production system the first section is structured in such a way that it first presents the former and continues with the latter. Finally, the chapter discusses the carrier and its function as well as the control logic of FPS.

3.1 Future Production System and its layout

The modeling system, or the real-world system, is made up of the so-called Future Production System (FPS). This system will be implemented in year 2012, solely due to a production release of an all-new Saab 9-3 model, and implies extensions of the current production system (CPS). The FPS, and therefore the modelling system, can broadly be viewed as a system consisting of three different sections – the 'Future Production Main Line (FPML)', 'Future Conveyor System for Side Panels Outer' (FCSSPO) and 'Future Conveyor System for Side Panels Inner' (FCSSPI). These three sections communicate with each other with help of various programmable logical controllers, sensors and algorithms.

As briefly discussed in section 1.2, Saab's FPS will be manufacturing five different body models. These are as listed below.

- Saab 9-3 Sedan (model 440)
- Saab 9-3 Sedan (model 540) - [New in year 2012]
- Saab 9-3 Combi (model 444)
- Saab 9-5 Sedan (model 650)
- Saab 9-5 Combi (model 651)

It means that both the FCSSPI and the FCSSPO must be able to deliver side panels to all of these five body models, which in turn imposes some requirements on the system and its layout. In the following sections, the layout of the FPS is presented. In order to highlight the differences between the CPS and FPS, the following section first presents a description of the CPS followed by a description of the FPS.

3.1.1 Current Production System

The Current Production System (CPS) is able to handle four different body models. Three of these (model 440, 444 and 650) are today in full production, and the fourth (651) is manufactured sporadically for testing purpose. The body model 651 will go into full production within the nearest future. As for the FPS, the CPS can be viewed as a system consisting of three different sections – 'Current Production Main Line' (CPML), 'Current Conveyor System for Side Panels Outer' (CCSSPO) and 'Current Conveyor System for Side Panels Inner' (CCSSPI) – which also communicate with each other with various means. Figure 3a shows a schematic representation of the CPS, and its three sections.

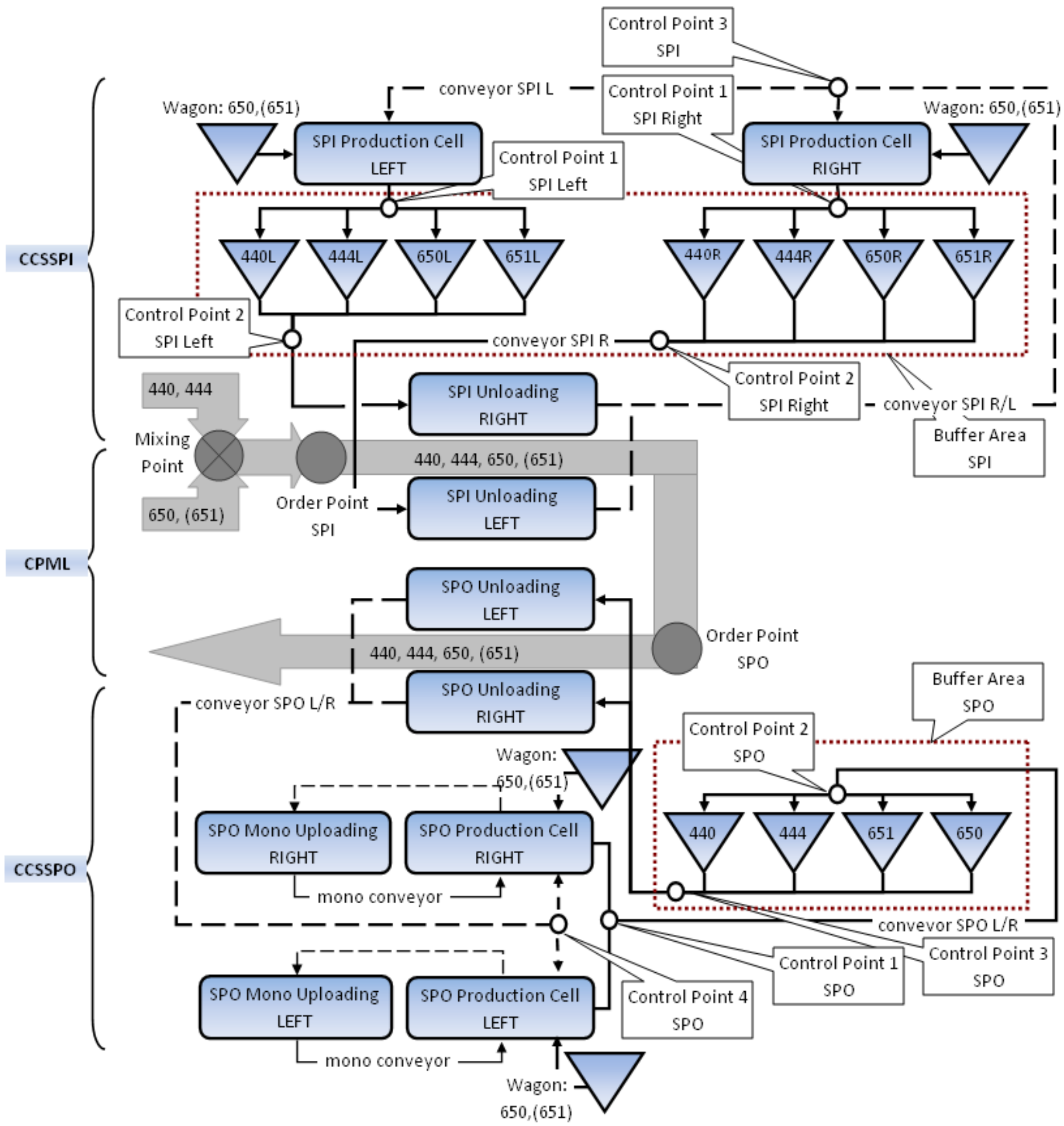


Figure 3a: Schematic overview of the CPS

More specifically, the figure shows the transport route – from uploading station to unloading station (marked as solid lines) – of both SPO and SPI (right and left). All side panels are transported by carriers (see section 3.3) to their specific target locations. After the unloading procedures, the carriers return empty to their origin destinations (marked as dashed lines). As shown in figure 3a, the label of body model 651 is marked with parentheses in order to highlight that this body model is not yet in full production.

3.1.1.1 Current Conveyor System for Side Panels Outer

The Current Conveyor System for Side Panels Outer (CSSPO) involves both refinement and delivery of side panels. The system is comprehensive and ranges all the way from the mono uploading stations to the unloading stations positioned at the CPML (left and right respectively). A passage through the entire system, without disturbances and waiting, takes approximately 30 minutes.

More specifically, the CCSSPO can be viewed as two processes – one transport process for SPO right (**SPOR)** and one for SPO left (**SPOL**) – both driven by a specific number of carriers. More specifically, both processes for SPOR and SPOL are driven by 36 carriers each[2]. The process, for each side, starts in the 'SPO mono uploading' station where an outermost part of the SPO (which is made in one piece) is manually loaded onto an elevator and then hoisted up to the 'mono conveyor', located at ceiling level. Once the elevator and the outermost part of the SPO is in right position, the part is transferred to the 'mono conveyor' which in turn transports the part with help of so-called mono carriers into the 'SPO production cell'. Moreover, the right and left 'mono conveyor' have identical tasks, but they do differ in the length of the conveyor. The 'mono conveyor' for SPO right is significantly more comprehensive and longer than the 'mono conveyor' for SPO left. Thereby, it requires more time to deliver an outermost part of SPOR to the production cell than it requires delivering the outermost part of SPOL. Furthermore, today there are two operators who take turns to load the elevator with side panels. These two operators also have other work assignments which imply that this station is not always manned and thus not controlled at all time.

In each 'SPO production cell' which consists of several high-tech robots, the outermost part is refined to a final side panel – ready to be assembled with a body on the production main line. The last robot in the manufacturing sequence has in purpose to provide the carriers, and the 'conveyor SPO', with side panels. The robot can either pick a side panel that has just been machined in the production cell (model 440 or 444) or a side panel that is buffered on a 'wagon' (model 650 or 651), positioned next to the robot. If the robot is controlled to pick a panel from the wagon, it is always confined to pick the closest stored one. The wagon has a capacity of four panels and is manually replaced by a new when it is empty. In addition to

[2] Excluding so-called mono carriers operating in the mono conveyor (see figure 3a).

the robots, the ‘SPO production cell’ requires one operator. This operator is also partly responsible for the ‘mono uploading’ station. (See figure 3a)

All four SPO models (440, 444, 650 and 651) are then transported by carriers to the common ‘SPO buffer area’ (see figure 3a), where they are stored on model specific tracks. The buffer area of SPO includes two types of buffers, namely ‘pre-buffers‘ and ‘ordinary buffers‘. Figure 3b shows an overview of the ‘SPO buffer area’ where the dark (blue) and the light (white) triangles represent ordinary buffers and pre-buffers, respectively. The ‘pre-buffers’ are the ones in which side panels are stored temporarily if the ‘ordinary buffers‘ are full. The buffers differ from each other regarding capacity and design.

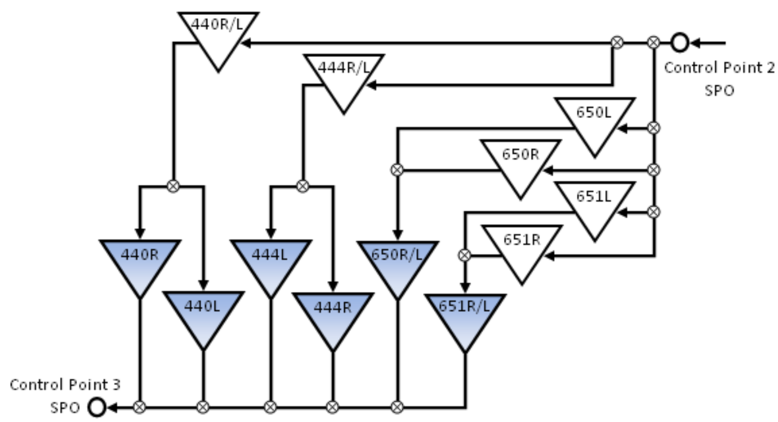


Figure 3b: Overview of the SPO buffer area

A side panel model leaves the buffer area only when a body, processing on the CPML, requests (orders) one. Since SPOL have a longer distance to travel before reaching the ‘SPO unloading left’ station than the SPOR have, SPOL is always the first to leave the buffer area. ‘Control point 2 SPO’ registers all incoming side panels and then forward them to the right model-specific buffer, while ‘control point 3 SPO’ controls if the one out checked side panel coincide with the requested ones. The corresponding control points in the CCSSPI work in the same way. Once the side panel has been unloaded, the empty carrier returns to the origin destination.

3.1.1.2 Current Production System for Side Panels Inner

The Current Conveyor System for Side Panels Inner (CCSSPI) is similar to the CPSSPO, except from that CPSSPI do not include any ‘mono uploading’ station as well as ‘mono conveyor’ (see figure 3a). Thus, no mono carriers are needed in purpose of transportation. Another difference is that CCSSPI consists of two completely separate (from production cell to unloading station) tracks for each side, SPI left (**SPIL**) and SPI right (**SPIR**). Thus, the CCSSPI avoids problems associated with shared conveyor tracks.

Like in CCSSPO, CCSSPI can be viewed as two processes – one transport process for SPIR and one for SPIL – both driven by a specific number of conveyor carriers. More specifically, the two processes are driven by 25 carriers each. The process for each side starts in the production cell in which smaller material components are merged together to a final side panel inner. The last robot in the production cell provides carriers and the 'conveyor SPI' with side panels from all four models, 440, 444, 650 and 651. Like in CCSSPO, the models 650 and 651 are stored (buffered) on a wagon positioned next to the last robot. The wagon has a capacity of four units and is manually replaced by a new when it becomes empty.

Side panels are transported from the 'SPI production cell' to the 'SPI buffer area' which is located next to the buffer area of SPO. The buffer area of SPI consist of model specific tracks where SPI right and SPI left are stored separately. The model specific buffers differ from each other regarding capacity and design. Like in 'SPO buffer area', a SPI is delivered only on request. When this occurs, both the SPI right and SPI left leaves the area at the same time. After the panel has been unloaded by robot the empty carrier returns to the production cells, waiting to be loaded with a new side panel.

3.1.1.3 Current Production Main Line

The Current production Main Line (CPML) transfers the four body models (including body model 651) through several complex work stations. Only one work station, out of 14 stations, is manually driven by an operator. All the other consist of one or a few complex robots, which are all operated automatically. Two such stations are 'SPO unloading' (left and right) and 'SPI unloading' (left and right) (see figure 3a). These two have in purpose to provide (frame) car bodies, processing at the CPML, with SPI and SPO, respectively. This is done with help of welding operations. Moreover, the operation times together with the line speed results in a throughput rate at approximately 17 jobs per hour which corresponds to a daily production rate at approximately 140 bodies.

In the beginning of the observed CPML, the bodies of Saab 9-3 series (model 440 and 444) and the bodies of Saab 9-5 series (model 650 and 651) are both transported on two separate lines (see figure 3a). Each model does always, at least, arrive in pairs on the two separate lines. Further downstream, the two lines are merged together in the so called 'mixing-point'. The mixing point is controlled by programmable logics and customizable parameter values. Along the CPML, there are also several sensors deployed to be able to control the flow of both SPI and SPO. For instance, two order points – one for ordering SPO and for ordering SPI – exists. When a body passes each of these points, a side panel (either a SPI or SPO) is ordered from the buffer area. (See figure 3a)

3.1.2 Future Production System

When the model range increases by a fourth (651[3]) and an additional fifth (540) body model in year 2012, all three systems described above – the CPML, the CCSSPO, and the CCSSPI – will be extended in order to meet the new requirements. Therefore, the FPS may be viewed as a sum of the CPS, discussed above, and also of a number of future extensions (investments) not yet implemented by Saab management. Figure 3c shows the FPS and its three subsections – the Future Production Main Line (FPML), Future Conveyor System for Side Panels Outer (FCSSPO), and Future Conveyor System for Side Panel Inner (FCSSPI) – including their future extensions. These extensions are concisely discussed in the following two sections.

3.1.2.1 Future Production Main Line

The Future Production Main Line (FPML) contains a couple of changes. Above all, the all-new body model 540 will require that an entirely new production line is implemented. This line will diverge from the production main line (CPML) after the unloading station SPI, and then later on merge with the main line again. Consequently, the new line will be placed in parallel with the main line. Further on, the body model 540 will require two new unloading stations – one for framing SPI and one for framing SPO. These two stations will be placed at the new production line. (See figure 3c)

The throughput rate of the two lines – the new 540 production line and the CPML – will have a throughput rate at 20 jobs per hour and 35 jobs per hour, respectively. When these rates are used, an extra operator will be hired to the SPO uploading station in order to meet the new requirements. This operator will have full responsibility for the uploading procedure for both SPOR and SPOL. The former two operators will only be responsible for the production cells.

3.1.2.2 Extensions of FCSSPO and FCSSPI

Both SPO and SPI for body model 540 will be manufactured exactly in the same manner as for body model 440 and 444. It means that the former will be initially, processed by the 'SPO mono uploading' station, then transferred by the 'mono conveyor' and finally processed by the 'SPO production cell'. It also means that the SPI for body model 540 will be processed by the 'SPI production cell'. (See figure 3c)

[3] Body model 650 will go into full production.

