HYPOTHESIS TEST OF A NEW LINE BALANCING APPROACH WITH DYNAMIC ALLOCATION OF ASSEMBLY OPERATIONS

Bachelor Degree Project in Automation Engineering
30 ECTS
Spring term Year

Alejandro Muñoz Llerena
Bruno Matías Troitiño Malavasi

Supervisor: Matías Urenda Moris and Gary Linnéusson
Examiner: Amos Ng
Executive Summary

Assembly lines are no longer systems designed to produce as much as possible at the lower cost. Nowadays several factors such as mass customization and variation in demand have led the manufacturers to consider the flexibility of the assembly systems as one of the most important facts to take into account when designing an assembly line.

In this context, this study attempts to test a new paradigm of the workload balance, which is based on a dynamic allocation of the assembly operations. In order to test the hypothesis, a real assembly system of engines has been used as a base model to implement the new approach. The work developed, uses the simulation as a means to carry out the study, which has required the development of several simulation scenarios. The hypothesis has been studied from two different approaches; on one hand a total dynamic allocation of assembly operations, which was expected to cause a wide operational range of the stations. On the other hand, the second approach implements a flow control which aims to reduce the operational range and workload fluctuations.

The results obtained show a significant improvement of the system performance in comparison with the current assembly line. It has been found that any improvement implemented in the system is directly reflected in the total performance of the line, regardless if the improvement is made in a system constraint. Moreover, the results have proven a better response of the system to changes in the frequency of models production.

Finally, based on the results, this study suggests several paths of future work in order to acquire the needed information to implement the hypothesis in the real world context.
Acknowledgements

First of all, we would like to thank Matías Urenda Moris for his invaluable assistance as well as his enthusiasm and availability to help us during this work. We share with him the passion for engineering and the passion for the same football club, Malaga CF. We would also like to thank Gary Linnéusson for his assistance and his advices, which were of great help. Marcus Frantzén, Ainhoa Goienetxea, Gunnar Bäckstrand, Martin Usener and our almost project partner Wansit Ampapun, have also contributed to the accomplishment of this project.

Me as Bruno, first of all I want to acknowledge and thank my family for the support provided during my student life, as well as the motivation and affection that they have always given me. Moreover, I would like to thank all my friends for their unconditional support, especially those friends whom I have met during this course and have shared many good moments.

Me as Alejandro, I would like to express the deepest appreciation to my family for their unconditional support, especially to my parents and siblings. I would also like to thank all my friends in Málaga who supported me during this course, as well as, all the people I met during this course who have become good friends and have been like a second family to me. Finally, I would like to thank to my girlfriend Ana for always being ready to help me in good and bad times.
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<td>Automated Guided Vehicles</td>
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<td>DES</td>
<td>Discrete Event Simulation</td>
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<td>GALBP</td>
<td>General Assembly Line Balancing Problem</td>
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<tr>
<td>JIT</td>
<td>Just in Time</td>
</tr>
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<td>MALBP</td>
<td>Mixed Assembly Line Balancing Problem</td>
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<td>MSP</td>
<td>Model Sequencing Problem</td>
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<td>Toyota Production System</td>
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<td>Predetermine Motion Time System</td>
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<td>Effective Process Time</td>
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<td>WIP</td>
<td>Work in Process</td>
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1 Introduction

The aim of this chapter is to provide the information needed to introduce the reader to the study which this thesis aims to present. Through a brief historical description of the issue in the background, the motivation of this study is shown, and the objectives are set. Moreover, a description of the methodology used is presented, as well as the limitations. The chapter ends by presenting the way in which this thesis is organized.

1.1 Background

Originally, assembly lines were developed for a cost efficient mass production of highly standardized products (Boysen, et al., 2007). This concept of assembly lines had its beginnings in 1913, when Henry Ford and his engineering colleagues constructed an assembly line to produce magneto flywheels, which quadrupled the production and dramatically reduced the price of the Model T Ford (Groover, 2007). However, since the times of Henry Ford and his Model T, the concept of the assembly line has changed significantly due to technological advances and the change in the demand behaviour, which led to the introduction of several “philosophies” of management. During the second part of the 20th century, Toyota developed a “waste” reduction based approach called Toyota Production System (TPS), which was the precursor of the Lean Manufacturing approach (Liker, 2004). In 1984, Eliyahu M. Goldratt published “The Goal”, a book which set the fundamentals of the Theory of Constraints (TOC) (Goldratt & Cox, 1984). TOC is focused on identifying the process constraints and restructure the organization around it. In 1985, Motorola developed the Six Sigma strategy, which aims to reduce the variability in manufacturing, in order to reduce the defects and failures in the delivery and customer service (Tennant, 2001).

The progress shown in the previous paragraph has affected the development of assembly lines. Assembly lines are no longer oriented to produce as much as possible at lower cost; due to the introduction of the Just in Time (JIT) approach by lean manufacturing, the production rate has had to be adapted to meet changing demand in order to reduce the in-process inventory and related costs. On the other hand, due to the development of more advanced automated production systems, assembly lines have recently also gained importance in the
low-volume production of customized products (mass customization) (Boysen, et al., 2007). In order to respond to different customer needs, the production systems must be able to produce a wide range of product variants. One example is the automotive industry, where in order to adapt to the customers desires and financial capabilities, most models have variants with several features.

Due to the high investment effort associated with designing, building and maintaining an assembly line, several variants of one or more models are usually manufactured simultaneously along the same assembly line (Xu & Xiao, 2008). Moreover, multipurpose automated or semi-automated machines have made it possible to manufacture different products and variants with negligible setup losses; this has led to the popularization of the so-called mixed-model assembly lines (Boysen, et al., 2007).

Mixed-model production has increased the magnitude of several existing production lines problems, such as line balancing (distribution of the workload along the line) or sequencing (sequence of production) (Boysen, et al., 2007). On the other hand, operators must perform different tasks in several sequences depending on the model variant, and this leads to more stochastic times. These issues directly affect the performance of the system, and must be studied in detail when an assembly line is designed (Uddin & Martinez Lastra, 2011).

For the aforementioned reasons, the (re)-designing stage of a production line has become crucial, which entails that the behaviour of the assembly system, under different conditions and configurations, must be known as accurate as possible. This will lead to an efficient utilization of the facilities, and therefore lower production costs (Scholl & Becker, 2003).

1.2 Problem statement and hypothesis deduction

1.2.1 Problem statement

The final assembly line of 13-litres engines in Volvo Powertrain is a mixed-model assembly line, where several models are manually assembled simultaneously, and thus share the same facilities. The production volume of each model is shown in Table 1.
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<table>
<thead>
<tr>
<th>Type</th>
<th>Production volume</th>
<th>Comment</th>
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<tbody>
<tr>
<td>€3</td>
<td>5%</td>
<td>Data mixed with €4</td>
</tr>
<tr>
<td>€4</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>€5</td>
<td>64%</td>
<td></td>
</tr>
<tr>
<td>P3520</td>
<td>15%</td>
<td></td>
</tr>
<tr>
<td>Dual Fuel</td>
<td>1%</td>
<td>Data not available</td>
</tr>
<tr>
<td>€6 Early</td>
<td>8%</td>
<td>Data not available</td>
</tr>
<tr>
<td>€6 Normal</td>
<td>2%</td>
<td>Data not available</td>
</tr>
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</table>

Table 1 Production rate of each model

As stated in the previous section, variations in the workload caused by variants leads to more complex balancing problems. Figure 1 displays the mean work times of the Euro 5 model in each one of the twenty-five stations that compose the final assembly line.

![Image](Image)

**Figure 1 Workload in each station of Euro 5 model**

As illustrated in Figure 1, in case of the Euro 5 model, idle times and overloads occur, and in combination with the manufacturing of the other models, the performance of the line is affected. As a result, there is still room for improvements in the Volvo final assembly line.
1.2.2 Hypothesis deduction: Dynamic allocation of assembly operations

The hypothesis, on which this project is based, provides a new approach of line control by means of a dynamic allocation of the assembly operations. Using this approach, the range of assembly tasks that each station performs is incremented. As a result, the assembly tasks could be performed by different stations along the line, as long as the assembly order is fulfilled. Figure 2 attempts to provide an example to illustrate the approach.