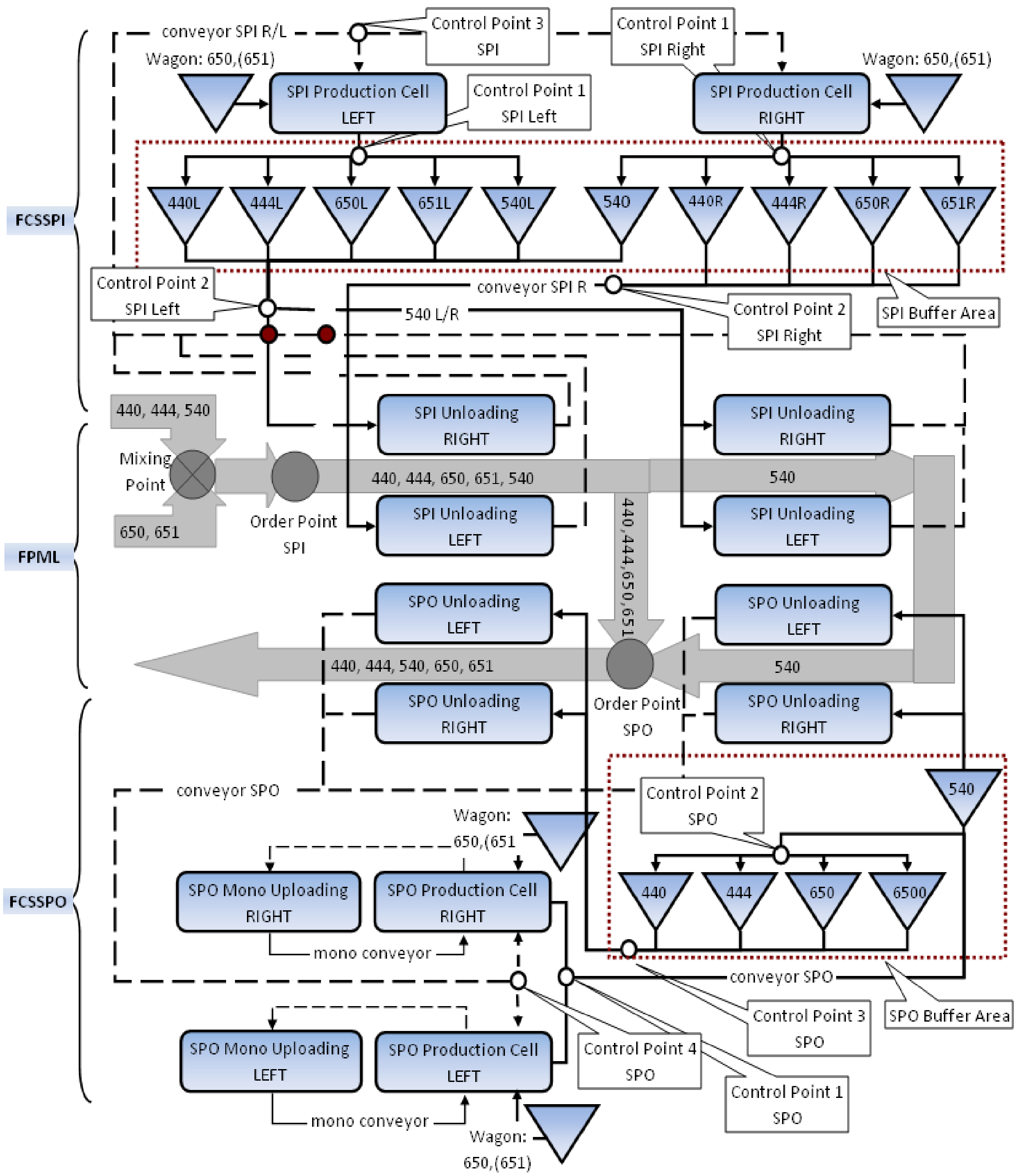


Figure 3c: Schematic overview of the FPS

The loading wagons, which are positioned inside both the 'SPI production cell' and 'SPO production cell', will in the FPS be loaded additionally with model 651. Thus, these wagons will constitute a buffer for both models 650 and 651. Moreover, the last robot in each 'production cell', the one which provide the conveyor system with different side panels, will not be able to choose between the two models stored on the wagon. Like in the CPS, the robot will always pick the closest one (the one in front of the queue).

The implementation of the new 540 model will also imply modifications of, and new investments in, both conveyor SPI and conveyor SPO. At first, both 'conveyor SPO' and 'conveyor SPI' will be expanded by an additional buffer each. In the conveyor for SPI, both the left and right side panels will leave the buffer area on the same conveyor track due to space limitations/requirements. In the conveyor system for SPO, side panels of model 540 will diverge from the common conveyor track to a separate buffer, located close to the new unloading stations at the main line. Thus, an extension of the current conveyor system for SPO will be required. The implementation will also require an extension of the current conveyors system for SPI. This extension is complex and involves a couple of serious solutions. Such solutions are two intersections marked as red (dark) circular dots in figure 3c.

3.2 Control logic of FPS

The three sections – the FPML, FFSSPO, and FCSSPI – will be communicating with each other in the same manner as in CPS, with some additions for body model 540. As discussed in section 1.2, the presence of the PLC and its control logic makes the modelling system even more complex. The control logic can either be attributed to the both conveyor systems (FCSSPO and FCSSPI) or the FPML.

3.2.1 Control logic of FCSSPO and FCSSPI

The control logic related to the future conveyor systems and its carriers has two significant functions. Firstly, the control logic has in purpose to prioritize the side panel model needed at most and, secondly, to restrict the number of a certain side panel model. Together, these two functions are used with the intention to make the intelligent decision – to order the most critical/needed side panel model at the very moment and thereby reduce the number of carriers required. Moreover the logic is used in all situations where side panels are loaded into the conveyor systems (e.g. in each mono uploading station). The logic is also used at the first station in each 'SPI production cell', where it decides which model to start to build.

The prioritization and restriction decisions are influenced by three types of parameters which are; customizable parameters, static parameters and dynamic parameters. All three parameters are specified for each individual model as well as for right and left side. Further on, the 'customizable parameters' can be divided into prioritization and restriction parameters. Both are used in order to optimize the decision of in what sequence the models shall be built relative to each other, as determined in accordance with the production forecast. The parameters could for instance be changed if there is a significant change between the relative production volumes of the body models.

The 'static parameter' controls the absolute number of transportations within a certain area in the conveyor system. Its value is usually decided depending on the size of the buffer and it is rarely changed. The intention of this parameter is to avoid so-called blocking situations when there is more carriers on their way (up) to a buffer than it can handle. If this occurs, it could imply that the last carrier stops just before the branch (see e.g. control point 2 SPO in figure 3c), and thus blocking other carriers trying to reach their buffers. Thus, a buffer can run out of carriers (side panels). When a buffer becomes empty, meanwhile a car body on the FPML request one side panel from that empty buffer, there is a risk that the entire conveyor system stops and thus also the production main line.

The ‘dynamic parameter’ counts the number of bodies of a certain model, positioned within a specific range on the production main line. It also counts the number of side panels in the conveyor system within certain intervals. The counting intervals on the production main line are as wide as possible and located upstream as early as possible. A wider interval means that more information is considered about the need in the nearest future. Two of the intervals on the main line are so-called floating intervals, meaning that their ranges are dependent on situation.

3.2.1.1 Prioritization and loading restriction algorithms

The applied algorithms of control logic have more or less the same structure regardless of conveyor system. Minor deviations regarding specific interval exists, depending on where the algorithms are used. Before a model is loaded into the ‘mono conveyor system’ or into a ‘SPI production cell’, a ‘prioritization ratio’ is calculated by the following formula:

$$\text{Prio.ratio} = \frac{\text{'Customizable priority value'} + \text{'Dynamic value main line'}}{\text{'Dynamic value conveyor'}}$$

The side panel model with the highest ratio value will be prioritized and thus loaded into a system. In situations where external circumstances (e.g. material shortage) prevent the side panel with the highest ratio to be processed, the side panel with the second highest ratio will be picked. The ‘customizable priority value’ is set by the production management and it is commonly used to control the last robot in both SPO production cells and SPI production cells. More specifically, the value is used to make the decision whether to pick a side panel of body model 44X or whether to pick a side panel of body model 65X. The ‘dynamic value conveyor’ continuously counts the number of carriers in a defined conveyor system area for each model and side. The ‘dynamic value main line’ counts the number of each model within a certain interval on the main line. When the prioritization ratio is calculated, restriction conditions are executed according the following expression:

$$
\begin{aligned}
&\max = CustomizableRestrictionValue + DynamicValueMainLine\\
&\mathit{if}\ \max \le StaticValueConveyor \quad and \quad \max \le DynamicValueConveyor \quad then\\
&\qquad ratio = 0\\
&elseif\ \ DynamicValueConveyor \ge StaticValueConveyor \quad then\\
&\qquad ratio = 0\\
&end
\end{aligned}
$$

The ‘CustomizableRestrictionValue’ is set by the production management and has mainly two functions. First, if there is no car body on the production main line within the interval for the ‘dynamic value main line’ parameter the condition allows the system to load as many carriers as defined by ‘CustomizableRestrictionValue’. Second, the higher the value of the ‘CustomizableRestrictionValue’ is, the less likely it is that the first *if*-expression with the two conditions becomes true and assigns the ratio value zero. A ratio equal to zero implies that the corresponding side panels is blocked and not allowed to be loaded into a conveyor system or initiated in a SPI production cell. A lower ‘CustomizableRestrictionValue’ increases thereby the probability of blocking scenarios. The *elseif*-expression compares the number of loaded carriers against the highest number of allowable loaded carriers. The ratio assigns the value zero if the number of loaded carriers is higher or equal to allowable number.

3.2.1.2 A third uploading restriction for the SPO production cells

As discussed above, the last robot in each ‘SPO production cell’ makes the decision whether to pick the panel from either the production cell (440 or 444) or from the wagon (650 or 651) located next to it. A too large difference in the number of loaded left and right side panels of a certain model in the buffer area of the same model may cause a blocking scenario in the pre-buffer area (see figure 3b). Therefore, a third requirement must be met due to the layout of the buffer area. This restriction controls that the difference between the number of left and right side panels of a certain model does not exceed a certain amount. For example, if the ordinary buffer of SPOR 440 and SPOL 440 is full and empty, respectively, meanwhile a SPO 440R is waiting in the common pre-buffer area for both SPO 440R and SPO 440L, no other SPO 440L are able to pass by (see figure 3b). By controlling that the difference between the number of left and right side panels of model 440 do not exceed a certain set limit, this situation can never occur. Except by the last robot, the third restriction is also used at control point 1 SPO since the relation between left and right side panel may change when panels with inferior quality are removed.

3.2.2 Control logic of FPML

The FPML is also linked with control logic. In the beginning, at the ‘mixing point’ (see figure 3c), logic operations (managed by a PLC) controls the mix of the two body model ranges Saab 9-3 (44x) and Saab 9-5 (65x). The control is based on a ratio value (mixing point ratio), set by Saab production management, which corresponds to the desired mix of body model range 44x and 65x at the production line. The control logic strives constantly to emulate this set ratio value. For example, let say that a ratio between model ranges 44x and 65x is set to one third. It means that the production management strives to get a mix where every third car body is of model range 44x and the other two are of model range 65x. If then the real ratio is higher than one third the control logic at the mixing point will give priority to pass bodies of model range 65x. On the contrary, if the real ratio is lower than one third the model range 44x will be prioritized. Except the ratio value, the production management also sets how many bodies of a specific model range that will pass through at a time. This batch size is set daily to the value of two. The overall intention of the mixture control is to level out the work load further downstream in the production.

To get side panels to the unloading stations, car bodies have to pass order points. There are one order point for ordering SPO and one order point for ordering SPI. When passing an order point, a request for one left and right side panel is sent to the buffer area and if the corresponding panels exist, they will be out checked from the buffer and start to move towards the unloading stations. Both side panels (left and right) must be in position in the buffer before they are allowed to be checked out. Material shortage in the buffer leads to a backlog order which will be executed as soon as one left and right side panel of the requested model has entered the buffer.

3.3 Carrier

Each side panel are transported to a station with a so-called carrier. A carrier consists of both an electric motor and also a fixture which the side panel are hanged onto. The fixture can handle all five models but is restricted to either left or right side panels. The electric motor moves the carrier forward and it alternates between three different speeds, which are all pre-programmed. The lowest speed is used when there are high requirements on accurate positioning, for instance at positions where loading and unloading procedures are executed. The middle speed is the most frequent used for transportation but on a few straight sections in the conveyor system the highest speed is used.

Each carrier is also equipped with an inductive sensor and a rangefinder. The inductive sensor stops the carrier immediately right before it collides with another carrier ahead. The rangefinder has in purpose to slow down the speed if the carrier travels with the highest speed and starts to approach another carrier. Both the inductive sensor and the rangefinder can only identify carriers which are located straight ahead on the same height. Hence, most of the conveyor tracks are divided into so called safety zones wherein only one carrier is allowed at a time. The safety zones are almost always present around curves as well as around ascending and descending tracks in order to prevent collisions which may damage both carriers and side panels.

Chapter Four
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METHODOLOGY

The purpose of this chapter is to describe as well as motivate the choice of analysis approach (methodology) used in the study. At first, the chapter presents an overview of chosen methodology, its structure and activities. This overview is thereafter followed up by more detailed discussions organized in accordance with the chosen methodology structure. The chapter begins by presenting the activities of the pre-study. Thereafter, applied activities to meet objective two and three of study are discussed in more detail.

4.1 Applied methodology of study

As discussed in section 2.2.2, literature in the field examines several different methodologies for modelling a system. A few of them are developed completely from scratch and others are just modifications intended for a specific purpose. This study is based on a slightly adapted version of the analysis methodology as defined by Banks *et al.* (2005, p.14-18). Figure 4a shows an overview of the applied methodology (study procedure) of study. The methodology can be divided into three major phases which are 'pre-study', 'development of model' and 'analyses of experiments'. These phases, and their activities, are described and motivated in the following sections.

The importance of a good problem formulation and setting of objectives cannot be stressed out sufficiently enough. As discussed in section 2.2.2.1, the step of 'problem formulation and setting of objectives' is critical when performing modelling projects since it sets the direction of the project. In this study, the problem was to a large extent initially communicated and formulated by Saab management. The communication was carried out especially through a couple of meetings with involved parties. It was of importance that involved parties really understood the problem. However, the problem formulation was later on slightly revised as new system discoveries were made.

Based on the problem formulation appropriate objectives were formulated. These objectives were essentially developed by the analysts. The objectives of study were in the same manner as for the problem formulation revised during the study (see figure 4a). Once the problem and the objectives were established a project plan, in the format of a Gant-Chart, was developed.

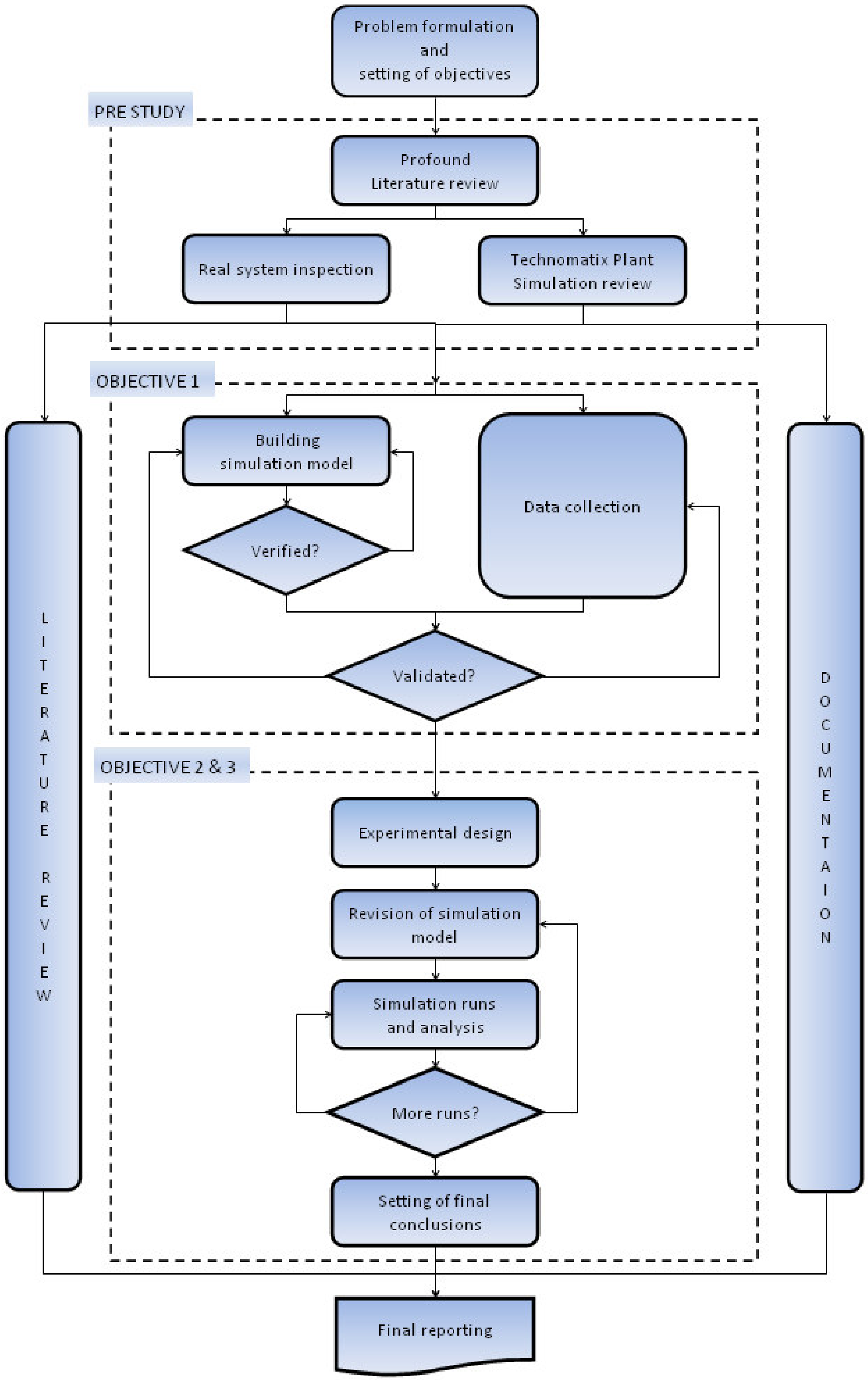

Figure 4a: Applied methodology of study

Throughout the study, more or less literature studies as well as documentation were carried out. As discussed in section 1.5 the theory was mainly obtained from books and scientific articles which all were relative up to date. The theory provided important knowledge in how to perform a simulation study and thus the theory contributed to an increased self-confidence. Further on, information given from meetings, measurements and other significant observations were documented throughout the study. In this way, previously documented and saved information could be retrieved very easily when there was a need for this. At last, documentation and theory formed the basis of the final report (see figure 4a).