![Figure 2 Dynamic allocation of assembly operations](image)

In Figure 2, when the stations work without dynamic allocation, the stations are only able to perform the green tasks. On the other hand, using dynamic allocation the stations are able to perform green and red tasks, the task range is incremented and stations may be able to perform a wider number of assembly tasks. With this approach, it is expected to obtain a more flexible balancing, a higher flexibility and therefore improve the performance of the assembly line.

The hypothesis has been studied from different approaches, which are described in detail in Chapter 5.

1.3 Aim and Objectives

This case study constitutes a bachelor degree thesis, and is part of the FLEXA research project carried out by Swerea, The University of Skövde and Volvo Powertrain. FLEXA research project takes place in the Volvo Powertrain factory located in Skövde, and this study
is focused on the final assembly line of 13-litres engines. The hypothesis that this project aims to test introduces a new paradigm of line control. It is expected that the implementation of this new control will produce significant changes in the behaviour and performance of the production system. Therefore, in order to test the assembly line under the conditions established by the hypothesis, a simulation model of the assembly line is necessary. This bachelor thesis is developed in parallel with a master thesis, with which it shares the data of the system.

The main aim of this thesis can be stated as follows:

*Study and compare the performance of a manual assembly line under the conditions established by the hypothesis.*

In order to achieve the main aim, several objectives must be accomplished:

- Build a simulation model, where the logic of the hypothesis is correctly represented
- Simulate different scenarios with the logic of the hypothesis
- Compare results of the performance between scenarios
- Set conclusions
- Provide improvement suggestions

### 1.4 Methodology

The methodology followed goes through different stages. These stages will be described in more detail in the next chapters.

- Hypothesis formulation.
- Reading literature about different topics related with the hypothesis.
- Visit the production line at Volvo powertrain to understand the behaviour of the system and to obtain the needed data.
- Data analysis.
- Create a simulation model and obtain the results by means of simulation software.
• Analyse how the systems works under the hypothesis conditions in the different scenarios.
• Formulate conclusions.

The simulation work has follows the methodology presented in section 2.3.7. The simulation software used is Tecnomatrix Plant Simulation 9, developed by Siemens PLM.

1.5 Limitations

This project has been developed in four months; therefore, in order to accomplish with the objectives set in a limited time frame, several limitations had been established.

The development of a simulation model entails several limitations. Generalizations and assumptions of the system features have been needed in order to be able to create a simulation model within the designated time period mentioned before. These issues are explained in detail in Chapter 4.

One important aspect that has not been considered is the human factor. In case of implementation of the hypothesis presented in this study, this fact must be taken into consideration in future works, in order to ensure that the workers’ rights are fulfilled.

Finally, other aspects such as economics details or the technical viability of the hypothesis have not been taken into account.

1.6 Contents and organization

1.6.1 Contents

This section describes the structure of the thesis and presents the project planning followed to accomplish with the work. The thesis is divided into 8 chapters:

Chapter 1 Introduction, the aim of this chapter is to introduce the reader to the thesis topic.

Chapter 2, Literature review, the purpose of this chapter is to provide the reader the theoretical knowledge needed to understand this thesis.
Chapter 3, *Assembly line description and Data analysis*, this chapter provides a description of the real production system and sets the base of the different simulation scenarios studied.

Chapter 4, *Simulation Model Design*, this chapter intends to provide an explanation about the process of designing the simulation model in order to understand how the simulation works.

Chapter 5, *Results and Analysis*, the aims of this chapter are to provide the description, the result and the analysis of each one of the scenarios studied.

Chapter 6, *Experiments*, in this chapter, experiments which involve one or more the scenarios are presented, in order to analyse their response under different conditions.

Chapter 7, *Discussion*, this chapter attempts to clarify the results obtained in the Chapter 6, providing a discussion where several facts are questioned and interpreted.

Chapter 8, *Conclusions and Future work*, the aim of this chapter is to provide the reader with a brief and concise description of the work carried out, the main findings and the conclusions achieved, as well as several research opportunities are suggested to be studied in the future.

### 1.6.2 Organization

Figure 2 presents the Gantt diagram, where the moment and duration of the different work stages are presented.

![Gantt diagram of the project planning](image-url)
2 Literature Review

The purpose of this chapter is to provide the theory on which this work is based. This theoretical survey aims to show known methods and approaches as well as to create a base of knowledge, essential to carry out this project.

The scope of this survey extends from general concerns, such as assembly lines, to specific ones, such as cycle time, in order to provide a theory which encompasses all the issues of this project. The structure of this chapter can be divided into three main parts:

- Assembly lines issues
- Discrete event simulation
- Philosophies of management

2.1 Introduction to manual assembly lines

“Assembly is part of the production system. Industrial-produced final products consist mainly of several individual parts and subassemblies that have mostly been manufactured at different times, possibly in separate locations” (Nof, et al., 1997). Assembly operations have been performed in manufacturing operations for a very long time. However, since the industrial revolution and, above all, since the emergence of the automotive industry, the design and management of assembly processes have arisen as one of the most important issues in manufacturing.

Despite the increasing use of automation in the production systems, assembly operations are still performed in most cases by human workers. This is due to the complexity of the assembly processes, the high number of components and the variation in the design of the products, thus automation frequently proves to be an expensive solution or technologically not feasible. Therefore, automation is usually only applied at some different levels in combination with manual operations.

The so-called manual assembly lines are production lines which consist in an arrangement of workstations where assembly tasks are performed by human workers. At each station, a portion of the total work is performed. Base parts are usually launched from the beginning of
the line, and moved between stations by mechanical transport systems or manually. Each base part travels through successive stations, where workers add components that progressively build the product (Groover, 2008)

2.1.1 Classification

To analyse real-world assembly systems is needed to take many factors into account, with the aim of organizing the different kinds of assembly lines; several classifications have been suggested. Some important classifications are shown below.

**Number and variety of products**

It is common that several models of a product share the same assembly line, and therefore the same lines can perform different assembly operations. Three different types of assembly line can be distinguished according to how much the production may be varied (Becker & Scholl, 2006) (Boysen, et al., 2007) (Fliedner, et al., 2006):

- **Single-model assembly line:** This is the traditional form of an assembly line, where only one product is produced and the work pieces are identical. Furthermore, if several variants of one product are manufactured in the line but neither setups or time variations in operation occur, the line can be treated as a single-model line.

- **Mixed-model assembly line:** Different product models are produced arbitrarily. In this type of assembly lines is typically assumed that setups operations can be reduced enough to be negligible. On the other hand, the variation in product models leads to significant variations in process times. This type of assembly lines presents the problem of sequencing, which is directly connected with the line balancing problem, which is discussed later in this chapter.

- **Multi-model assembly line:** Variants are produced in batches, with intermediate setups operations. Despite the fact that, typically, a certain degree of similarity in production processes is inherent even in batch production, setups operations are needed in order to adapt the processes to the different requirements of the variants.

Figure 3 depicts a description of the three aforementioned categories.
Assembly lines can be distinguished with regard to the control of job movement between stations. This control of the job is implemented by a cycle time (also called takt time), which is the time elapsed between two consecutive products of the line. "On average, each worker must complete the assigned task at his/her station within the cycle time, or else the required production rate will not be achieved" (Groover, 2008). Types of line control can be arranged in three categories (Boysen, et al., 2007).

1.-Paced lines: Process times of all stations are restricted by a given cycle time; therefore, those stations have a fixed production rate, which is equal to the cycle time. The pace is kept up by a continuously advancing material handling device.

2.-Unpaced synchronous lines: Work units are allowed to move only when all stations have finished their assigned operations. Therefore, faster stations must wait until the slowest station has finished its operations. Then, all stations pass on the work units at the same time and buffers are not needed.

3.-Unpaced asynchronous lines: Once the assigned operations are completed, stations are allowed to pass on the work unit to the next successor as long as it is not blocked. After having passed on the processed work unit, the station is able to continue working on a new work unit unless the predecessor is not able to deliver. To avoid blocking and starving, buffers are placed between stations. The purpose of these buffers is to absorb the fluctuations of the production flow, produced by deviations in the task times; therefore, unpaced asynchronous lines are meaningful only when task times are stochastic.
Due to stochastic task times, to obtain smooth station loads, or in other words, obtain an acceptable line balancing becomes one of the most important issues to take into account in unpaced asynchronous lines. A classification of task times is explained in detail below.

**Variety of task times**
The time elapsed during the performance of a task varies, depending upon several factors, of which the human factor is the most significant. A classification of task times is shown below.

**Deterministic task times:** Although task times are basically never deterministic, when operations are simple manual tasks or are executed by highly reliable automated stations, time deviations expected in performing the task are small enough to assume the task time as deterministic (Boysen, et al., 2007).

**Dynamic task times:** Variations of task times are caused by learning effects or improvements in the production process (Rekiek & Delchambre, 2006).

**Stochastic task times:** In this case, variations in task times are caused mainly by three factors:

- Deviations in human labour caused by skill and motivation
- Default of machinery
- Model-mix, which cannot be anticipated upfront

Between these three factors, deviations caused by human labor are the most significant (Boysen, et al., 2007). These deviations are explained in detail in the operator variability section.

**Line layout**
Workstations can be arranged in different ways, which determine the flow direction; several configurations are possible and the most important may be described in the following way:

**Serial line:** Workstations are arranged in a straight line, along the transport system, as illustrated in Figure 4.

![Serial line configuration](image)
**U-shaped line:** Workstations are arranged in the shape of a U, which means that stations in between the U are able to work at two segments of the line and work pieces can revisit the same station at later stage in the production process (Boysen, et al., 2007).

**Parallel stations:** Workstations are built with parallel or serial posts, where two or several workers can perform identical tasks. This configuration is suitable when the longest task time usually exceeds the cycle time (Rekiek & Delchambre, 2006).

**Parallel lines:** To duplicate the whole assembly line is common when the demand is high enough. The disadvantages of using this configuration are that more equipment and tooling are required (Rekiek & Delchambre, 2006).

**Material-Handling systems**

The movement of base parts between stations can be accomplished in different ways, using both manual and mechanical transport systems. Mechanical transport systems can be divided into three groups:

- **Continuous transport systems:** A conveyor transports the work parts with constant velocity and in a continuous manner.

- **Synchronous transport systems:** Work parts move in sync between stations, with discontinuous movement.

- **Asynchronous transport systems:** The movement of the work units along the line is independent of each other. The work unit leaves the operation when the task has been completed, and the operator releases the unit (Groover, 2007)

Within the asynchronous transport systems it is important to highlight the automated guided vehicles (AGVs), which can be defined as self-propelled vehicles guided along defined pathways and powered by on-board batteries. At the Volvo Powertrain assembly line, AGVs are used as load carriers, and they are therefore are used to move unit loads between stations (Groover, 2008).
2.2 Manual assembly lines problems

2.2.1 Line balancing

The assembly line balancing problems consist in assigning an ordered sequence of tasks to the workstations, so that the performance of the line is improved in some extent and no precedence constraints are violated (Kriengkorakot & Pianthong, 2007). **Precedence constraints** are technological restrictions which determine the order of tasks performance.

Configuration planning of a future line has great relevance, due to high capital investment needed. Because of this, assembly line balancing problem arises whenever an assembly line has to be configured or redesigned. As mentioned above, to solve line balancing problems, the performance of the line must be improved in some extent, which means that many parameters can be measured, and therefore different objectives could be set when solving line balancing problems (Scholl, 1995).

**Capacity-oriented goals:** This objectives deals with maximize the capacity utilization, and it is directly related to the line efficiency. Most general capacity objectives are shown as follows:

- Given cycle time, minimize number of workstations.
- Given number of workstations, minimize cycle time.
- Obtain smoother workload in all the stations, therefore minimize idle times and overloads.

**Cost-oriented goals:** These objectives deal with cost of machinery, tools, wages etc. which are related to the cycle time and the number of workstation, for detail see (Becker & Scholl, 2006) and (Scholl & Becker, 2003).

Generally in literature, only one objective is taking into consideration; nevertheless several goals may be taking into account. A combination of the presented objectives and others can be considered in multi-objective optimization.

Bearing in mind the classifications shown in 2.1.1 (Classification of manual assembly lines), as well as the precedence constraints and objectives, Becker & Scholl have classified the assembly line balancing problem as it is illustrated below in Figure 5.
**SALBP:** This problem encompasses serial lines where only one product is manufactured. Within this category many subcategories have been established regarding objectives (Becker & Scholl, 2006)

**GALBP:** These problems are extensions of SALBP that take into account other assumptions, such as mixed-model production, multi-model production or line layout. GALBP includes several subcategories, where it is important to point out Mixed Model Assembly Line Balancing Problem (MALBP) and Model Sequencing Problem (MSP).

**MALBP** and **MSP:** These subcategories encompass assembly lines that produce several models of one generic product in an intermixed manner. In this case, station tasks have to be assigned taking into account that task times depends on the model. MALBP are more difficult to solve than SALBP, due to different task times must be assigned to each station, depending on the model (Kriengkorakot & Pianthong, 2007), because of this MALBPs are strongly related with MSPs (Sequencing problem 2.2.2).

### 2.2.2 Sequencing problem in mixed-model assembly lines

When several variants of one base product are produced in the same production line in an intermixed manner (Mixed-model production line), tasks times are directly dependent on the variant of the product to be assembled. These variations in tasks times produce both overloads and idle times and thereby the line efficiency is affected. These problems can be avoided if the production follows a sequence, which alternates variants that causes overloads with variants that requires less work time (Boysen, et al., 2007). Therefore, sequencing problem
can be defined as the attempt to find a sequence of product variants which meets the forecasted demand and maximize the utilization of the assembly stations (Rekiek & Delchambre, 2006).

As mentioned above, sequencing and line balancing problems are strongly related; in literature usually both problems are treated as if they were the same problem. It is possible to assume that sequencing problems are an extension of the balancing problem, which only occurs in mixed-model assembly lines (Hwang & Hiroshi, 2010). On one hand, line balancing problem is a long-term problem, which aims to design the optimal distribution of the workload. On the other hand, sequencing problem is a short term problem, which based on the tasks distribution of line balancing problem, aims to find an optimal production sequence in order to increase the utilization of the stations. Therefore, line balancing commonly is solved first, and sets the basis to solve the sequencing problem (Hwang & Hiroshi, 2010). When solving line balancing problem, sequencing problem can be anticipated by using horizontal balancing (Merengo, et al., 1999), which seeks to reduce the variance of station times of all models.

Product variants are launched according to a scheduling, where products are arranged in the sequence set and meeting the production volumes expected for each model. In literature two kinds of scheduling can be stated (Merengo, et al., 1999).

**Off-line scheduling** (Static scheduling): The production schedule is made before launching the production. The demand of different variants is known in advance, and therefore the sequencing problem can be solved taking into account the production rate expected for a period of time (shift, day, week etc.) (Rekiek & Delchambre, 2006).

**On-line scheduling** (Dynamic scheduling): Due to the fact that the production rate of the line must accomplish with the JIT requirements (such as maintain low stocks), production scheduling needs to facilitate this (Uddin & Martinez Lastra, 2011). On-line scheduling is performed while the facilities are working, at each decision problem that arises, the results are immediately evaluated and a decision is taken (Rekiek & Delchambre, 2006).
2.2.3 Operator variability

This section is focused on the variability of the process time that workers take to perform manufacturing tasks. Three sources of process time variability have been identified by Doerr and Arreola-Risa (2000); among them, operator variability can be considered as the most important. The other two are: “the task itself and the environment where the task is performed”.

On the other hand, operator variability depends on who is performing the task. Different workers which are performing the same task will take different process times. This is due to physical and physiological parameter as the worker’s ability, experience, discipline, manual dexterity, incentives, motivation in the job, etc. (Hopp & Spearman, 2001). With respect to this point, it is important to highlight the learning curve phenomenon, which is easy to visualize in workers who perform manual tasks (Groover, 2007). This phenomenon is explained by Groover (2007) as follows: “when the worker accomplishes the task over and over, the time required for each successive work cycle decreases as he or she learns the task”. This also involves that several variants of tasks make the specialization of the workers difficult.

When balancing the assembly line, operator variability can be a problem because it causes continuous variations in the stations workload. In order to know the optimal allocation of the workers in the production line, this unbalance must be studied.

**Predetermined motion time system**

In order to study the operator variability, Predetermined Motion Time Systems (PMTS) provide the standard time that the operators require to perform manual tasks by means of an analysis of motion times together with a set of procedures, techniques and information. (Groover, 2007).