Finally, a consistent way of thinking throughout the study was the mindset 'Symptom – Cause – Remedy' discussed in section 2.1.3. By applying this universal problem-solving sequence, improvements were realized in a structured way.

4.2 Review of literature, system and software

Except the literature studies that where conducted continuously during the project, a profound literature review was carried out in the very first. It involved identification of related scientific journals, articles and books but also obtaining essential knowledge about what to consider before and during a simulation study. For instance, as a result of the literature review a determination of whether discrete-event simulation was an appropriate tool for the intended purpose at hand was considered before (Banks *et al.* 2005, p.14).

Another central activity in the pre-study was to inspect and thus understand the Future Production System (FPS), also synonymous with the real-world system in this thesis, of the body plant. To understand this system, several hours were initially spent on the shop floor as well as in the conveyor system at ceiling level. Different kinds of questions were asked to different employees in order to understand key aspects such as entities (side panels), constraints (e.g. capacity of conveyor) and resources (e.g. carriers). Also, specific production scenarios were arranged in order to discover things that might be missed in the problem formulation. The overall goal was here to understand the production system sufficiently enough to accurately model it.

In parallel with the inspection of the future production system, a thorough learning of the software Technomatix Plant Simulation was carried out. The learning included both meetings with people who were familiar with the software as well as performing of a series of basic tutorials. For instance, a meeting was held with an experienced and skilled consultant from Siemens Industry Software AB.

4.3 Development of the simulation model

The pre-study provided a thorough understanding of the FPS which was a necessary in order to be able to fulfil objective number one – to develop a simulation model of the real world system. In addition, all commonly cited activities except model conceptualization were undertaken. It involved activities such as data collection, model translation as well as verification and validation of the simulation model. Model conceptualization was not here undertaken as a separate step since the software in use (Technomatix Plant Simulation) was 'very visually' in itself. Thus, it was preferable to merge the activity of model conceptualization into the activity of ´building a computerized model'. The activities of data collection, model translation, and verification and validation are described in the following sections.

4.3.1 Data collection from FPS

The data collection of study was only superficially managed in the same manner proposed by Johansson *et al.* (2008), discussed in section 2.2.2.2. The approach was used repeatedly during the study.

The data collection procedure from the real-world system started with an identification of relevant parameters. As previously mentioned, this work was conducted in parallel with the construction of the computerized simulation model (see figure 4a). While the parameters were identified, the accuracy of the same was also specified. Since output of a simulation model relies heavily on input data and its quality, it was very important to collect input data with sufficient accuracy. The level of accuracy was in particular determined by the time it required to collect the same. Once relevant parameters were identified as well as accuracy requirements specified, the data were categorized in accordance with the proposal by Robinson *et al.* (1995, p.63). A data sheet was created for this purpose in order to facilitate the process. The bullet list below shows some examples of data parameters of study, categorized as 'available data' (category A), 'not available data but collectable data' (category B) and 'not available and not collectable data' (category C). Also, specified accuracy requirements are given in the brackets. The listed data parameters are somewhat simplified.

- **Category A (available data):**
  - Operation and down times (e.g. CT, MTBF, MDT etc.) [± 0,5 seconds]
  - Number of operators and their responsibilities
  - Conveyor rail dimensions [± 5 millimeters]
  - Control logic parameter values (e.g. priority- and restriction values)
  - Buffer capacities

- **Category B (not available but collectable data):**
  - Dimensions of carrier [± 5 millimeters]
  - Location of safety cutters (safety zones) [± 25 millimeters]
  - Carrier travelling time [± 0.5 seconds]
  - Waiting times for carriers (e.g. switch- and identification stops) [± 0.25 seconds]
  - Location of control logic- and safety cutters [± 25 millimeters]

- **Category C (not available and not collectable data):**
  - Operation times at the FPML (e.g. CT, MTBF, MDT etc.) [±0 seconds]
  - Mix of body models progressing on the FPML
  - Production volume of each body model
  - Throughput rate of FPML for FPS [± 0.05 JPH]

When the data was categorized, both available and not available data were collected. Available data such as operation times and control logic parameter values were all compiled from various documents supported by the production management at Saab. Also, dimensions of the entire conveyor track system were given through a drawing developed in AutoCad. It was of great importance to get these dimensions as accurate as possible since many other parameters were dependent on these dimensions (such as speed of carrier and buffer capacity).

The data that were not available were either collected through measurements or given through estimations carried out by responsible. Measurement of various times, such as traveling and waiting times of carriers, were all realized through simple time studies. In general, all time measurements/studies were carried out three times in order to be able to calculate average times. Thus, the time measurements were controlled for true deviations but also for human mistakes. Even though some of the studied waiting times were very short (less than five seconds), all times was measured by a stopwatch. Another great activity when collecting data that were not available was to measure the location of both safety- and control cutters. These locations were measured by using a simple measuring stick. Much time were spent on measuring various times as well as cutter positions in the conveyor system. Thus, this activity represented by far the largest portion of the total time spent on data collection.

Further on, a large portion of the collected data was categorized as not available and not collectable. This was because of that several resources, such as the related machines to the FPS, did not yet exist and thus not available for measurements and analysis. All data that belonged to this category was estimated in some way. For example, the throughput rates – a pace of 20 jobs per hour for the production of the 540 model and a rate of 35 jobs per hour for the production of 440, 444, 640 and 644 models – were both decided by our supervisor at Saab. These two rates would represent the future (in year 2012) customer demand.

Only a small portion of the collected data was considered as so-called 'raw data'. Much of the gathered data, such as given operation and break down times, were already pre-analyzed by the Saab management and thus no further analysis of this data was required. However, as a next step in the process all raw data that were collected were analyzed and transformed to enable a representation of the same in the simulation model. For instance, a carrier speed for a specific conveyor track section was calculated by dividing the distance of the same section with the traveling time it required to travel this section. Here, in this example, the distance and the traveling time were both considered as raw data and the carrier speed was seen as a representation of the two. The analysis of raw data did not require any major efforts since all collected raw data were seen as constant.

The step of data collection accounted for a large portion of the total study time. The main cause was poor availability of data regarding the conveyor system (e.g. measurement of conveyor distances and cutter positions etc.).

4.3.2 Simulation model building

The building of the simulation model was carried out in parallel with the data collection from the real-world system. The data collected from this system were of course the most essential part of the input model, but not the only. Knowledge from prior experience as well as information from literature reviews were also essential resources in the model input. Figure 4b summarizes all essential input data resources of this study. The frame of the data and the real-world system is thicker than the other frames in order to highlight the superior importance of this resource. The prior experience was primarily obtained from the course 'Simulation of Production Systems' conducted in fall 2009 at Chalmers University of technology.

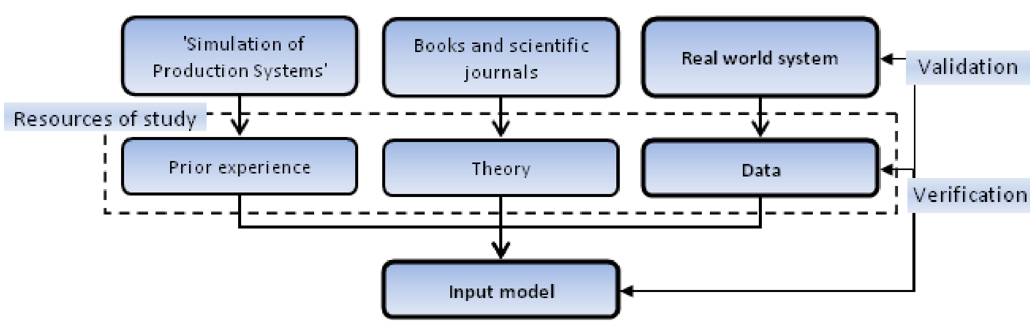

Figure 4b: Modelling simulation inputs of study (Source: modified picture, Banks 1998, p.57)

Through the work of model translation, relatively small sections of model logic were added and then verified before more logic was added. By doing so, major error coding and thus time wasting was avoided. The approach is in line with the theory discussed in section 2.2.2.5. Moreover, the applied methodology can be compared to the approach of 'depth first', discussed in section 2.2.2.2. It means that a relatively small section of the system was modelled in full detail rather than that the entire model or a major section of it was build with a minimal level of detail. Thus, the activities in the input data management process discussed above was carried out repeatedly.

4.3.3 Verification and validation of the model

Verification and validation were both carried out continuously during all phases of the modelling process. Once a suitable result, or an intermediate status, was achieved it was verified and validated in order to detect potential faults. By doing so, faults could be detected very quickly and thus no major recoding was necessary.

Even though the verification and validation was carried out through the whole modelling process, a lot of effort was especially put into ensuring that the final computer model, and its behaviour, reflected the collected input data at hand as well as the real-world with sufficient accuracy. Figure 4b illustrates these two activities. To check if the model reflected the input data with sufficient accuracy, subsets of the model code was verified. The procedure can be viewed as a so called 'verification and white-box validation', discussed in section 2.2.2.4, and was realized in several ways. The code was for instance verified by the analysts going through the code, line by line. Various aspects such as timing, control of flows and control of elements were verified. This was a very time-consuming process but increased the reliability of the model. In order to get a more objective point of view several important parts of the code were additionally verified with help of responsible at Saab. For example, several hours were spent going through all the code regarding the control logic with a maintenance employee. By doing so, a few error codes were found which later on were corrected and approved by concerned responsible.

Also, much of the validation work constituted of so-called 'black-box validation**'**, discussed in section 2.2.2.4. A lot of effort was put into determining that the overall model, and its output behaviour, reflected the real-world system with sufficient accuracy. The superior best method for this purpose was to analyse events by studying the animation window. The use of the animation window made it easier to control various aspects such as buffer capacities and control logics. For example, by studying the animation window it was easy to determine if a specific body model positioned at the ordering point on the production line triggered a release (launch/start) of right kind of side panel from the buffer area. In addition to the animation window, different global and local variables were used in order to control the overall model and its behaviour.

4.4 Identification of relationships and bottlenecks

Once objective number one – to develop simulation model of the FPS – was fulfilled the focus was on objective number two and three. These two objectives involved *to identify the relationship between the number of carriers for each subsystem (inner & outer) and the throughput rate out of the future production system* as well as *identify all potential bottlenecks that prevent the system to reach its maximum throughput rate*. Activities such as experimental design, model revision, production runs and analysis were all undertaken for this purpose.

4.4.1 Experimental design and revision of model

In the first step after the development of the simulation model, the experimental design was carried out. As discussed in section 2.2.2.5, selecting warm-up time and actual experiments as well as deciding run time and number of replications are all fundamental issues to set when designing experiments. These four issues, together with the various pre-studies, formed a kind of a rough experimental plan of how desirable results would be produced and thus achieve objectives of study. Furthermore, these issues were addressed in a specific order. Figure 4c shows the experimental design of study including all four issues and their order of priority. The initially selected warm-up time as well as the decided run time and number of replications were applied through all executed experiments. The following sections examine the processing/treatment of these four issues.

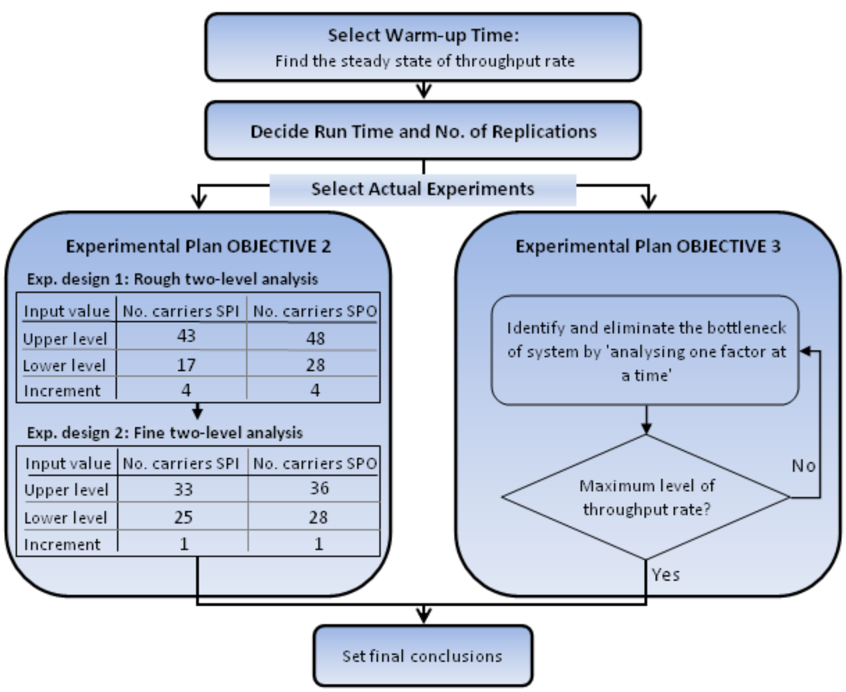

Figure 4c: Experimental design of study

4.4.1.1 Selecting warm-up time

The warm-up time was selected initially through a simulation run in which the interaction between the 'instantaneous hourly throughput rate of bodies' and the 'real time' was observed. The purpose of the measurement was to provide data on when in real time a steady state of the throughput rate was reached. By doing so the initial conditions could be selected and thus a biased result could be avoided. Diagram 4a presents the relationship between the throughput rate and the real time. As the diagram shows, a steady state of throughput rate was reached after approximately five days of production, indicated by the vertical (red) line in the diagram. Since no production takes place on the weekends, the warm-up time was set to seven (7) days (five days of production plus two days of no production).