2.3 Simulation

2.3.1 Introduction

Computer simulation has been developed in parallel with computers. In its beginnings, the complexity of the systems and the computation limits were a significant problem that has
been reduced over time. These problems have diminished with the increasing performance of computers.

In manufacturing systems, the line balancing problem is increased due to the operator variability; this issue has been a hard problem to solve due to its complexity. In this context, simulation has emerged as an essential tool. (Praca & Ramos, 1999). In the automotive industry the use of simulation has also grown in order to study the behaviour and performance of the future changes in the production lines (Steineman, et al., 2012).

Nowadays, simulation is a usefulness tool to imitate situations that can happen in real life by means of a model, with the aim of understanding the behaviour of any system. Before using simulation it is of benefit to understand the advantages and disadvantages of it, with the aim of knowing whether it will be the appropriate tool or not. “A system is defined as a group of objects that are joined together in some regular interaction or interdependence toward the accomplishment of some purpose”. (Banks, et al., 2001)

Studying a system can be done on the real system or through a model of the system. “A model is the representation of a system for the purpose of studying the system” (Banks, et al., 2001). This model, in turn, can be a physical or a mathematical model. Simulation is one solution to study a mathematical model; the other solution is analytical as it is shown in Figure 6.

Figure 7 “Simulation, Modelling & Analysis” (Law and Kelton, 2007)
Through simulation, it is possible to model and analyse systems without the risks or costs that would be involve in the real system.

When a hypothesis or improvement is tested in reality, it is sometimes required to stop the production. This situation involves idle time and costs, whilst using of simulation avoids these disadvantages.

Manufacturing systems analysis and design is becoming one of the most important applications in the field of simulation. The reason is the complexity due to the amount of variables that have to be taken into account (Praca & Ramos, 1999). As Law (2007) argues in his book, Winter Simulation Conference (WSC) attracts hundreds of people every year showing that simulation is becoming the most used tool among the "operations-research techniques".

Other application areas for simulation are: the study of military weapons, communications networks, healthcare systems, computer systems, financial or economic systems, designing and operating transportation systems, evaluating designs for service organizations and etc. (Law & Kelton, 2007).

### 2.3.2 Discrete Event Simulation

As described by Jerry Banks (2010) in his book, “Discrete-event systems simulations are the modelling of systems in which the state variable changes only at a discrete set of points in time. The simulation models are analysed by numerical methods rather than by analytical methods”.

Shown in Figure 7, a DES is a simulation technology that is used to describe system models which are stochastic, dynamic and discrete in their nature. Stochastic means the same as probabilistic, in other words, contains random variables. On the other hand, deterministic is one that contains no random variables. Dynamic is referred to systems that change over time unlike static that referred to systems at a particular point in time. Unlike discrete system, a continuous system is one in which the state variable(s) change continuously over time (Banks, et al., 2001).
The system model based on DES has many different components, among them, the main ones are:

**Entity:** Dynamic objects or components in the system that move around and in occasions leave the simulation. In our model the entities are the different variant types of engines.

**Attributes:** Properties or characteristics that contain all entities and that make the programing easier by storing important data or information.

**Event:** An instantaneous occurrence from the event list that can change or not the state of a system when it is processed.

**Event list:** A list of events that are processed in function of the time, beginning for the lowest time event and so on.

**Simulation Clock:** A clock that allows knowing and controlling the time of simulation.

Other components in a DES are i.e. variables, resources, queues, buffers, etc. For a more detailed description of these components and its functions, see Bangsow (2010).

To simulate DES model, a time-advance mechanism is needed, which will control the simulation clock of the system. This mechanism goes chronologically through all points in
time following the event list until no events are left or the simulation is stopped (Law & Kelton, 2007).

2.3.3 Advantages and disadvantages of using DES

Simulation is used to study systems which are very complex, or that cannot be solved by others means whether mathematical or analytical. Some advantages of DES are cited below and thoroughly describe in Law and Kelton (2007) and Banks (2010).

- DES provides a way to evaluate a manufacturing system without the need of interfere in the real system.

- Simulation allows an accurate study of complex systems that cannot be solved by others ways.

- Through simulation, the performance of different scenarios can be obtained and compared in order to obtain the best solution.

- Simulation also allows the study of a system with a total control of the time i.e. in a compressed or expanded time.

However, simulation has disadvantages as well. Some of them are cited below:

- Sometimes, building and simulating a simulation model can be expensive and time consuming.

- Simulations models require a deep programming knowledge. On the other hand, two simulation models made by different developers are unlikely that be the same results.

2.3.4 Selecting input distribution

In a stochastic simulation study with random input data, the specification of an appropriate probability distribution is a necessary task. As Law (2007) states in his book, “a failure to choose the correct distribution can also affect the accuracy of a model’s results, sometimes drastically”.

In order to know the adequate distribution family the input data are used according to one of the following methods:
• The trace driven simulation, which consists of using the data collected directly in the simulation.

• Empirical distribution, that as its name indicates, consist of using the data collected to define an empirical distribution, which is used in the simulation.

• Theoretical distribution, which the data collected are fitted to a theoretical distribution, which is used in the simulation.

Law (2007) argues that among the three methods, the use of a theoretical distribution is the best choice. Some advantages to use this method are: the ability to “smooth out” the data and generate wider range of values, and that it is easier to change the parameters of the distribution.

In this study, the only input data required is the time that the workers require to perform an activity. This study takes into consideration the operator variability which is model by means of a theoretical distribution. The distribution family chosen is the Johnson family, among which distributions Johnson $S_B$ has been implemented.

The Johnson distribution family was published in 1949 by Johnson, N. L. in the article “Systems of frequency curves generated by methods of translation”, in the journal Biometrika. This distribution family has the flexibility as the main characteristic (Wheeler, 1980).

The system of frequency curves for the variable $x$ that describe Johnson (1949) is defined in the follow equation:

$$z = \gamma + \delta \log f(u), \quad u = (x - \xi) / \lambda$$

Where $z$ is a standard normal variable, $\gamma$ is a shape parameter, $\delta$ is a shape parameter (being $\delta > 0$), $\xi$ is a location parameter, $\lambda$ is a scale parameter (being $\lambda > 0$), and $f$ has three possible forms:

$S_L$: $f(u) = u$, the log normal;

$S_U$: $f(u) = u + \sqrt{1 + u^2}$, an unbounded distribution;

$S_B$: $f(u) = u/(1-u)$, a bounded distribution;
**Why Johnson SB distribution?**

To create a distribution, that represents the real behaviour in a reliable way, it is necessary a huge amount of data. In this case, the data obtained is not enough for this purpose. In his book, Law and Kelton (2007) stated that the distribution family of Johnson SB “often provides a better fit to data sets than standard distributions such as gamma, lognormal, and Weibull”. Urenda et al. (2008) also argues the use of Johnson SB distribution to describe the variability of manual tasks due to: “its high scalability and bounded nature”.

An example of Johnson SB distribution is illustrated in Figure 8.

![Johnson SB distributions](image)

**Figure 9 Johnson SB distributions (Law & Kelton, 2007)**

In Figure 8, the shape parameters $\alpha_1$ and $\alpha_2$ correspond to $\gamma$ and $\delta$ respectively. As can be seen, the curves are displaced and deformed, depending on the shape parameters. This allows fitting a curve easily to the data.

**2.3.5 Output data analysis**

A proper analysis of the output data is an important factor that should be taken into account. Unfortunately, it is common that a simulation model is considered as valid, after a single simulation run and of any length (Law, 2007), due to the unknown consequences.

Analysing the output data in a right way is essential due to the randomness in the results from the probability distribution of the input data. This involves that the same model must not have the same output values each time that the simulation starts.
Law and Kelton (2007) argue that the output-analysis remains a problem; due to the complexity to apply the required methods and that "there is no completely accepted solution". A brief discussion about how to choose the parameters of a simulation study is exposed in the next paragraphs.

**Steady state and replications analysis**

First of all, to perform this analysis it is necessary to know the type of system that is studied: terminating simulation or non-terminating simulation. The term terminating refers to simulations where the initial conditions are important and have a specific length. On the other hand, non-terminating refers to simulations with a long period of time or simulations that run continuously.

The replications analysis is necessary due to the variability of the output data described above. This analysis provides the number of replications enough to obtain a reliable result. The process to determine the appropriate number of replications begins by choosing a random number of replication and running the simulation. Then the results of this simulation together with a level of confidence (which objective is to show the reliability of the simulation results) is used to determine whether the number of replications is enough or more replications are needed.

In the analysis of the system output, two behaviours can be encountered. The warm-up time or transient is the period of time, from the moment when the system starts running until the output becomes stable. The behaviour in this period of time is unstable and the results obtained should not be taken into account. On the other hand, the steady state is reached when the output reaches the stability. The results are reliable in this period of time.

In their book Law and Kelton (2007) claims that in order to determine the warm-up period, the Welch procedure is "the simplest and most general technique". Both procedures are used in the Chapter 5 in order to know the warm-up time and the number of replications needed in the simulation output data analysis.

**2.3.6 Plant Simulation**

In this thesis, Plant Simulation software has been used to test different hypothesis on the production line of Volvo Powertrain. Plant Simulation software is a discrete-event simulation
tool developed by Siemens PLM Software. This program can be used to model, simulate and analyse production systems with the aim to optimize its performance in a faster and smarter manner (PLM, 2013).

Plant Simulation allows to control and program the behaviour of the objects by means of an own programming language called SimTalk. For this purpose a component called method is used, which is activated when certain events occur, and where the programming takes place.

The most important advantages of using this simulation program are: hierarchical structure in programming, library and object management, and the possibility of perform an automatic analysis of the simulation results (PLM, 2013).

By using this software it is possible to create and analyse different scenarios before the real system is constructed. This allows the reduction of time needed to research and find the adequate solutions to the problems stated.

2.3.7 Method

In a simulation model many steps have to be followed in an orderly manner. Authors use different method, in this thesis the methodology used is the one proposed by Banks (2010), which is showed in the Figure 9.
In the step number 1, the problem is set. Once the objectives that the simulation has to accomplish are stated, it is time to build up the model and collect data, to subsequently translate it into the simulation software.
The next two steps are verification and validation of the simulation model. Banks et al. (2010) stated that “if the input parameters and logical structure of the model are correctly represented in the computer, then verification has been completed”. On the other hand, the validation is achieved when the simulation model has behaviour accepted or accurate enough, in comparison with the current model.

In the step number 8 “Experimental design”, it has to be established the conditions of simulation, i.e. the length of simulations runs, the number of replications, etc.

The following step is to run the model in order to obtain and analyse the output data. The output data obtained in previous step will determine whether or not more runs are needed in the step number 10.

Finally, all the steps described above will be documented and reported, and the implementation will depend on whether the results are accurate enough.

2.4 Production philosophies

In the following sections the current and most important approaches of production philosophies are briefly described.

2.4.1 Lean

In 1980s, the term Lean appeared for the first time; this concept was based in the new philosophy in which the Japanese organized and managed the Toyota Company after World War II (Womack & Jones, 2003): The Toyota Production System (TPS), which developed “an alternative to mass production”, and consequently, “led to raise productivity and quality levels by allowing the flexibility of skilled production with the volume efficiencies of mass manufacturing” (Womack, et al., 1990).

Just in time (JIT) is one of the fundamental pillars of TPS. The Japanese market “was very small, with few exports” and JIT emerged in relation to the need to adapt the production systems to the growing demand (Cusumano, 1994).JIT is defined by Grover (2007) as: “a manufacturing strategy in which parts required in production and/or assembly are received immediately before they are needed in the plant”.

26
Lean production is defined as: “an adaptation of mass production in which workers and work cells are more flexible and efficient by adopting methods that reduce waste in all forms”, understanding as waste “anything that does not add value to the final product or service, in the eyes of the customer” (Groover, 2008). Another brief description of Lean is “doing more with less” (Bicheno & Holweg, 2009).

Some of the most meaningful lean principles described by Liker (2004) are:

- Use “Pull” systems to avoid overproduction.
- Level out the workload
- Standardized tasks are the foundation for continuous improvement and employee empowerment.
- Long-Term philosophy

An important concept in a Lean organization is that mistakes are seen as opportunities to improve and learn, and not as a reason of punishment. (Bicheno & Holweg, 2009)

### 2.4.2 Theory of Constraints

Eliyahu Goldratt developed the Theory of Constraints (TOC) in his book “The Goal”, in which he established that “the goal of a manufacturing organization is to make money”. Furthermore, he stated that the three measurements in which the goal is expressed are: throughput, inventory and operational expense listed in priority order. Goldratt defines these concepts in the follow way:

**Throughput:** “It is the rate at which the system generates money through sales”.

**Inventory:** “It is all the money invested in purchasing things that it intends to sell”.

**Operational Expense:** “It is all the money that the system spends to turn inventory into throughput”.

The next definitions, described by Bicheno (2009), are necessary in order to have a better understanding of this theory:

“A constraint is a resource with the highest load. A bottleneck is a resource that is unable to meet current demand. A constrained critical resource is a resource that has the potential to become a bottleneck.”
Finally Goldratt (1993) provides the following steps in order to achieve the goal:

- Identify the system's constraint(s).
- Decide how to exploit the system's constraint(s).
- Subordinate everything else to the above decision.
- Elevate the system's constraint(s).
- Warning! If in the previous steps a constraint has been broken, go back to step 1, but do not allow inertia to cause a system's constraint.

2.4.3 Six Sigma

Before the mid-1980s the Greek letter sigma (σ) was used as a statistical symbol that represented the standard deviation about the mean or average. After that, Motorola introduced other use for σ as an improvement concept called Six Sigma (Pande, et al., 2000).

The Six Sigma strategy is focused on removing the variation, the causes of errors, defects and delays in the production processes. It was developed by the companies in order to meeting the customer requirements (Gutierrez & De la Vara, 2009); this involves the need to study the customers profoundly.

“The term Six Sigma derives from the spread or variation inherent in any process. Essentially, the Sigma level shows how many defects it will be expected, on average, for that process” (Bicheno & Holweg, 2009). The goal is to achieve a level of Six Sigma, which means to produce “only 3, 4 defects for every million activities or opportunities” (Pande, et al., 2000).

In order to reach the Six Sigma level, the improvement methodology of DMAIC (Define, Measure, Analysis, Improve and Control) is used as a closed-loop process. This method provides a structured approach to continue improvement.

Nowadays, Lean manufacturing, together with Six Sigma are some of the most important strategies to attain first class manufacturing. And as explain Bicheno (2009), both are very close, “waste reduction is central to Lean, and variation reduction is central to Six Sigma”.
3 Assembly line description and Data analysis

Having identified the problem and set the objectives in the introduction chapter, the next step of the methodology described in the literature review, is the model conceptualization and the data analysis (section 2.3.7). This chapter provides a description of the real production system and will set the base for the simulation scenarios studied in the following chapters.

3.1 Assembly line description (model conceptualization)

To conceptualize the real-world facilities, it is necessary to understand the system to be modelled. The information presented below has been obtained through visits to the factory and also provided at meetings with several people in charge of different areas of the production system. The layout of the final assembly line of 13-liters engines is shown in Figure 10.

![Figure 11 Layout of the assembly line at Volvo Powertrain](image)

As illustrated in Figure 10, after the basic assembly process, the engines enter the final assembly line, which is the final step in the production process. The first element that the engines have to go through is a buffer of 60 places that has as objective to absorb the fluctuations in the flow that may occur in the previous assembly steps. Engines are stored in the buffer and leave it in the same order as they entered it; an engine leaves the buffer when
the first station (S0100) requires a new engine to assemble. The first four stations in the production line are arranged in series and supplied by two pre-assembly stations, where the cover and the turbo are added. After being processed by station S0220, the production flow is split into two identical parallel branches that perform the same assembly tasks in the same order. Each one of the fourteen stations located on the parallel branches are arranged in series and supplied by one pre-assembly station, which is located at station S0900, where the compressor is added. The engines leave the final assembly line after passing through the final quality control. It is important to clarify that the case study is focused on one of the parallel branches of the final assembly line, as pointed out in Figure 10.

Based on the classification proposed in section 2.1.1, it is possible to describe the production line, specifically the studied area, taking into account the following five parameters:

1. **Line layout:** Serial

   The area of study is one straight branch of the system, more specifically, from station S0300 to station S1500. Stations located in this area are arranged in a serial manner and they are able to work on only one engine at a time.