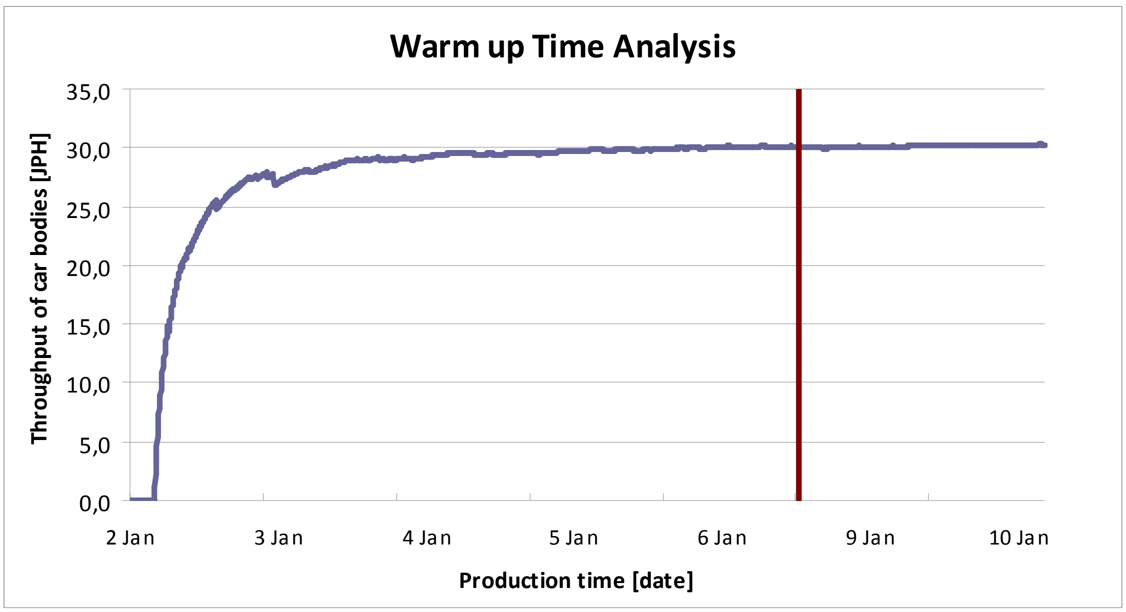

Diagram 4a: Specification of warm-up time

4.4.1.2 Deciding run time and number of replications

The total simulation run time was set to fifty (50) days (including warm-up time and weekends) which corresponded to 31 production days (approximately 248 production hours). Thus, all output measures were collected during a period of 31 days excluding warm-up time and weekends. The length of the run time was actually based on several simulations with different run times. Simulations with a long run time (e.g. above 50 days) did not show any abnormal behavior in output in comparison to the ones with a short run time (e.g. below 30 days). Therefore, a conclusion was that the model events occurred between relatively short and regular intervals and thus the length of run time was not a critical factor. The simulation of 31 production days seemed to be sufficiently good enough as well as a not too time consuming.

Furthermore, the number of replications was set to twenty (20). By applying the amount of 20 replications, deviations due to unfortunate random events were reduced. These kinds of events were very rare but could cause major problems if they were present. An example of such an event would be a lock-out in the conveyor system due to a lack of carriers. The number of replications made it also possible to establish reliable statistical analysis. The balance between decided run time and number of replications was also considered to be appropriate in order to achieve credible and statistically correct results.

4.4.1.3 Selecting actual experiments

As a final issue the actual experiments (scenarios), concerning both objective two and objective three, were designed and selected. The most important criterion in the selection of design was its ability to meet set objectives. Another important goal when selecting the actual experiments, or experimental plan, was to minimize the total number of experiments and thus to save time. Two different experimental plans were naturally applied for the two objectives (see figure 4c).

For the development of the two experimental plans several activities, of those discussed in section 2.2.2.5, were undertaken. These included activities such as definition of experimental goals, identification of independent and dependent variables, selection of an experimental design and validation of design properties. Also, a couple beneficial tools were applied in order to facilitate the activity at hand. For instance, a fishbone diagram was applied in order to facilitate the identification activity of independent and dependent factors. A simplified such a diagram is shown in appendix A. Moreover, the 'experimental design' for objective three was broadly in line with the approach of 'one factor at a time analysis' (see section 2.2.2.5).

More specifically, concerning objective two – *to identify the relationship between the number of carriers for each subsystem (inner & outer) and the throughput rate out of the future production system* – the actual experimental plan was divided into two steps. Since little understanding of the interactions existed, the first planned experimental design was intended to provide and identify a rough picture of the relationship. Therefore the input value (number of carriers) of SPI and SPO was incrementally increased by four within specified boundaries (see figure 4c). Thus, an extensive area could be identified with low precision in order to find the area of interests. As a second step, a more detailed identification was performed around the area of interest. The number of carriers for SPO and SPI was then varied incrementally by one and thus a more presentable diagram was produced.

Furthermore, the two experimental designs for objective two were made up of so-called 'two-level experimental designs'. It meant that the two input values, 'number of carriers SPI' and 'number of carriers SPO', were diversified independently of each other within the specified boundaries. Thus, several experiments were realized in only one simulation run. The number of experiments in each experimental design was then decided by the increment size (4 and 1) which was entered into a table for each input value. Even though only two input values were applied, the design resulted in a large amount of experiments. For example, the specified values in the experimental design intended for the rough analysis resulted in 36 experiments (see figure 4c). By considering that each experiment consisted of twenty replications one may realize that this was a time consuming part.

In order to fulfill objective three – *to identify all potential bottlenecks that prevent the production system to reach its maximum throughput rate* – the improvement process for throughput, developed by Goldratt, was generally applied. Its five steps, discussed in section 2.1.2, were practiced in order to increase the throughput rate and thus improve the system. At first, the constraining factor (bottleneck) was primarily identified by just watching the amount of work in front of concerned resources. This method was chosen due to its simplicity. Once there was a strong suspicion of a weak link in the system, it became object for a deeper analysis in order to ensure that this resource really was the bottleneck. If it proved to be so, the barrier of resource was eliminated in some way in order to improve the throughput. The focus was not here to carry out deep analyses of identified bottlenecks but rather to point out which those were. If the new throughput rate was equal to the maximum throughput rate specified in objective one, no more simulation runs was needed. If throughput level was below the maximum rate, the cycle was repeated once more.

In order to realize all the selected actual experiments, minor revisions of the developed simulation model in objective one were required (see figure 4a). These revisions were carried out repeatedly, once a new experiment was decided to run.

4.4.2 Simulation runs and analyses

Simulation runs and analyses was realized in line with the experimental plan discussed above. Thus, a large number of replications were executed and each replication consisted of a unique set of random values. Due to the large amount of replications a total number of 24 computers were used. The large number was necessary in order to realize the study within a reasonable time frame.

Moreover, analyses were to a large extent carried out in Microsoft Office Excel. Technomatix Plant Simulation (the software in use) had a function that on command automatically transferred all desirable global or/and local data variables to a work sheet in excel. Thus, the analysis was facilitated.

Chapter Five

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RESULTS AND ANALYSIS

The following chapter presents the results and analysis from simulation runs carried out during the simulation study. The chapter is divided into three subsections. At first, results and analysis associated with the development of the computerized simulation model is presented (objective one). This is followed by a presentation of the relationship between number of carriers for each system (FCSSPO and FCSSPI) and the throughput rate (objective two). At last, bottlenecks are identified and eliminated in purpose to reach the maximal throughput rate out of the production system. In turn, each subsection starts with a presentation of the results followed by analysis. Input data from the FPS are collocated in appendix B.

5.1 Objective one

In order to fulfill objective one – *to develop, with necessary and reasonable assumptions, a DES model of the FPS and thereafter to specify the maximum throughput rate out of the system without any disturbances* – of study, a few but necessary specifications of layout, control logic values and throughput rate out of FPS was required. These were not given by Saab production management and were considered to be both economically feasible as well as necessary in order improve the FPS even further. Moreover, the graphic interface of the developed simulation model and experimental results are shown in appendix C and appendix D, respectively.

5.1.1 Specifications of layout and control logic

The implementation of the FPS required several specifications of the layout and control logic. The following sections present the major and most demanding ones.

5.1.1.1 Static parameter value for SPO 540 model

The introduction of the new body model 540 entailed that new control logic parameter values were needed to be determined. These parameters were initially set to be the same as for model 440 due to the similarity between the production processes for these two models. But this assumption resulted in an overcapacity of carriers in the 540 SPO buffer. The static parameter for the 540 model in the mono uploading station, which has a limiting effect on the number of carriers in the 540 SPO buffer, was thereby analyzed even further.

The result of these analyses is presented in diagram 5a and it shows the average wait time that each car body has to wait on carriers in the unloading station in relation to static parameter value. As shown in the diagram, a higher static parameter value leads to a lower average wait time.

Based on the diagram, the static parameter value was determined to ten (10). It implies that only a maximum of 10 SPOL and 10 SPOR loaded carriers of model 540 are allowed to be in the area between the mono uploading station and the beginning of 540 SPO buffer at the same time (see figure 3c in section 3.1.2.2).

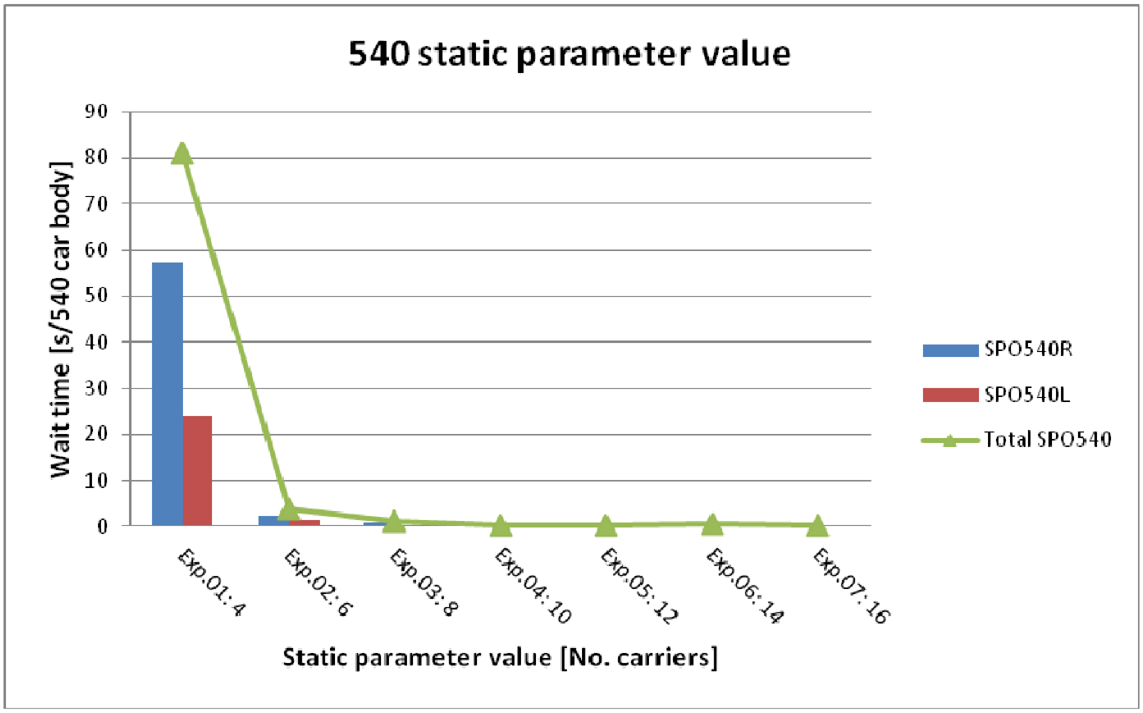

Diagram 5a: Specification of model 540 static parameter value

The buffer capacity of model 540 was found to be substantially higher than the capacity of the other buffers. In addition, the 540 SPO buffer is also placed next to the 540 unloading station, which means that the carriers have generally a shorter distance to travel in order to make a complete transportation cycle compared to the other models. By reducing the 540 static parameter value to 10, more carriers were available for the other side panel models without affecting the wait time for model 540.

5.1.1.2 SPI conveyor track prioritization rules

The expansion of the SPI conveyor track for model 540 induced two track intersections (see solid dots in figure 3c in section 3.1.2.2). This caused problems between the inflow of loaded carriers on the current conveyor track and the return flow of empty carriers, approaching from the 540 unloading station. A layout is presented in figure 5a and it clarifies how each SPI conveyor track is branching and reuniting around the two unloading stations.

Simulation analysis showed that car bodies on the main line is easily affected in terms of longer wait times in the unloading stations if wrong prioritizations are made at the two intersections. More specifically, the analysis showed that it is important that loaded carriers are prioritized in front of empty ones in order to attain an efficient flow through the intersections, but also to avoid collisions between carriers. Prioritization rules are also needed where carriers are reunited at the common return flow (see figure 5a). The most favorable results were given when the empty right carrier had the highest priority, followed by empty left carriers and finally the empty 540 carriers.

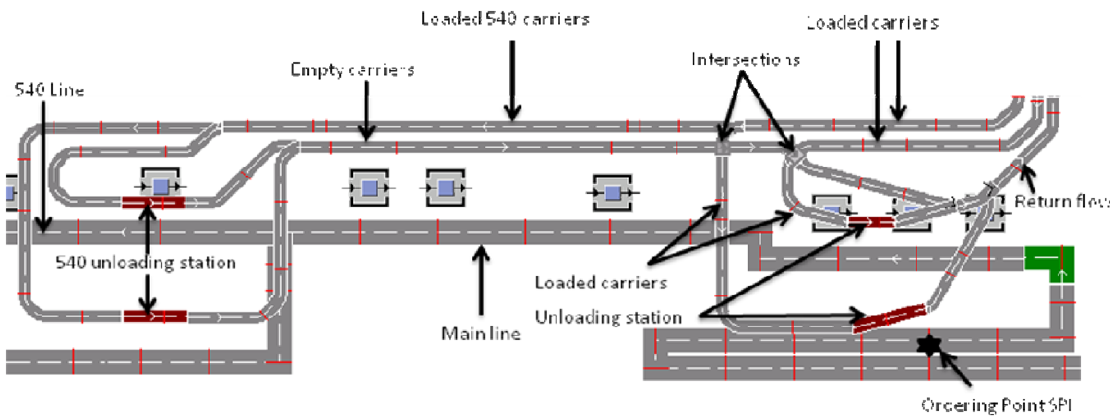

Figure 5a: Overview of the area around SPI unloading stations

The area around both the track intersections and were the return flow is reunited are divided into two so-called safety zones. The safety zones are shown in Figure 5b as (red) lines. Only one carrier is allowed to be within each safety zone simultaneously, except for the two lines marked as 'special condition'. If no empty carrier from the 540 unloading station is passing through the safety zones around the intersections, one carrier each is allowed to enter the 'special condition' area simultaneously.

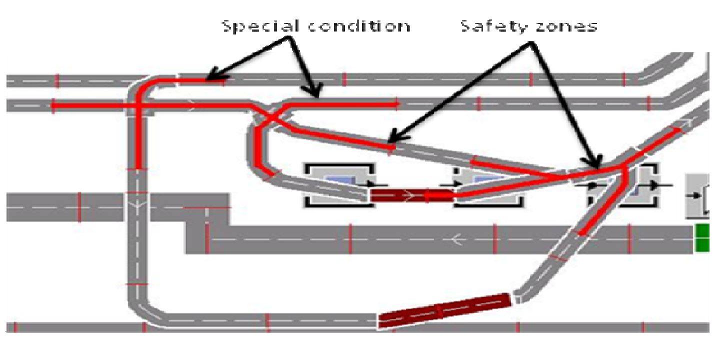

Figure 5b: Safety zones around SPI unloading stations

The safety zone around the reunited return flow is located close to the unloading station for right carriers. This implies that carriers enter the safety zone as soon as they have unloaded their SPI. Hence, the safety zone must be empty if the right carrier at the unloading station should be able to give way for subsequent ones as it leaves the station. If no prioritization rule exists it is highly possible that car bodies have to wait on side panels when empty right carriers are prohibited to leave the unloading station due to the traffic ahead of them. Hence, right carriers should have the highest prioritization to enter the safety zone. When the SPI left are unloaded, the carrier has two potential stop positions before it enters the common track and is thereby not as critical as for the right carriers, but should be prioritized in front of empty 540 carriers.

5.1.1.3 Check-out restriction parameter value

The control logic decides which model to build and priorities in the SPI production cells. It makes decisions depending on the current number of loaded carriers of each model within a certain interval, starting from the 'production cells' to the 'control point 2 SPI' (see figure 3c in section 3.1.2.2). When car bodies are passing the 'ordering point SPI', side panels are checked out from the 'SPI buffer area' and passing the control point 2 SPI. Thereby, they are considered as used and removed from the PLC interval.

The placement of the unloading stations for model 540 is more far away from the ordering point SPI compared to the unloading stations for the remaining models. Also the time between passing the ordering point SPI to when a car body is in position in the unloading station, is longer for 540 car bodies than for remaining models. The future conveyor track for SPI makes it thereby possible to check out significant number of 540 SPI before they are used. Consequently, the control logic in the SPI production cell will prioritize the 540 model when its number of loaded carriers is decreasing within a certain interval. This could lead to wrong prioritizations where 540 SPI occupies carriers which should be available for other models. This situation has been avoided by introducing check-out restrictions for the 540 model. The restriction implies that it is only allowed to be a certain number of loaded SPI 540 carriers between the control point 2 SPI Left and the 540 unloading stations. When the maximum number of out-checked 540 carriers is reached, the subsequent 540 orders will be placed in a separate backlog for 540 models. Once the 540 carriers are allowed to enter the restricted area, orders from the separate 540 backlog are moved back to the ordinary SPI backlog and prioritized. The check-out restriction parameter was analyzed by measuring correlation between the wait time for the 540 car bodies and the number of allowable loaded 540 carriers (see diagram 5b). The restriction value was set to three (3) in order to assure that the new check-out restriction rule itself will not cause any delays to the 540 unloading stations.

Diagram 5b shows how the wait time at the unloading station decreases with the number of allowed 540 carriers after control point 2 SPI. There is a significant decrease in wait time when the restriction parameter increases from one to two units. The next increment of the restriction parameter shows a more modest decrease in wait time followed by insignificant differences in wait time for the remaining experiment. The wait time in experiment three occurs due to buffer shortages which are not connected to the restriction parameter. A theoretical estimation also indicates that there is no need to have a higher restriction value than three (3). The cycle (operation) time of 540 unloading station is about 148 seconds and the transportation time (from buffer area to unloading station) for both left and right 540 SPI carrier is 324 seconds. Hence, 3 cycles in the 540 unloading station are sufficient for a fourth 540 SPI carrier to reach its destination in time.

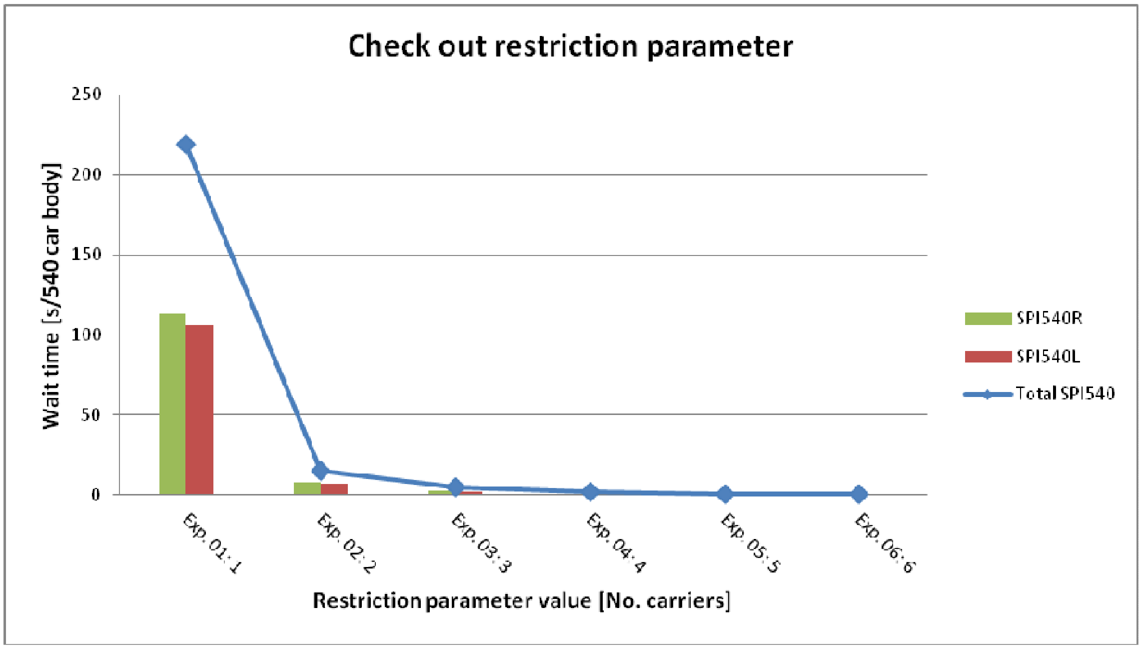

Diagram 5b: Specification of check-out restriction value for 540 SPI

5.1.1.4 SPI 540 Buffers

The available space for the expansion of the two SPI buffers is confined due to the already existing conveyor tracks. The 540 SPI buffer capacities (right and left) were estimated by calculating the number of carriers that would fit on the suggested conveyor track distance for the buffers. The capacity for the SPI buffers was decided to be eight (8) carriers for both left and right side.

5.1.2 Specification of throughput rates out of FPS

Objective one also included throughput rates specifications. Firstly, the maximal throughput rate out of the FPS, without any disturbances, was determined. Secondly, the throughput rate out of the FPS, consisting of the same number of carriers available for the CPS (36 carriers for each SPOL and SPOR system, 25 carriers for each SPIL and SPIR system), was determined. This rate was determined as a reference for upcoming improvements.

5.1.2.1 Maximal throughput rate without any disturbances

The simulation model was initially executed in order to specify the FPS's maximal throughput rate of car bodies, without any disturbances. The maximal throughput rate without any disturbances was specified to 36.1 jobs per hour (JPH). It means that without any downtimes and material shortages at the unloading stations the model can manufacture a maximum of 36.1 car bodies per hour which correspond to a daily production rate at 290 car bodies.

5.1.2.2 Reference throughput rate with today´s number of carriers

Today, there are 36 carriers in each sub-system (right and left) of CCSSPO and 25 carriers in each sub-system (right and left) of CCSSPI. By applying these numbers of carriers to the FPS, the average throughput rate of car bodies was determined to 32.8 JPH with a standard deviation of 0.1 JPH. The simulation was based on 20 observations. Furthermore, the total wait time for which the car bodies had to wait in the unloading station due to lack of side panels, showed to be as high as 16.2 seconds per car body for SPO and 11.0 seconds per car body for SPI.

5.2 Objective two

The first analysis of objective two was executed in order to get a rough overview of how the number of carriers would affect the throughput rate. A multilevel experiment with a variedly number of carriers for both SPO and SPI was carried out (see section 4.4.1) and the result is presented in diagram 5c. Moreover, all experimental throughput results related to objective two are examined in appendix E.

Diagram 5c shows that the throughput rate reaches a stable level when the number of SPO carriers (for both right and left) and SPI carriers (for both right and left) are 32 and twenty 25 (experiment 09), respectively. As a second step of analysis, a more precise analysis was executed in order to find the optimal number of carriers for each conveyor system. The result presented in diagram 5d, shows that the throughput rate becomes stable when the number of SPO carriers (for both right and left) and SPI carriers (for both right and left) are approximately around thirty-one (31) and twenty-six (26) (experiment 29), respectively.

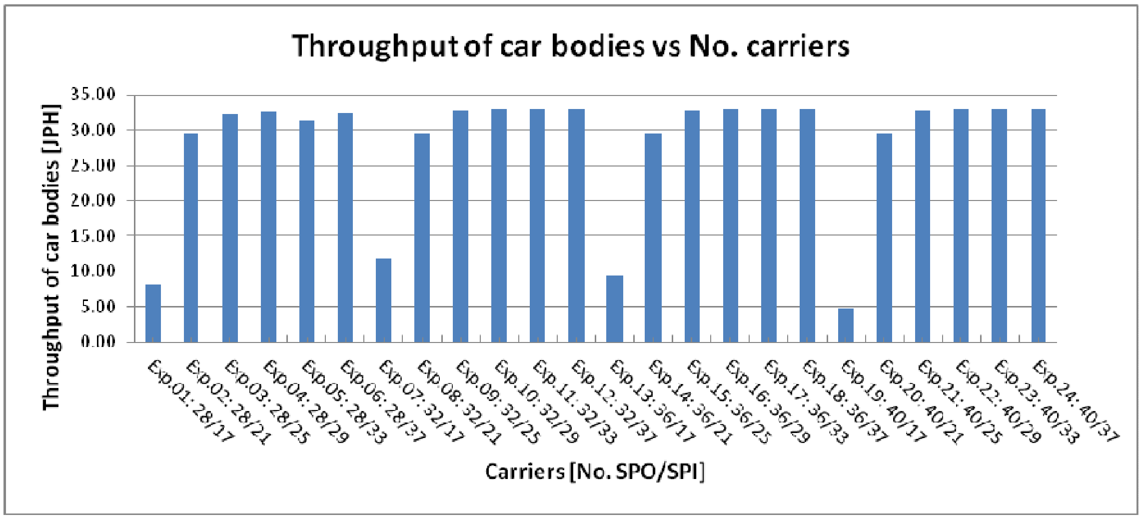

Diagram 5c: Specification of optimal (rough two-level analysis)

The CPS consists of 36 SPO carriers and 25 SPI carriers for both the right and left side panels. According to the simulation model, there is no need for additional carriers if the FPS remains as it has been describe in the report. The recommendation is instead to transfer carriers from the FCSSPO to the FCSSPI, which will, according to the developed model, result in an increased throughput compared to the initial state. By only reposition four carriers from FCSSPO to FCSSPI will give an increased throughput corresponding to thirty-three (33.0) JPH

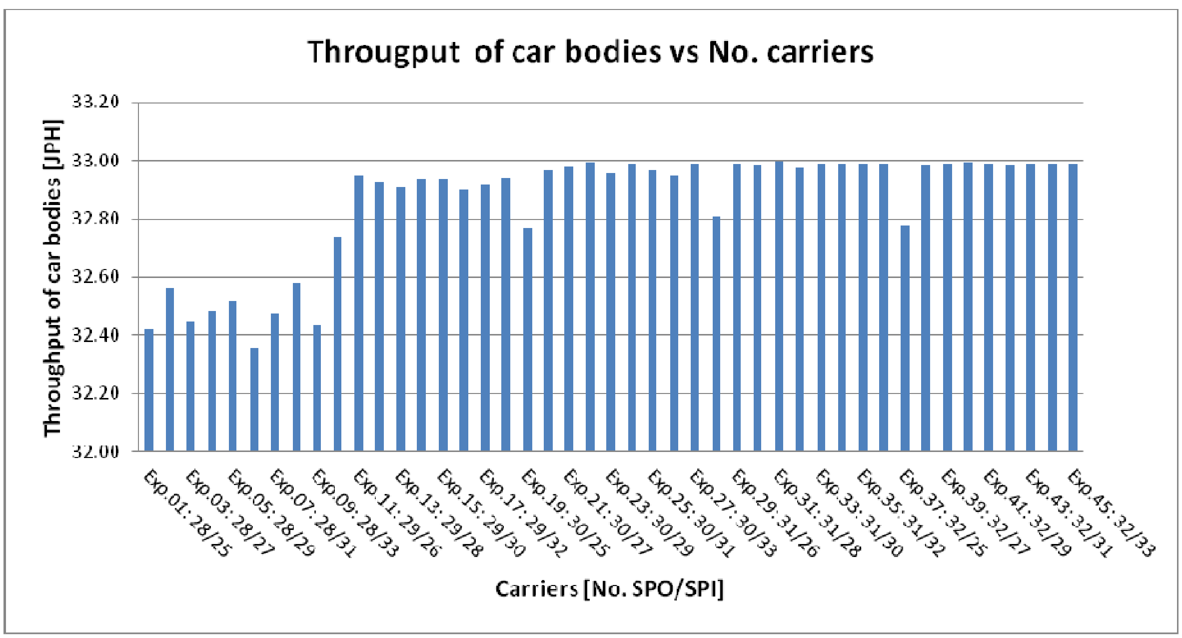

Diagram 5d: Fine two-level analysis

with a standard deviation corresponding to 0.04 JPH. According to diagram 5d, additional carriers will not increase the throughput significantly and is thereby considered to be unnecessary investments.

Diagram 5e represents the time that the unloading stations need to wait on carriers when a car body is in position for mounting side panels, accentuates the outline that the performance of the conveyor systems will not be improved by increasing the number of carriers. The wait time for SPO decreases when the number of SPO carriers increases from 28 to 29 and subsequently remains constant when the number of SPO carriers increases. Every ninth experiment in diagram 5e shows a trend of reduced SPO wait time and also a decreased throughput as shown in diagram 5d. The trend occurs when the number of SPI carriers is as low as 25 and thereby becomes the bottleneck. The SPO carriers will then have more time to fill their buffers and reach the SPO unloading stations in time, whence the wait time decreases. Due to the by far higher wait time for SPO compared to SPI, the FCSSPO is considered to be the bottleneck in the FPS.

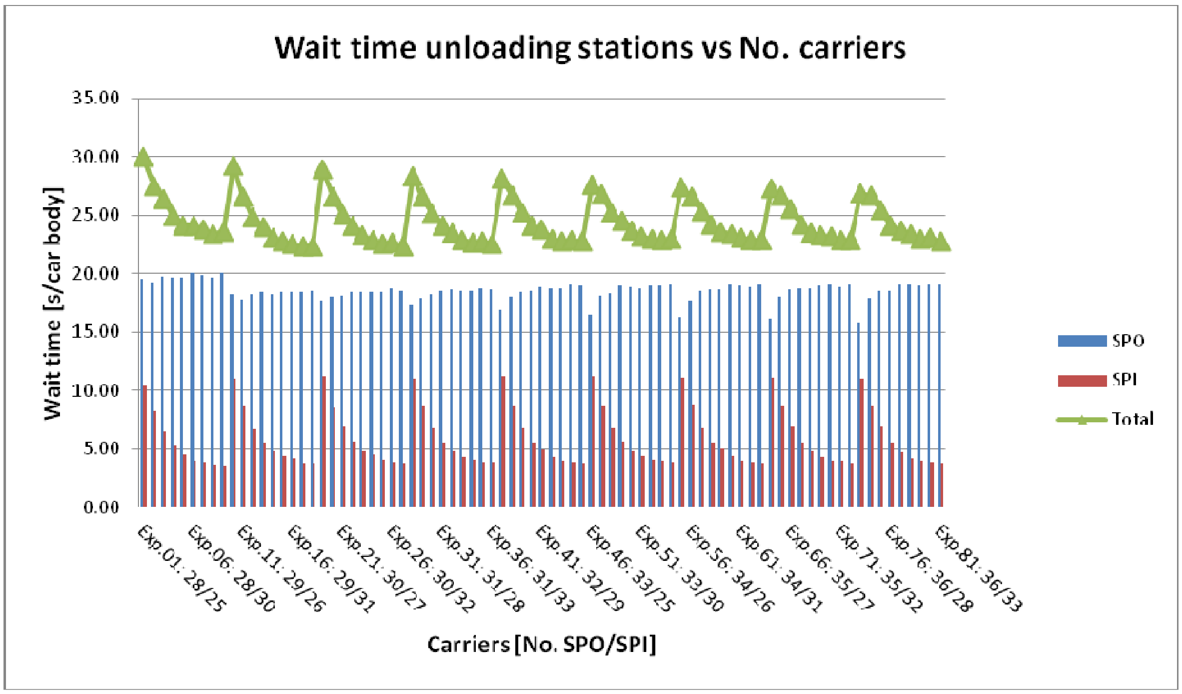

Diagram 5e: Illustration of the relationship between wait time and no. carriers

5.3 Objective three

The identification of bottlenecks in FPS has been carried out in several steps. As mentioned in the previous chapter, the wait time for SPO was considerable higher than for SPI. The bottleneck identification began thus by analyzing the FCSSPO. Moreover, all experimental throughput results related to objective two are examined in appendix F.

5.3.1 Bottleneck one – mono uploading station

Observations of the DES model showed that the SPO bottleneck was located at the very beginning of the FCSSPO, namely at the two mono uploading stations (for SPOL and SPOR). Only one operator is responsible for the mono uploading stations which induces that only one side panel can be processed at a time. Increasing the number of operators at the mono uploading stations to two operators implies that right and left mono side panels can be loaded simultaneously and thus no waiting time will exist. The insertion of one operator resulted in an increased throughput rate of car bodies. Diagram 5f shows the increased throughput in relation to different number combinations of SPO carriers and SPI carriers.

By adding an extra operator, the throughput rate of car bodies was increased from 33.0 JPH to 34.4 JPH when using a combination of thirty-three (33) SPO carriers and thirty-two (32) SPI carriers. Diagram 5f and diagram 5g below shows that both the throughput of car bodies and the wait time at the SPI unloading station is at their worst state when the number of SPO carriers is 29. Thus, the number of SPO carriers is considered to be the bottleneck in this very state. When the number of SPO carriers increases, the bottleneck moves to the number of SPI carriers.