2. **Line control:** Unpaced asynchronous

   The line is not paced; each station must execute a fixed list of tasks, which depends on the variant of the engine. After completing the list, the engines are transferred to the next station.

3. **Number and variety of products:** Mixed-Model

   As described in Table 1, several variants are simultaneously produced in an intermixed manner, and share the same facilities. On the other hand due to the flexibility of the manual labour, the production line does not have set-up times.

4. **Variation in task times:** Stochastic

   Manual labour causes variation in the execution of the operations; thus times cannot be regarded as deterministic.
5. **Material-handling system**: Asynchronous transport system

The engines are transported by AGVs (AGVs are described in section 2.2.1), which have a capacity of one engine and move independently of each other. The can obviously be blocked if there is another AGV in front.

Table 2 depicts important information about the production scheduling and the production volume of the line.

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Mon-Thurs. (15.6 hours)</th>
<th>Friday (7.6 hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput (Mon-Thurs.)</td>
<td>270 engines/day</td>
<td></td>
</tr>
<tr>
<td>Throughput</td>
<td>17.31 engines/hour</td>
<td></td>
</tr>
<tr>
<td>Throughput (studied area)</td>
<td>8.65 engines/hour</td>
<td></td>
</tr>
</tbody>
</table>

*Table 2 Production information of the assembly line*

### 3.2 Data analysis

The cycle time data available have been provided by the AVIX system (AviX ®, 2013), whose values are based in a Predetermined Motion Time System (PMTS), which are explained in detail in section 2.2.2. A master thesis, which was carried out in parallel with this project, had the aim to evaluate the extent to which the AVIX data comply with the average value of real-time measurements (Ampapun, 2013). Although a significant difference between AVIX data and measurement values was expected, this survey has been performed using AVIX as a mean time value due to the lack of sufficient average real-time values. The historical data values are not variant defined and they differ from real station time due to operator pre-assembly before the station time is triggered. An example of AVIX data is shown in appendix 2, where the time of each task of a particular station and a short specification are displayed. On the other hand, a description of the work that involves each task performed has not been necessary as it has no relevance in the present study; thus, the tasks have been considered as blocks of time, without taking into consideration the kind of work that represents this block of time.

In order to be able to model the stochasticity of the time (operator variability) during the simulation, AVIX data have been modelled with Johnson SB distribution due to its suitability
(section 2.3.4). As stated before, the AVIX data have been considered as mean time value; therefore AVIX values are the values from which the Johnson SB distribution generates the time values used during the simulation; this is described in more detail in section 4.4.

Due to the lack of data for the Dual Fuel and €6 models, these models have been omitted and their production volumes distributed over the rest of the models. On the other hand, in the available data, €3 and €4 have been considered as the same model due to their similarities and low production volume. As a result, the production values took into account during the study is shown in Table 3.

<table>
<thead>
<tr>
<th>Type</th>
<th>Production volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>€3-€4</td>
<td>11%</td>
</tr>
<tr>
<td>€5</td>
<td>72%</td>
</tr>
<tr>
<td>P3520</td>
<td>17%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
</tr>
</tbody>
</table>

Table 3 Production rate of each model used in simulation

The different engine variants showed in Table 3 have important differences in the number of tasks performed during the assembly process and also in the time values. Table 4 summarizes the most significant values of each model.

<table>
<thead>
<tr>
<th></th>
<th>€3-€4</th>
<th>€5</th>
<th>P3520</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nº of assembly tasks</td>
<td>99</td>
<td>114</td>
<td>109</td>
</tr>
<tr>
<td>Total production time</td>
<td>1h 23m 6.5s</td>
<td>1h 26m 52s</td>
<td>1h 25m 14s</td>
</tr>
<tr>
<td>Longest task</td>
<td>3m9s (S0500)</td>
<td>3m 44s (S1200)</td>
<td>3m 44s (S1200)</td>
</tr>
<tr>
<td>Mean task time</td>
<td>50 s</td>
<td>44 s</td>
<td>48 s</td>
</tr>
<tr>
<td>Mean station time</td>
<td>5m 56s</td>
<td>5m 55s</td>
<td>6m 16s</td>
</tr>
</tbody>
</table>

Table 4 Significant production values by model
3.3 Summary

Model conceptualization and data analysis are essential steps to understand the studied system. Once a conceptual model of the real process flow and its activities has been acquired and values (such as time or production volumes) have been collected and analysed, the next step consists in translating this conceptual model into a simulation model. The process of transformation from the real system to a simulation model involves simplifications and assumptions (handle by the conceptual model) and it is necessary to have the suitable tools to be able to simulate the behaviour of the real-world facilities in a valid way.
4 Simulation Model Design

The next step in the methodology is the model translation; therefore this chapter intends to provide an explanation about the process of designing the simulation model, generalizations of the real-system and an explanation of the most important aspects when designing the models.

4.1 Assumptions and Simplifications

Several features of the real production system had to be changed or omitted in the simulation model, for different reasons.

Station S0400: The function of the station S0400 is to perform a quality control, which has a very short time (30 seconds). This station will be removed in the near future and has a little relevance in the behaviour of the system, therefore station S0400 will not be considered in simulation models. Except in the current line model, with the purpose of validate it.

Buffers allocation: Between stations S0400-S0500, S0500-S0600, S0800-S0900 and S1300-S1400 there is space for placing an AGV, which usually waits to be able to enter in the next station. Therefore these free spaces in the production line can be considered as buffers. Except in the current line model, buffers are not taken into consideration.

Pre-assembly stations: This stations works in parallel with the assembly line, and regardless of the line; therefore pre-assembly stations have been omitted.

Transporting time: The time needed by the AGVs to move from one station to the next is assumed to be constant, with a value of 15 seconds.

Scanning time: Scanning is the last task in every station and has 5 seconds of processing time. This task has been omitted from the task list and added to the transporting time between stations. Results showed later confirm that this does not imply significant changes in the behaviour of the system.
60 places buffer: The buffer of 60 places located at the beginning of the line is considered infinite, which means that the system is not affected by the fluctuations in the production flow caused by the basic assembly line.

Breakdown time and maintenance time: Due to the fact that the studied system is a manual assembly line, breakdown are shorter and more limited compared to a machining line. These are dealt with the use of an effective process time (EPT) approach which is modelled through the JohnsonSB distribution (Urenda, et al., 2008). This means that variations generated by smaller breakdown problems at the assembly stations are considered to be extra-long cycle times. The EPT approach gives the opportunity to aggregate the minor stops into the regular cycle time distribution.

4.2 Model translation

Tecnomatrix Plant Simulation 9 software was used to develop the simulation models. An in-depth study of the simulation software was required in order to make the most of the program resources and achieve the desired behaviour. Plant Simulation provides its own programming language, named SimTalk, with which it is possible to program the behaviour of the simulation. This is of great importance when there is a lack of a predetermined tool to perform a specific requirement. As stated in Chapter 2 (section 2.3.6), SimTalk code is contained in components called methods, which are triggered when certain event occurs.

In order to be able to test the hypothesis under different scenarios, several models have been needed. Nevertheless, all models have essentially the same structure, varying solely in specific features. Figure 11 depicts the base layout used to construct the models; each component is described as follows.
**Source and Drain:** The source represents the buffer of 60 places located at the beginning of the assembly line. As stated before, this buffer is considered as infinite; therefore the interval of creation of engines in the source is zero seconds. On the other hand, due to the intermixed production of models, the source produces engines in a random sequence. The drain represents the end of the assembly line; this component collects important statistical facts such as the throughput of the system.

**Single process** (from S0300 to S1500): Each one of the work-stations along the line is represented by one single process, which has the name of the station. In all the developed scenarios, each single process must be able to execute a list of tasks, or in other words, execute tasks one by one in a determined order; an explanation about how it has been achieved is shown below, in section 4.1. Moreover the processing time of the single process is assigned by the Johnson SB method, which is explained later in section 4.4.

**Conveyors** (from L300-500 to L1400-1500): Conveyors between stations simulates the transport of the engines. As stated before, the transport time has been set in 15 seconds.

**Event controller:** This component controls the running time of the simulation, managing several parameters, such as warm-up time or the duration of the simulation.