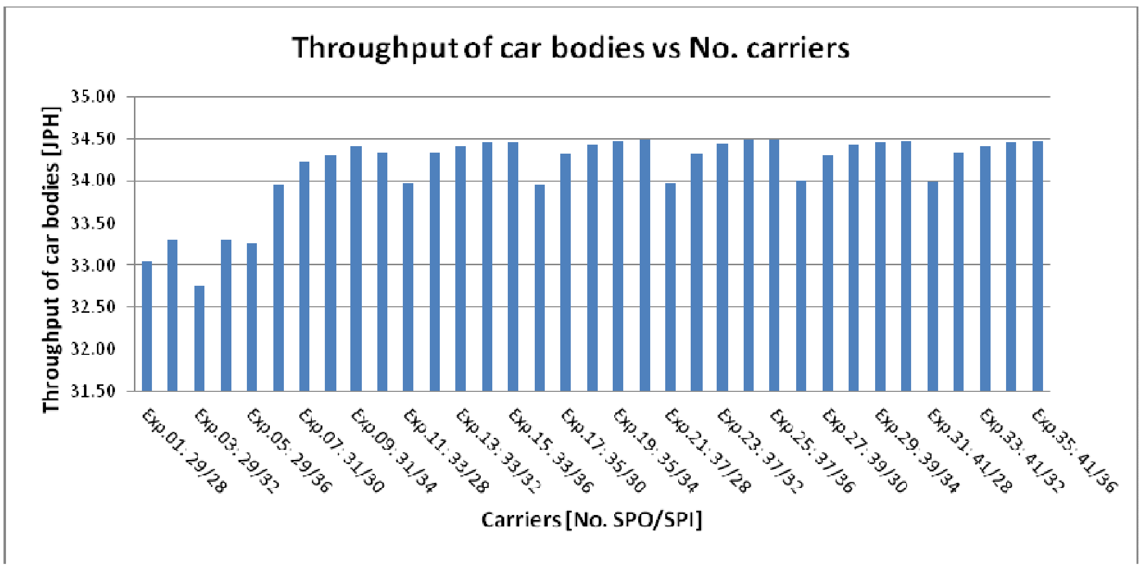

Diagram 5f: Illustration of the relationship between the throughput and no. carriers (two operators)

Both figure 5f and figure 5g also shows that when the number of SPI carriers is 28, assumed that the number of SPO carriers is more than 29, the throughput drops while the wait time for SPI unloading stations increases. The bottleneck is in this scenario determined to be the number of SPI carriers. When both the number of SPO and SPI carriers increases the total wait time decreases and then becomes stable. Further studies showed that the wait time for the SPO unloading stations is still much higher compared to the wait time for the SPI unloading stations.

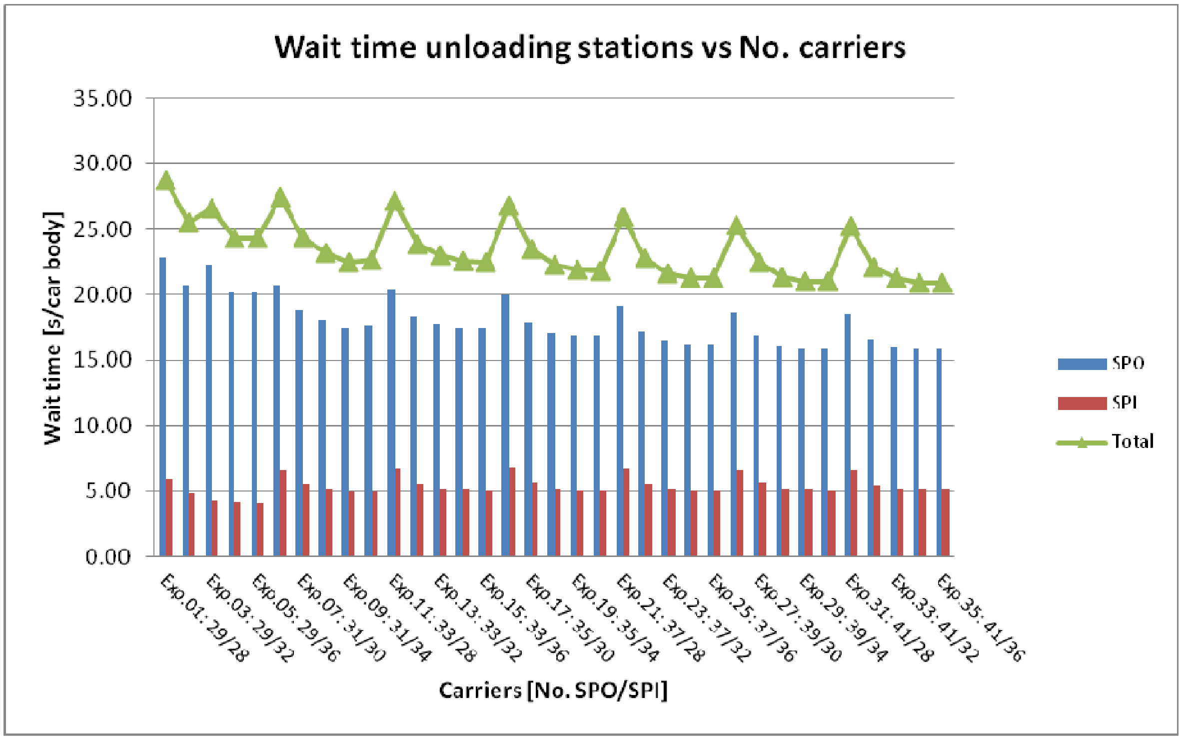

Diagram 5g: Illustration of the relationship between wait time and no. carriers

Observations showed that the significant difference in wait time between SPO and SPI occurs mainly when the car bodies on the main line enters the SPO unloading station with a certain gap (see figure 5c).

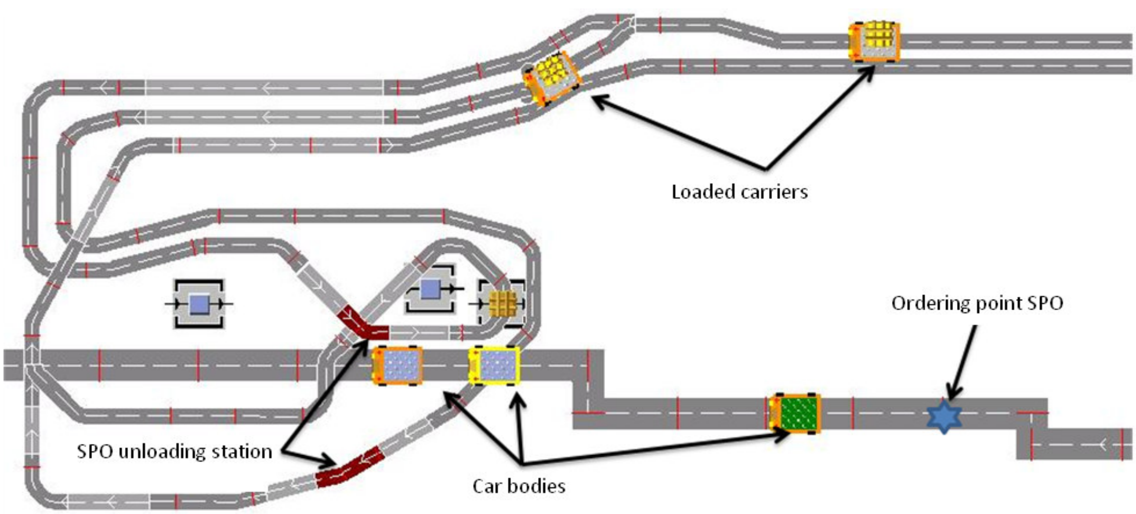

Figure 5c: Overview of the area around SPO unloading station

The ‘ordering point SPO’ is placed seven car body positions in front of the SPO unloading station in order to give SPO carriers time for their transport. The time it takes when a car body passes the ‘ordering point SPO’ until it enters the ‘SPO unloading station’ varies depending on the number of car bodies ahead. The time-consuming transportation distances for the SPO carriers requires a number of car bodies in front of the ordering car body, if the corresponding SPO carrier should be able to reach the SPO unloading station on time. The gap between car bodies in front of the SPO unloading station mainly occurs due to operator breaks and when several 540 car bodies, which diverge from the mainline, appear after each other. The only station on the main line where an operator performs the value adding work is located subsequent to the SPI unloading station. As mentioned earlier, several other stations require operators providing them with material while the process itself is automated by robots. When breaks occur or when the production ends for the day, only the manual station stops directly. All other stations have the possibility to run five additional cycles since they can be fed with material in advance. Since the SPI unloading station is located in front of the manual station, it only has the possibility to end the current work cycle and stay idle during breaks and at the end of the daily production. This gives the SPO unloading station the advantage to process a total of 20 car bodies each day while the SPI unloading station is idle. The large transportation distance in front of the SPO unloading station will act as a buffer and contribute so that the SPO unloading station can process about 5 car bodies during each production stops. The additional production time for the SPO unloading station is more than sufficient for the station to recover the lost production due to wait time. Thereby, the SPI unloading station is considered as the bottleneck in this stage.

5.3.2 Bottleneck two – merging point in FCSSPI

Analyses of the DES model showed that the second bottleneck was located at the merging point where three return tracks are joined together to a common return flow (see figure 5a). Even if empty carriers from the SPI unloading station are prioritized to passing through the merging point, carriers were prohibited to leave the SPI unloading station in time and thereby blocking the station from loaded carriers. Improving the capacity of the common return track eliminated the bottleneck at the merging point and thus resulted in an increased throughput rate as shown in diagram 5h.

More specifically, the throughput rate totaled 36.1 JPH. Thus, the maximal throughput rate of 36.1 JPH, determined in objective one (see section 5.1.2.1), was reached. It is thereby shown that there is no need to have more than thirty-six (36) SPO carriers and thirty-four (34) SPI carriers. Furthermore, the SPI wait time per car body and SPO wait time per car body in the same experiment dropped as shown in diagram 5i.

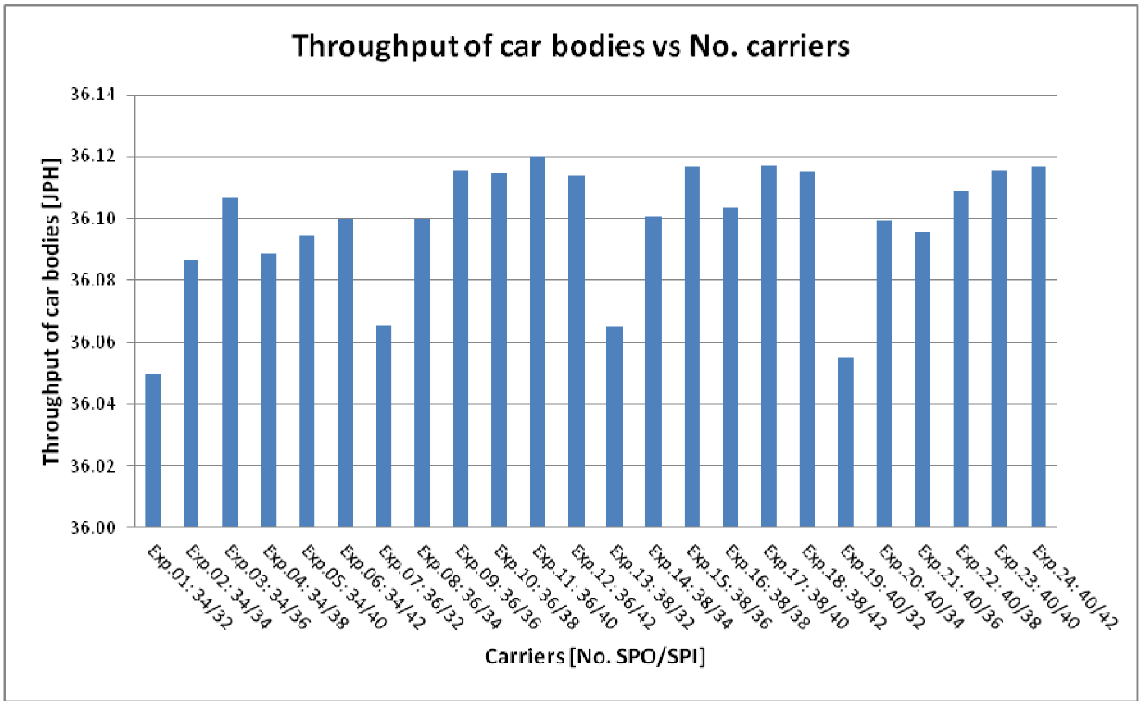

Diagram 5h: Illustration of the relationship between throughput rate and no. carriers

As mentioned in section 3.3, the conveyor track needs to be programmed into so-called safety zones around curves and slopes in order to avoid collision between carriers. These zones imply safety gaps between the carriers which result in decreased transport capacity per time unit on the track. At the merging point where three tracks are joined together to

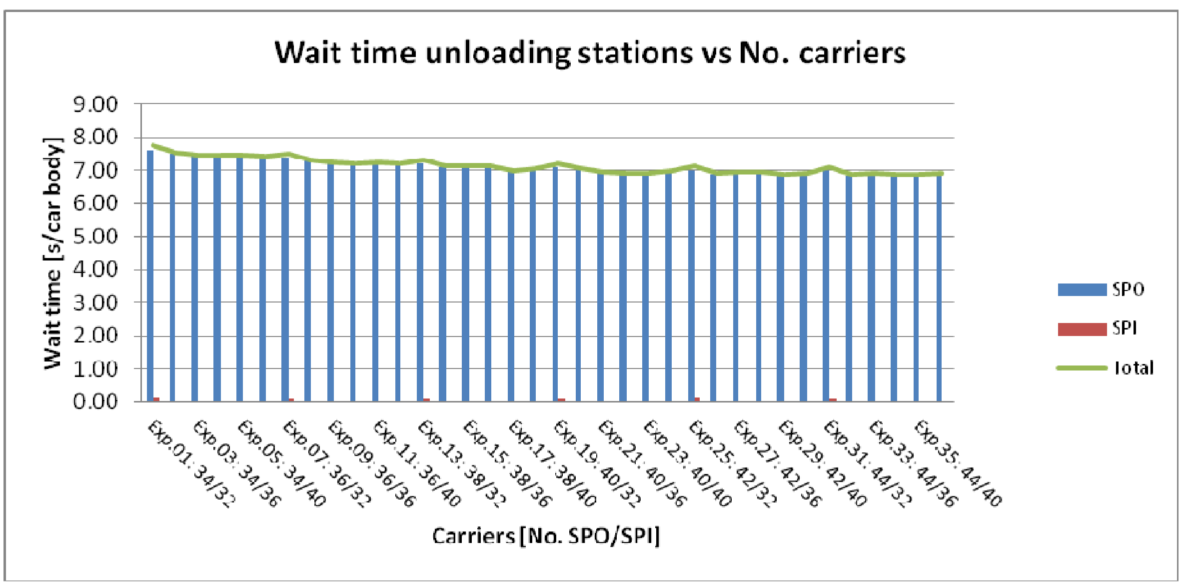

Diagram 5i: Illustration of the relationship between wait time and no. carriers

one common return track, the safety gaps on the common return track acts as bottlenecks by confining the flow (see figure 5b). By minimizing the safety gaps, located around the merging point and along the common return track, as much as possible will remove the bottleneck and increase the flow on these conveyor tracks. Since the reprogramming of safety zones requires high accurateness from the real system, no suggestion regarding the new design of the safety zones has been carried out with the simulation model.

Diagram 5i also shows that the wait time in the SPO unloading station was reduced from 16 seconds down to 7 seconds. The reduction occurs due to the situation described in section 5.3.1. Since the throughput of SPI unloading station is improved, car bodies enters the SPO unloading station more frequently which implies that there most of time is a buffer in front of the SPO unloading station. The buffer induces more time for the SPO carriers to reach the SPO unloading station and thereby the wait time decreases.

Even though the maximal throughput rate at 36.1 JPH was attained, the waiting time at 7 seconds per car body in the SPO unloading station is still high. Analyses showed that these waiting times were not due to bottlenecks in the FCSSPO. Instead the relative high waiting time was due to the main line and its control logic. For instance, by moving the ordering point SPO further upstream, SPO could be ordered much earlier and thereby got more time in order to reach the SPO unloading station before the ordering car body. As a result, the waiting time for the ordering car body in the SPO unloading station would decrease. Diagram 5j shows a drop from 7 seconds to 5.6 seconds (in Exp. 1) and to 4.6 seconds (in Exp. 2-4). These adjustments of FPML did not have any effects on the throughput rate though and therefore no further analyses were carried out.