**Experiment manager:** This tool allows the managing and design of experiments.
Init and Endsim Methods: Init method is used to put the system in an initial state, each time that the simulation starts. Endsim method reset several values of the system such as table values.

Tables (TableFile, Frequencies and TaskAllocation): Tables are elements which can be read and written during the simulation. Therefore are useful elements to change input values or obtain output values.

- TableFile: Contains the time value of each task, depending on the engine variant.
- Frequencies: Contains the value (in percentage) of the production rate for each variant.
- TaskAllocation: Allows changing the task range that each station is able to do.

The other components of the layout, such as buffers or indicators located under the single processes have the purpose of execute list of tasks and model the time variability. These components are explained in detail as follows.

4.3 Execution of tasks lists

One important aspect of the production system behaviour is the execution of tasks lists. Tasks performed by each station must be executed one by one, following a predetermined order. On the other hand, tasks cannot be interrupted, therefore are considered as individual work blocks. Since the software lacks a tool to execute these requirements, an alternative method based on programming, has been developed using a fictitious buffer (buffers which are above each single process in Figure 11) as a step between the end of a task and the beginning of the next task. When certain condition is fulfilled, the loop ends and the engine is transferred to the next station. The sum of all the tasks performed by a single process results the total working time of the station. Figure 12 shows the logic diagram used to execute tasks lists.
4.4 Modelling of time variability

As previously stated in section 2.2.2, time operator variability is of great relevance in the performance of production systems, therefore it is an aspect that must be taken into account in order to have reliable results. Johnson SB distribution has been defined in section 2.3.4 as a suitable distribution to model the time variability of a manual assembly line, among other reasons, because that it only need the mean time as input value. In this case AVIX data have been used as mean time. The time variability, or in other words, Manual Effective Process Time (Manual EPT) is modelled through the tool shown in Figure 13.

The method takes the mean time as an input and returns a random value after passing through the Johnson SB distribution; this random value is assigned as process time of the corresponding single process and displayed in the red indicator illustrated in Figure 11. Manual EPT reflects a station variability that also takes into consideration minor stops.
Manual EPT tool can be configured by changing four parameters, two bound parameters and two shape parameters which are described in detail in section 2.3.4. Thus, the Johnson SB distribution contained in the method can be modified to obtain the most suitable configuration of the distribution. This tool has been developed by Jacob Svensson and Matías Urenda Moris (Urenda, et al., 2008).

4.5 Summary

First of all, the model structure explained in this chapter shows the base structure of the simulation model, from which the rest of the scenarios are developed. After the description of the model translation, the next step is the experimental setup, in this particular case it is necessary to perform several experimental setups, one for each scenario proposed. All the scenarios proposed have their particular characteristics that differentiate them from the base structure.
5 Results and Analysis

One of the aims of this chapter is to provide a description of each one of the six scenarios studied; among them, two have been deducted from the results of previous scenarios. In order to provide the reader with the needed information to understand the behaviour of each scenario, the chapter presents an experimental setup description, which describes the main features that differentiate each scenario from the base model structure, presented in the previous chapter. Moreover, the calculations of the simulation parameters are presented.

On the other hand, due to the fact that some scenarios have been deducted from the results of previous ones, in order to provide an understandable structure, the results and analysis of each scenario have been included in this chapter; thereby, each scenario is studied following the structure presented in Figure 14.

Figure 15 Scenarios analysis process

In connection with the simulation methodology (explained in detail in section 2.3.7), this chapter provides the verification and validation of the simulation model, as well as the experimental design, thus ending the development of simulation model.
5.1 Introduction

As stated in the introduction chapter, the aim of this study is to simulate a real-world production system under the hypothetic conditions. These conditions can be regarded from a twofold perspective, on one hand, only taking into account the dynamic allocation of the assembly activities. On the other hand, the other perspective places the emphasis in the control of the production flow, which is expected to be unstable due to the dynamic allocation of the operations.

In addition to the twofold hypothesis approach, in order to have a basis to compare the results obtained, it is fundamental to take into consideration a scenario which models the real-world facilities as accurately as possible.

These three configurations stated before are presented in the Figure 15, and set the hypothesis configuration level.

![Figure 16 Studied scenarios](image)

**Predefined scenarios** show the name of the scenarios set according to the proposed configurations. In the case of current line, the difference between “Current line 1” and “Current line 2” will be explained later.

**Deducted scenarios** level presents the name of the scenarios deducted form the result of the previous ones. In order to obtain outcomes closer to the optimal values, these scenarios introduce improvements in the behaviour.
5.2 Steady state analysis and simulation parameters

In this project a non-terminating simulation is studied, which involves a steady state analysis and the study of the simulation run length described in section 2.3.5. The variability explained in the same chapter in reference to the replications analysis does not affect the system sufficiently to need a high precision in the output value.

In order to perform the replication analysis, 10 replications have been chosen as initial number of replications with a confidence interval of 90%. The results obtained are:

- Throughput per hour = 8.2255
- Standard deviation = 0.0267

The equation of the standard deviation is the follow:

\[ s = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n - 1}} \]

Where \( n \) is the number of observations, \( x_i \) is a sample and \( \bar{x} \) the mean.

After this, the absolute precision has been adjusted to 0.016, which provides a good accuracy. The next steps have been to calculate the standard error and the number of replications needed. For this purpose, an excel table has been used as it is shown in Table 5, which performs the calculus of the two variables using a TINV function. This function returns the t-value of the t-distribution as a function of the probability and the degrees of freedom. The equation of the standard error and the number of replications are shown below:

\[ \text{Standard error} = t_{1-\alpha/2,n-1} * \frac{s}{\sqrt{n}} \]

\[ \text{number of replications} = \left( \frac{t_{1-\alpha/2,n-1} * \frac{s}{\sqrt{n}}}{\text{absolute precision}} \right)^2 \]

Where

\( t = \) t-distribution with 1-\( \alpha/2 \) and \( n-1 \) degrees of freedom,
Results and Analysis

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\[ s = \text{standard deviation}, \]
\[ n = \text{number of observations}. \]

The next table depicts the values from which the standard error and the number of replications needed have been calculated.

<table>
<thead>
<tr>
<th>Output</th>
<th>Throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence Interval (%)</td>
<td>90</td>
</tr>
<tr>
<td>Nº replications used</td>
<td>10</td>
</tr>
<tr>
<td>MEAN</td>
<td>8,2255</td>
</tr>
<tr>
<td>STDEV</td>
<td>0,0267</td>
</tr>
<tr>
<td>Standard error</td>
<td>0,01548</td>
</tr>
<tr>
<td>Absolute precision</td>
<td>0,016</td>
</tr>
<tr>
<td>Number of replications needed</td>
<td>9,36</td>
</tr>
</tbody>
</table>

**Table 5 Calculation of the standard error and the number of replications**

As can be seen in Table 5, the standard error is lower than the absolute precision, and the value of the number of replications needed is 9.36, what involves that the number of simulations needed used, 10 in this case, is enough. On the other hand, the method used to determine the warm-up time is the Welch procedure, which is described by Law and Kelton (2007) as follows:

Step 1- the model run for a length of m units and n replications (10 observations in this case) and observations of each unit are recorded.

Step 2- the average number of observations of n replications for each unit is calculated and illustrated in a plot.

Step 3- to smooth out the high frequency of plot, the moving average method is used and the result is a smoother plot.

Step 4- once the quite smooth curve is obtained from the moving average, the length of the warm up period can be determined by finding the x-value at which the curve starts becoming steady).

After this procedure the Figure 16 has been obtained.
As can be seen in Figure 16, the system requires only a short time period to reach the steady state. The warm-up period has therefore been adjusted to 12 hours or 43200 seconds. Following the rule that the warm-up time take a 5% of the total length, the length of the simulation runs has been adjusted to 10 days or what is the same 864000 seconds. All output results of the different scenarios have been calculated using these parameters, which are shown in Table 6.

<table>
<thead>
<tr>
<th>Confidence Interval (%)</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nº replications</td>
<td>10</td>
</tr>
<tr>
<td>Warm-up time</td>
<td>12 hours</td>
</tr>
<tr>
<td>Simulation length</td>
<td>10 days</td>
</tr>
</tbody>
</table>

**Table 6 Simulation parameters**

### 5.3 Current line 1

In line with the methodology explained in section 2.3.7, this scenario aims to provide the verification and validation of the simulation model, by means of the comparison of the results obtained after the simulation with the data of the real-world facilities. Therefore, this scenario
must simulate the real-world facilities as accurate as possible, taking into consideration that the simulation model developed only covers one parallel branch of the assembly line.