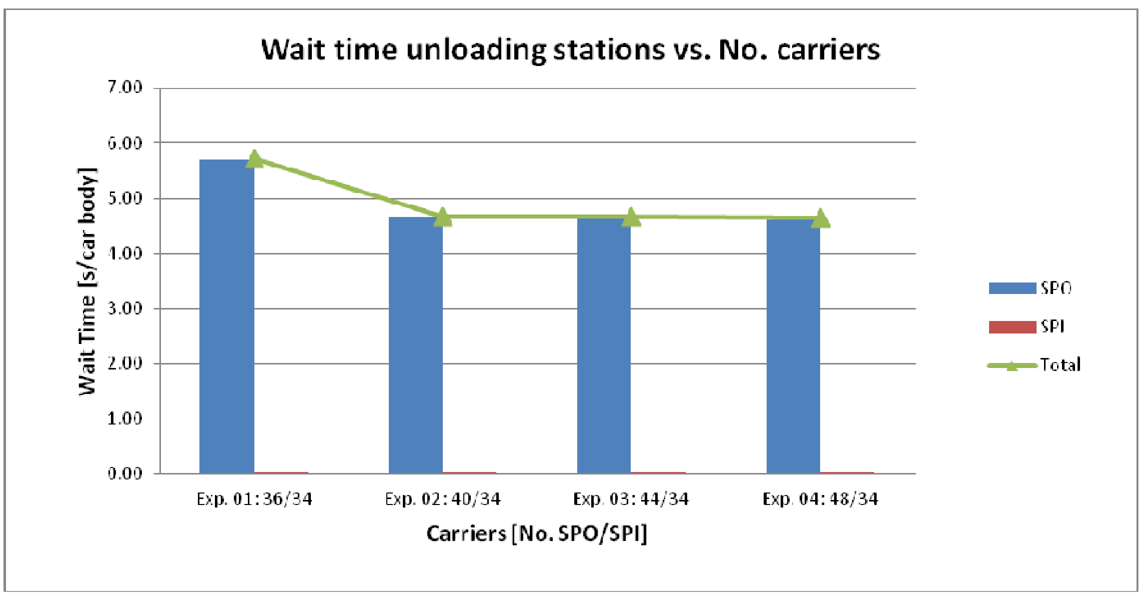

Diagram 5j: Wait time as a result of moving the SPO ordering point upstream

5.3.3 Sensitivity analysis regarding mixing point ratio

The mixing point ratio (see section 3.2.2) given by the production management has been kept constant throughout the study. But according to Saab production management there may be circumstances when they need to change the ratio. A sensitivity analysis has thereby been carried out in order to see how a changed mixing point ratio would affect the results. Seven different mixing point ratios, including the original, have been analyzed and the result is presented in diagram 5k.

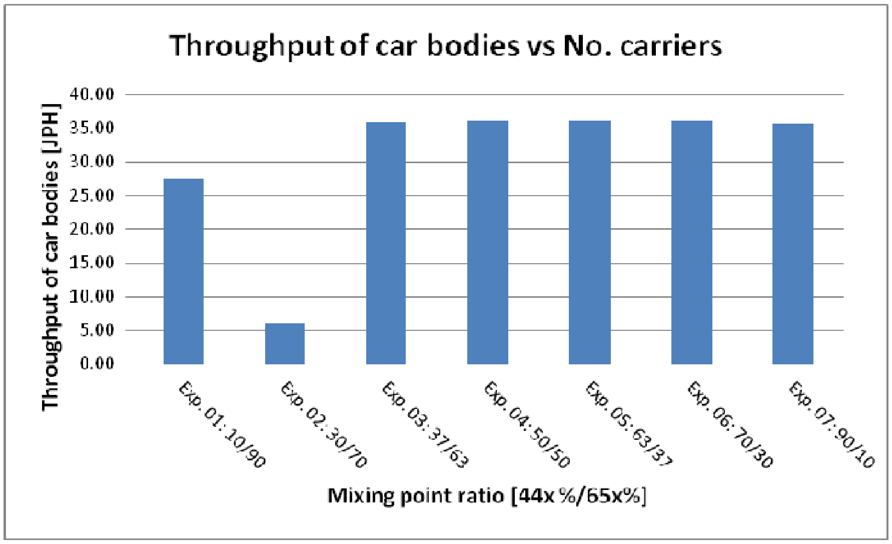

Diagram 5k: Sensitivity analysis of mixing point ratio

The originally mixing point ratio given by the production management is the one shown in experiment 5. The ratio means that the production strives to manufacture a sequence of 63 percent of 44x model group and 37 percent of 65x model group. According to the diagram, changing mixing point ratio has negligible impact on the result as long as the majority of the mix consists of the 44x model group. The result gets affected when the 65x model group is overrepresented in the ratio. It is thereby possible that the recommendation and identified bottlenecks are not valid in these situations. But according to the production management are ratios where the 65x model group is overrepresented unlikely to be used. The reason why the results gets affected negatively is probably because the control logic at both the SPO and SPI uploading stations is programmed to prioritize side panels belonging to the 44x model group. The wait times for the unloading stations indicate the same trend as the throughput of car bodies.

Chapter Six
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CONCLUSIONS AND RECOMMENDATIONS ON FURTHER STUDIES

This final chapter presents a summary of the results and analysis, described in previous chapter, as well as provides recommendations for further studies. The chapter starts with a concise examination of the outcomes of this study, discussing the conclusions to all three objectives. Thereafter, the chapter concerns a recommendation on further studies.

6.1 Conclusions

To go back to the issues examined in the end of the problem description (see section 1.2), one can now conclude that this study has brought results to all of these. For instance, the FCSSPO and FCSSPI will not handle the new higher throughput rate implemented in year 2012. This due to a couple of bottlenecks related to these systems. Also, various relationships have been identified between the number of carriers and the throughput rate as well as the number of carriers and the material shortage waiting time. Below, the outcomes for each objective are examined one by one.

In line with the first objective, a computerized simulation model was developed in order to analyze the capacity of the FPS. The study of FPS, and the simulation model showed that a few, but necessary, specifications of the layout and the control logic was required. First of all, the static parameters for the new body model 540 at the mono uploading station are not necessary to be as high as for the body model 440 and 444. A high 540 parameter value tends to wrong prioritization among the carriers which results in an overcapacity of loaded carriers with the 540 model. The static 540 parameter was determined to be 10. Further more, the expansion of the SPI conveyor system induced complex conveyor intersections. Prioritization rules connected to the intersections are required in order to avoid collisions between carriers and to achieve an efficient flow of carriers. Analyses showed that loaded carriers should be prioritized in front of empty ones. Where empty carriers from three different tracks are entering a common return track, empty right carriers should have the highest priority, followed by empty left carriers and finally the empty 540 carriers. The extension of SPI conveyor system requires also a check-out restriction parameter which limits the number of loaded 540 carriers in the area after control point 2 SPI Left. The buffer sizes for the 540 SPI is determined to be eight units for both left and right sides due to surrounding restrictions. As a final step, the maximal throughput rate out of the FPS, without any disturbances, was determined to 36.1 JPH. Moreover, the throughput of FPS, including the same number of carriers as for the CPS, was determined to 32.8 JPH. This rate was considered as a reference.

By mixing with the number of carriers, the DES model showed that the future conveyor system has the capacity to supply the main line with side panels up to a corresponding throughput rate at 33.0 JPH. In order to attain this rate, the number of SPI carriers must be increased by four – from 25 to 29 carriers. Analyses showed that the FCSSPO had an overcapacity of approximately five carriers (only 31 of 36 carriers were needed) and a transfer of 4 carriers, from the FCSSPO to FCSSPI, could cover the insufficient number of carriers in FCSSPI. Thus, investments in additional carriers are considered to be unnecessary since the throughput rate will not become higher than 33.0 JPH.

In order to reach the maximal throughput rate at 36.1 JPH, two bottlenecks were identified and eliminated. As examined in objective two, increasing the number of carriers will not be enough to increase the throughput rate due to other already existing bottlenecks. Analyses showed that the lack of operators in the mono uploading stations was limiting the number of loaded SPO carriers which in the end resulted in material shortage at the SPO unloading stations. By using two operators, instead of one, more SPO could be loaded at the mono uploading stations and thus was the bottleneck eliminated. The improvement required 33 SPO and 32 SPI carriers before the FPS became constrained due to the second bottleneck. The second bottleneck was located in the return flow of empty carriers in the FCSSPI. Analyses showed that empty carriers located in the SPI unloading stations were blocked to leave their positions due to carrier queues in front of them. As a result, loaded SPI carriers were prohibited to reach SPI unloading stations on time. The bottleneck was eliminated by improving the capacity of the return track and thereby reducing queues of empty carriers. By using 36 SPO and 34 SPI carriers together with the eliminations of the bottlenecks, resulted in a throughput rate at 36.1 JPH which is equal to the determined maximal throughput rate out of the FPS without any disturbances. Thus, it is recommended to invest in an additional 18 carriers - 9 devoted to transportation of SPIR and 9 devoted to transportation of SPIL. Table 6a shows an overview of the identified bottlenecks, as well as the action to eliminate the same, for each simulation run that were realized.

At last, the outcomes of this study show that DES was successfully applied in order to provide decision support for Saab's future investments. The benefits have included…. as well as better identification when carrying out bottleneck analysis. Moreover, the outcomes of this study have also given, and will probably continue to give, rise to fruitful discussions among concerned decision-makers during the project. DES has been, from our point of view, an indispensible tool for solving the intended purpose of study.

Table 6a: Overview of simulation outcomes

No.	Obj.	Bottleneck of FPS	Action	No. of carriers [SPO/SPI]	Throughput [JPH]	Incremental size [JPH]
Ref.	**1**	**N/A**	**N/A**	**36/25**	**32.8**	**N/A**
1	**2**	**No. of carriers**	**Redistribute no. of carriers**	**31/26**	**33.0**	**0.2**
2	**3**	**No. of operators**	**Increase the no. of operators**	**N/A**	**N/A**	**N/A**
3	**3**	**No. of carriers**	**Increase the no. of carriers**	**33/32**	**34.4**	**1.4**
4	**3**	**Return flow SPI**	**Increase return flow capacity**	**N/A**	**N/A**	**N/A**
5	**3**	**No. of carriers**	**Increase the no. of carriers**	**36/34**	**36.1**	**1.7**

6.2 Recommendations on further studies

This study identifies the relationship between the number of carriers of each subsystem (inner and outer) and the throughput rate of bodies out of the FPS. The study also includes a profound identification and analysis of potential bottlenecks when increasing the throughput rate for 540 as well as for 440, 444, 640 and 644 to 35 jobs per hour and 20 jobs per hour respectively. To do so, a discrete-event simulation model was developed.

The study also includes several delimitations (see section 1.5). These involve various sensitivity analysis of parameters/variables such as product mix, control logic parameters and conveyor rail design whose values in this study have remained constant. Since all these parameters/variables eminently have a major impact on the optimal number of carriers to achieve the specified throughput rate, it would be of interest to investigate these further.

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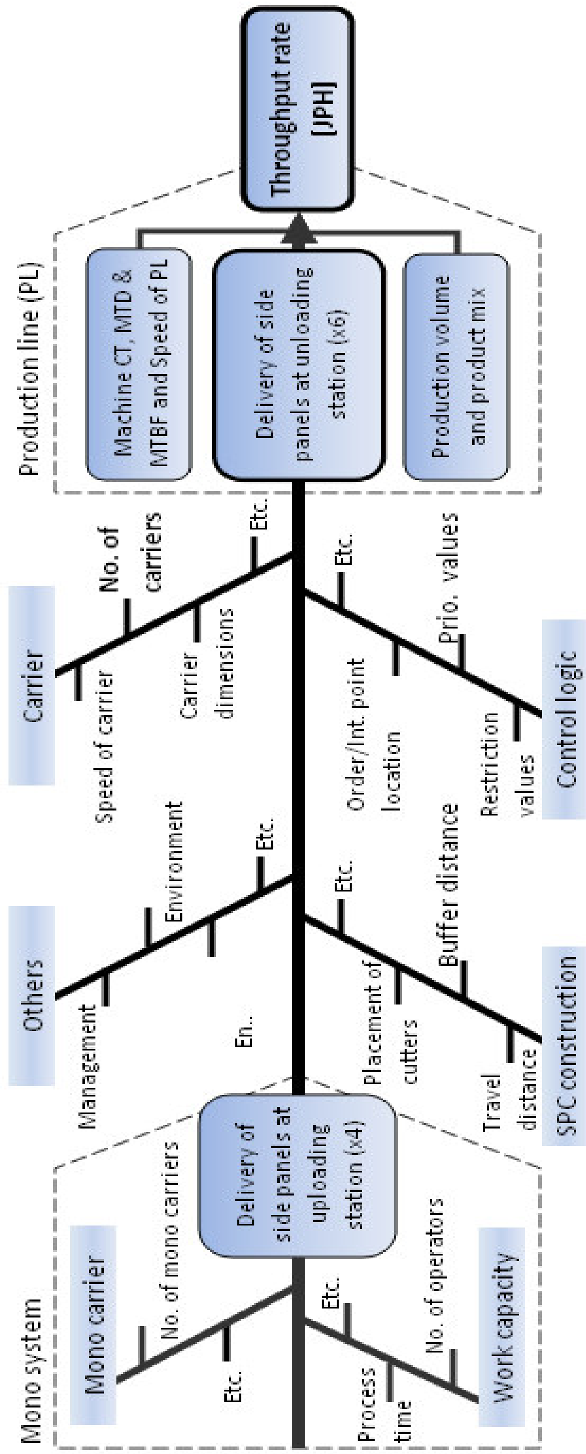
Table of Appendices

Appendix A: Fishbone Diagram



Appendix B: Data Input

Conveyor Carrier					
Number	**No**	**Length (Reserved)**	**[m]**	**Speed**	**[m/min]**
Mono SPO Carrier Right	12	SPO Carrier	3.71	Speed 2	3.4
Mono SPO Carrier Left	10	SPI Carrier	3.40	Speed 4	25
SPO Carrier Right	36			Speed 6	60
SPO Carrier Left	36				
SPI Carrier Right	25				
SPI Carrier Left	25				

PLC Logic Parameters Conveyor System			
Conveyor System Mono SPO R/L	**Base value**	**MaxStat**	**MaxDyn**
Model 440	10	7	24
Model 444	10	6	22
Model 540	10	7	10
Conveyor System SPO R/L			
Model 440	10	9	13
Model 444	10	9	12
Model 540	10	9	13
Model 650	2	3	7
Model 651	2	3	7
Conveyor System Mono SPI R/L			
Model 440	15	5	8
Model 444	15	5	7
Model 540	15	5	8
Conveyor System SPI Right			
Model 440	6	5	8
Model 444	6	5	7
Model 540	6	5	8
Model 650	2	4	6
Model 651	2	4	6
Conveyor System SPI Left			
Model 440	6	5	8

Model 444	6	5	7
Model 540	6	5	8
Model 650	2	4	7
Model 651	2	4	7

PLC Logic Parameters Main Line

Mixing Point	**Group model 44x**	**Group model 65x**	**Production Forecast**	**44x [%]**
STN 300	22	13	Model 440	41.20
Batch Size			Model 444	31.50
STN 300	2	2	Model 540	27.30
StartJig	2	2		**65x [%]**
			Model 650	50.70
			Model 651	49.30

Mono Uploading Station SPO

Activity	**Time [hh:mm:ss]**
Operator walk between stations	60
Elevator cycle	55
Pick and place 440R side panel in elevator	Erlang(23,2)
Pick and place 440R side panel in elevator	Erlang(26,2)
Pick and place 540R side panel in elevator	Erlang(23,2)
Pick and place 440L side panel in elevator	Erlang(28,2)
Pick and place 444L side panel in elevator	Erlang(33,2)
Pick and place 540L side panel in elevator	Erlang(28,2)
Failure Interval	Negexp(01:38:00)
Failure Duration	Erlang(2:00, 1:25)
Availability	98%
No. Operators	1

Replace wagon inside Side Panel Production Cells

Activity	**TMU**
Release wagon from truck	182
Drive forward 10 m	100
Pull hand brake	120
Get of truck	220

Go to empty wagon	250
Release brake	20
Delay start/stop	45
Bring empty wagon to truck	280
Turn 90 degrees	15
Connect wagon to truck	258
Go to loaded wagon	250
Bring loaded wagon to cell	1600
Delay start/stop	105
Turn 90 degrees	11
Pull brake	20
Go to truck	250
Total TMU	3726
Total Time [s]	LogNorm(134,5)
Failure Interval	Negexp(01:38:00)
Failure Duration	Erlang(2:00, 1:25)
Availability	98%
No. Operators responsible for all 4 wagons	1

Main line, 540 Line and Working Time	
Speed [m/s]	0.47
Processing time MainLine Stations [s]	75
Processing time 540 Line Stations [s]	148
Turn Table Rotation Speed [degree/s]	10
STN 05 Elevator Cycle [s]	15
STN 350 Elevator Cycle [s]	15
Production Time Mon-Fri [hh:mm]	07:00-16:14
Production stops due to personnel absence	09:08-09:15, 11:38-12:06, 14:14-14:21
Staff working time Mon-Fri [hh:mm]	07:00-16:06
Staff pauses [hh:mm]	09:00-09:15, 11:30-12:06, 14:06-14:21

Outer Side Panel Production Cell Right and Left				
Station	**Cycle time**	**Failure [hh:mm:ss]**		**Availability**
	[s]	**Interval**	**Duration**	**[%]**
Stn 10 (requires Operator)	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 20 (requires Operator)	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 40	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 50				
Loading procedure not incl.	49	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Loading Procedure (44x, 65x)	40, 68.5	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Total Availability				92
No. Operators Right Production cell				1
No. Operators Left Production cell				1

Inner Side Panel Production Cell Right				
Station	**Cycle time**	**Failure [hh:mm:ss]**		**Availability**
	[s]	**Interval**	**Duration**	**[%]**
Stn 10 (reqiures Operator)	82	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 20	82	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 40	82	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 50				
Loading procedure not incl.	42	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Loading Procedure (44x, 65x)	40, 65	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Total Availability				92
No. Operators				1

Inner Side Panel Production Cell Left				
Station	**Cycle time [s]**	**Failure [hh:mm:ss]**		**Availability [%]**
		Interval	**Duration**	
Stn 10 (requires Operator)	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 20	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 40	89	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Stn 50				
Loading procedure not incl.	49	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Loading Procedure (44x, 65x)	40, 70	NegExp(1:59:13)	Erlang(2:00, 1:25)	98.35
Total Availability				92
No. Operators				1

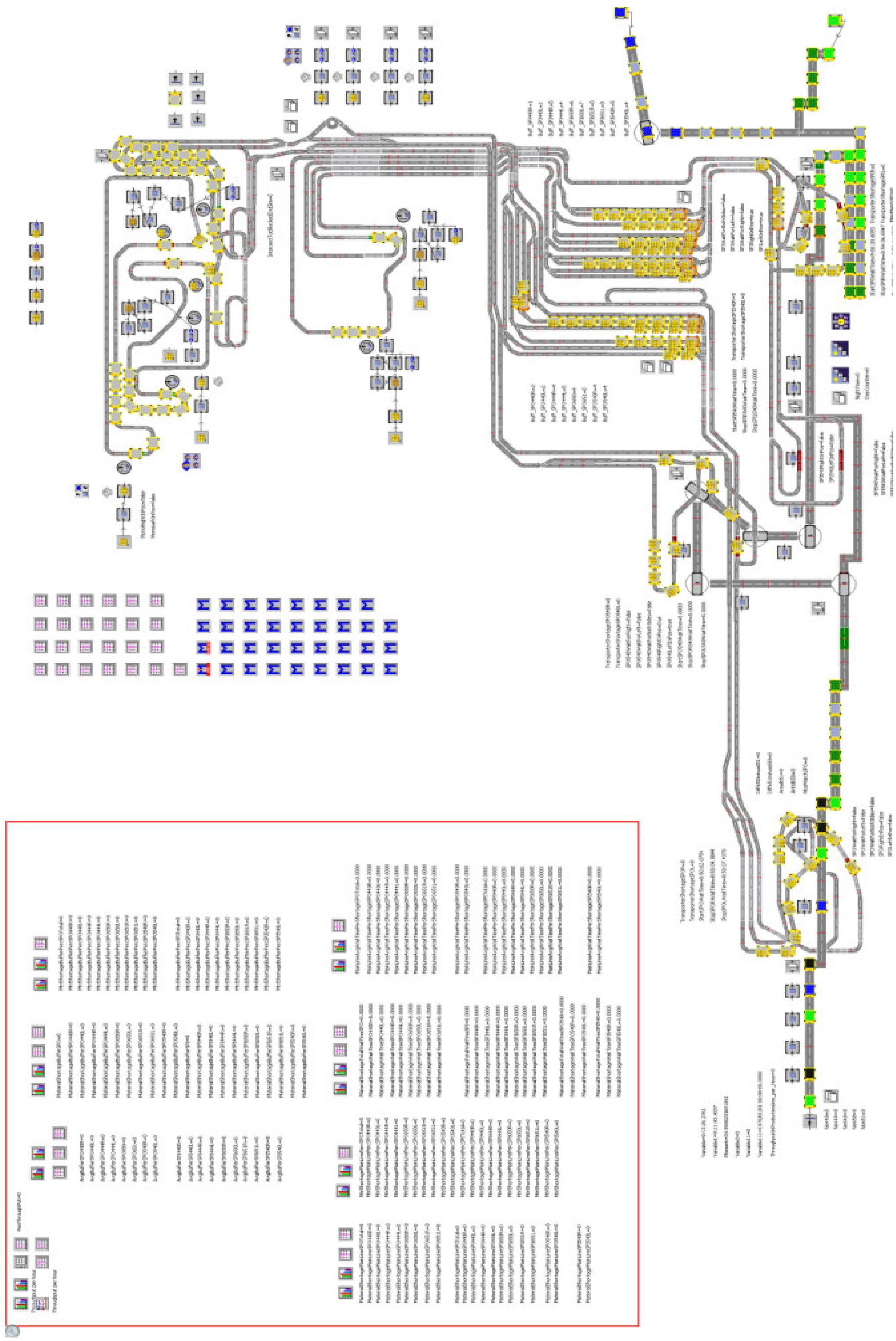
Side Panel Outer Conveyor System Transportation Times	
Distance	**Time [mm:ss.s]**
Right Side Panel	
Production Cell Right - Inspection Track Right	40.5
Inspection Track Right	1:29.5
Track Switch (W/o change, W change)	1.5, N/A
Inspection track Right - Control Point 1 SPO Right	41.1
Track Switch (W/o change, W change)	3.5, 7.0
Control Point 1 SPO Right - Control Point 2 SPO	2:33.5
Track Switch (W/o change, W change)	3.5, 4.5
Left Side Panel	
Production Cell Left - Inspection Track Left	33.5
Inspection Track Left	1:30.5
Track Switch (W/o change, W change)	1.5, N/A
Inspection Track Left - Track Switch Return Flow	30.5
Track Switch (W/o change, W change)	1.5, N/A
Track Switch Return Flow - Control Point 1 SPO Left	1:01.0

Track Switch (W/o change, W change)	3.5, 7.0
Control Point 1 SPO Left - Control Point 2 SPO	2:31.0
Track Switch (W/o change, W change)	3.5, 4.5
Buffer 440	
Control Point 2 SPO - Pre-Buffer 440	1:00.5
Track Switch (W/o change, W change)	2.0, 4.0
Pre-Buffer 440 - Buffer 440R	23.5
Buffer 440R	N/A
Buffer 440R - Control Point 3 SPO	24.0
Pre-Buffer 440 - Buffer 440L	21.5
Buffer 440L	N/A
Buffer 440L - Control Point 3 SPO	24.5
Buffer 444	
Control Point 2 SPO - Pre-Buffer 444	58.5
Track Switch (W/o change, W change)	2.0, 4.0
Pre-Buffer 444 - Buffer 444L	24.5
Buffer 444L	N/A
Buffer 444L - Control Point 3 SPO	29.0
Pre-Buffer 444 - Buffer 444R	23.5
Buffer 444R - Control Point 3 SPO	36.0
Buffer 650	
Control Point 2 SPO - Pre-Buffer 650L	1:12.0
Track Switch (W/o change, W change)	2.0, 4.0
Pre-Buffer 650L - Buffer 650	30.5
Control Point 2 SPO - Pre-Buffer 650R	1:17.5
Track Switch (W/o change, W change)	2.0, 4.0
Pre-Buffer 650R - Buffer 650	26.5
Buffer 650	N/A
Buffer 650 - Control Point 3 SPO	40.0

Side Panel Inner Conveyor System Transportation Times	
Distance	**Time [mm:ss.s]**
Right Side Panel	
Production Cell Right - Control Point 1 SPI Right	3:31.0
Track Switch (W/o change, W change)	2.5, 4.0
Buffer 440R	
Control Point 1 SPI Right - Buffer 440R	41.5
Buffer 440R	N/A
Buffer 440R - Control Point 2 SPI Right	41.5
Buffer 444R	
Control Point 1 SPI Right - Buffer 444R	41.5
Buffer 444R	N/A
Buffer 444R - Control Point 2 SPI Right	36.5
Buffer 650R	
Control Point 1 SPI Right - Buffer 650R	29.0
Buffer 650R	N/A
Buffer 650R - Control Point 2 SPI Right	33.0
Control Point 2 SPI Right - Offloading Station Right - Production Cell Right	
Control Point 2 SPI Right Stop Time	3.5
Control Point 2 SPI Right - 1 pos. Before Offloading Station Right	1:44.0
1 pos. Before Offloading Station Right - Offloading Station Right	30.5
Offloading Station Right - 1 pos Before Common Return Track	21.0
Track Switch (W/o change, W change)	2, 2
1 pos Before Common Return Track - Return Track Right	2:29.5
Track Switch (W/o change, W change)	2, 2
Return Track Right - Production Cell Right	4:25.0
Left Side Panel	
Production Cell Left - Control Point 1 SPI Left	4:57.0
Track Switch (W/o change, W change)	2.5, 4.0
Buffer 440L	
Control Point 1 SPI Left - Buffer 440L	36.5
Buffer 440L	N/A
Buffer 440L - Control Point 2 SPI Left	57.0
Buffer 444L	
Control Point 1 SPI Left - Buffer 444L	37.0
Buffer 444L	N/A

Buffer 444L - Control Point 2 SPI Left	56.0
Buffer 650L	
Control Point 1 SPI Left - Buffer 444L	30.0
Buffer 444L	N/A
Buffer 444L - Control Point 2 SPI Left	50.5
Control Point 2 SPI Left - Offloading Station Left - Production Cell Left	
Control Point 2 SPI Left Stop Time	3.5
Control Point 2 SPI Left - Offloading Station Left	4:01.5
Offloading Station Left - 1 pos. Before Common Return Track	23.5
Track Switch (W/o change, W change)	2, 2
1 pos Before Common Return Track - Return Track Left	2:35.5
Track Switch (W/o change, W change)	2, 2
Return Track Left - Production Cell Left	4:13.5

Appendix C: Graphic interface of simulation model



Appendix D: Experimental results (objective 1)

Mean Value and Standard Deviation For Throughput Cars Objective 1		
Exp. No.	**Std.**	**Mean**
Check out restriction		
1	30,6	8119
2	19,2	8157
3	27,8	8127
4	23,9	8128
5	36,9	8119
6	36,6	8110
540 Mono Uploading Static Parameter		
1	23,1	8127
2	31,7	8131
3	21,8	8142
4	24,5	8139
5	29,8	8130
6	35,1	8141
7	35,2	8128
Reference model		
1	28,7	8131

Appendix E: Experimental results (objective 2)

Mean Value and Standard Deviation For Throughput Cars Objective 2			
Exp. No.	**No. SPO/SPI**	**Std.**	**Mean**
	No. Carriers Coarse Incremental Steps		
1	28/17	2249,4	2019
2	28/21	45,3	7324
3	28/25	45,3	8018
4	28/29	41,1	8063
5	28/33	1218,0	7790
6	28/37	54,9	8025
7	32/17	2464,1	2944
8	32/21	42,3	7347
9	32/25	29,4	8135
10	32/29	10,3	8180
11	32/33	12,1	8179
12	32/37	10,5	8181
13	36/17	2439,2	2338
14	36/21	34,3	7340
15	36/25	33,7	8136
16	36/29	8,2	8178
17	36/33	11,5	8183
18	36/37	6,9	8178
19	40/17	1894,3	1176
20	40/21	36,1	7335
21	40/25	21,8	8127
22	40/29	13,4	8178
23	40/33	11,6	8184
24	40/37	7,4	8180
25	44/17	1402,4	1958
26	44/21	54,7	7325
27	44/25	25,4	8134
28	44/29	10,2	8179
29	44/33	10,3	8181
30	44/37	13,3	8180
31	48/17	2099,9	2121
32	48/21	42,2	7337
33	48/25	22,1	8138

34	48/29	56,9	8164
35	48/33	10,9	8183
36	48/37	12,7	8183

Mean Value and Standard Deviation For Throughput Cars

Objective 2

Exp. No.	No. SPO/SPI	Std.	Mean
	No. Carriers Fine Incremental Steps		
1	28/25	57,4	8040
2	28/26	34,1	8075
3	28/27	41,8	8048
4	28/28	35,2	8056
5	28/29	48,3	8065
6	28/30	51,4	8024
7	28/31	54,3	8053
8	28/32	40,0	8080
9	28/33	54,3	8044
10	29/25	28,7	8119
11	29/26	17,0	8172
12	29/27	15,8	8166
13	29/28	17,7	8162
14	29/29	17,0	8168
15	29/30	19,8	8168
16	29/31	18,2	8159
17	29/32	26,0	8163
18	29/33	13,7	8170
19	30/25	29,4	8126
20	30/26	14,4	8176
21	30/27	12,1	8179
22	30/28	12,0	8183
23	30/29	12,8	8174
24	30/30	15,6	8182
25	30/31	11,2	8176
26	30/32	8,4	8172
27	30/33	11,1	8180
28	31/25	22,6	8137
29	31/26	11,8	8180
30	31/27	9,5	8180
31	31/28	10,7	8184

32	31/29	6,0	8178
33	31/30	10,0	8181
34	31/31	8,2	8182
35	31/32	7,6	8181
36	31/33	12,0	8181
37	32/25	27,0	8128
38	32/26	9,1	8180
39	32/27	10,2	8181
40	32/28	10,1	8182

Appendix F: Experimental results (objective 3)

Mean Value and Standard Deviation For Throughput Cars Objective 3.1 2 Operators at Mono Uploading			
Exp. No.	**No. SPO/SPI**	**Std.**	**Mean**
	No. Of Carriers		
1	29/28	37,6	8194
2	29/30	67,4	8257
3	29/32	609,6	8126
4	29/34	54,3	8258
5	29/36	67,7	8248
6	31/28	24,1	8420
7	31/30	22,5	8488
8	31/32	26,4	8508
9	31/34	21,3	8534
10	31/36	20,4	8517
11	33/28	21,7	8427
12	33/30	15,2	8515
13	33/32	16,3	8535
14	33/34	13,7	8546
15	33/36	11,9	8548
16	35/28	14,5	8423
17	35/30	16,4	8512
18	35/32	20,4	8541
19	35/34	16,8	8551
20	35/36	12,8	8555
21	37/28	16,7	8428
22	37/30	13,3	8513
23	37/32	14,8	8542
24	37/34	15,8	8554
25	37/36	15,1	8554

Mean Value and Standard Deviation For Throughput Cars Objective 3.2			
Exp. No.	**No. SPO/SPI**	**Std.**	**Mean**
1	34/32	12,2	8940
2	34/34	9,0	8949
3	34/36	11,8	8954

4	34/38	12,1	8950
5	34/40	6,1	8952
6	34/42	11,2	8953
7	36/32	10,8	8944
8	36/34	9,1	8953
9	36/36	7,1	8957
10	36/38	8,3	8956
11	36/40	8,0	8958
12	36/42	7,9	8956
13	38/32	7,9	8944
14	38/34	9,7	8953
15	38/36	8,6	8957
16	38/38	9,6	8954
17	38/40	8,7	8957
18	38/42	9,2	8957
19	40/32	13,0	8942

Mean Value and Standard Deviation For Throughput Cars Objective 3.3

Exp. No.	No. SPO/SPI	Std.	Mean
1	36/34	10,8	8954
2	40/34	9,1	8956
3	44/34	7,6	8951
4	48/34	8,3	8952

Mean Value and Standard Deviation For Throughput Cars Objective 3.4 Sensitivity Analysis SPO/SPI 40/34

Exp. No.	44x/65x	Std.	Mean
1	1/9	12,0	6822
2	3/7	1466,1	1504
3	13/22	9,6	8910
4	1/1	1,7	8929
5	22/13	7,1	8953
6	7/3	7,5	8947
7	9/1	17,4	8876