5.3.1 Scenario description
In order to be able to obtain an accurate simulation of the real-world facilities, several of the simplification and assumptions stated in Chapter 4 (section 4.1) had to be changed. Mainly two modifications have been undone.

- Station S0400 is taken into account
- Buffers are taken into account and are located in the same place as real system

5.3.2 Experimental setup
The experimental setup of this scenario has no differences with the base model explained in Chapter 4; therefore, special features have not been needed. Moreover, it has been proven that the structure and the input data of the simulation model correctly represents the real world facilities, thus complying with the verification step.

5.3.3 Results and analysis
As stated in the scenario aim section, the most relevant results are those that provide information to compare with the data of the real system, in order to validate the model. In this case the throughput obtained is the most meaningful data to compare. The results of the real system have been presented in Table 2, presented in Chapter 3. This comparison is showed in Table 7.

<table>
<thead>
<tr>
<th>Throughput (Eng./hour)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real system</td>
</tr>
<tr>
<td>Current line 1</td>
</tr>
</tbody>
</table>

Table 7 Throughput values of Real system and scenario Current line 1

Table 7 shows a minor difference, only 0.87 %, between the throughput of the real system and the simulation model.

Other important aspects to compare are the production mix levels in the simulation, which has to be identical to the percentage shown in Table 3 (section 3.2). After a simulation of 240 hours the sink element of the model shows the following results, described in Table 8.
Table 8 shows that the frequency of variant production is correctly simulated; therefore the similarities in both results (throughput and variant frequency) lead to the conclusion that the simulation model developed and its features accomplish with the real system behaviour, and therefore the model is validated.

Finally, it is important to highlight the influence of the station S0400 in the performance of the line, since this station is not taken into account in the rest of the scenarios (see section 4.1). Figure 17 shows the utilization graph obtained.

As illustrated in Figure 17, the station S0400 has the lowest working time in front of the lowest waiting time in station S0500, which means that the station S0400 can be considered...
as a buffer. Due to the reason exposed in Chapter 4 (in section 4.1) and the confirmation that station S0400 is not a bottleneck station it is justified its omission in the next scenarios.

5.4 Current line 2

5.4.1 Scenario aim
This scenario aims to simulate the real system, but unlike with the previous scenario, implementing the simplifications and assumptions stated in Chapter 4. The results obtained have been used as benchmark to compare with the results of the rest of the scenarios.

5.4.2 Scenario description
The configuration of this scenario is the same as previous, with the difference that in this case all the simplifications and assumptions explained in section 4.1 have been taken into consideration.

5.4.3 Experimental setup
The experimental setup of this scenario has no differences with the base model explained in Chapter 4; therefore special features have not been needed.

5.4.4 Results and analysis
The results obtained are shown in Table 9, which presents the values of the most meaningful parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Current line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>8.225 Eng./hour</td>
</tr>
<tr>
<td>Utilization</td>
<td>72.42 %</td>
</tr>
<tr>
<td>Lead time</td>
<td>1:37:23</td>
</tr>
</tbody>
</table>

Table 9 Current line 2 results

As might be expected, in the comparison with the scenario Current line 1, the results show a reduction in the throughput, caused by the elimination of the buffers and the station S0400. For this reason the lead time has also decreased. On the other hand, the elimination of the station S0400 has produced an increment in the mean utilization of the stations. The utilization graph with thirteen stations, without station S0400, is illustrated in Figure 18.
One important aspect to take into consideration is the fluctuation of the workload, which have an important influence in the operator variability (for a detailed explanation, see section 2.2.3). In order to obtain a meaningful result of this parameter, the fluctuations in the workload have been measured in the last station S1500, resulting in the Figure 19, where the y axis value of each column represents the working time needed by the station to finish the engine.

In this case, the fluctuations appreciated in the graph are caused by the difference in the workload of each engine variant and due to the variability in the assembly work. This variability is explained in detail in section 2.2.3.
5.5 Scenario 1

5.5.1 Scenario aim
To evaluate the production line under a total dynamic allocation of the assembly operations is the main target of this project, and this scenario attempts to test and obtain the results of the system under this configuration.

5.5.2 Scenario description
Total dynamic allocation of the assembly operations means basically that all the stations of the line are able to do all the assembly operations; in other words, there is no restriction in the task range of the stations. On the other hand, the execution order of the assembly operations has not been modified. When an engine enters in a station, the station performs the assembly tasks until the moment in which the next station is empty. When this occurs, the station finishes the task that is performing at that time, and then passes on the engine to the next station.

5.5.3 Experimental setup
In order to be able to simulate the behaviour described in the previous section, the logic of the station operation was modified. This could be achieved through programming the station logic as it is described in Figure 20, where the only condition to transfer the engine is that the next station must be empty.

Figure 21 Flowchart of the station Scenario 1
Results and Analysis

If compared Figure 20 with Figure 12 shown in Chapter 4, the only difference appreciated is in the condition box, and it is the main difference between this Scenario and the base model described in Chapter 4.

5.5.4 Results and analysis

Table 10 shows several key parameters obtained from this scenario, and the comparison with Current line 1 results.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario 1</th>
<th>Current line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>9.084 Eng./hour</td>
<td>8.225 Eng./hour</td>
</tr>
<tr>
<td>Utilization</td>
<td>85.27 %</td>
<td>72.42 %</td>
</tr>
<tr>
<td>Lead time</td>
<td>1:23:37</td>
<td>1:37:23</td>
</tr>
</tbody>
</table>

Table 10 Scenario 1 results

Table 10 shows an improvement in all the parameters measured due to the dynamic allocation of tasks, which reduces the blocking and waiting times in a significant way. Figure 21 depicts this improvement.

In the previous figure, waiting times represents the time during which the stations wait until the previous station finishes the task that is performing at that time. On the other hand, the blocking times have been avoided in almost all the stations, except in S1200, S1300 and
S1400. In order to understand the reason of these blocking times, the fluctuation graph of the last station (S1500), showed in Figure 22 provides meaningful information.

![Figure 23 Fluctuations graph of Scenario 1](image)

The variation in the workload presented is highly irregular; it presents an alternation between long and short workloads which means that frequently the engines enter the station with many tasks still to be performed, as well as frequently the engines enter with all the assembly tasks already performed. The gaps in the graph, which represent a workload with a value of zero, mean that the engine has reached the stations already completed, in other words, with all the assembly tasks already performed. This fact helps to explain the blocking times presented in Figure 21, that can be explained as the time during which the station is blocked because it has finished the engine and is not able to pass on the work-piece. This issue is the motivation for the suggestion of a new scenario, which is explained in the next section.

The elimination in the restrictions of the task range of each station, leads to stations that perform a high range of tasks. In order to know the real extent of this task range, the following graphs have been obtained. The X axis of the graph is limited by the number of tasks; on the other hand, the Y axis shows how many times certain task has been performed. Figure 23 shows (from left to right) the results of stations S0300 (first station), S0600, S1300 and S1500 (last station).
The previous chart shows an expected bell-shaped structure for intermediate stations (S0600 and S1300) and a rectangular triangle shape for the first and last stations. At the top of each graph there are located the most frequently performed tasks. By contrast, less frequently tasks are located at the sides of the graphs. S0600 and S1300 graphs show a left and right inclined shape, respectively.

Table 11 is presented in order to provide a numerical description of the facts explained before, where can be seen the values of the station range extent, as well as the most common task, around which the previous graphs have its maximum value.

<table>
<thead>
<tr>
<th>Station</th>
<th>Task range (from-to)</th>
<th>Most common task (Nº)</th>
<th>Most common task (Nº of times performed)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>€3-€4</td>
<td>€5</td>
<td>P3520</td>
</tr>
<tr>
<td>S0300</td>
<td>1-52</td>
<td>1-73</td>
<td>1-62</td>
</tr>
<tr>
<td>S0500</td>
<td>2-60</td>
<td>2-81</td>
<td>2-73</td>
</tr>
<tr>
<td>S0600</td>
<td>3-64</td>
<td>3-82</td>
<td>3-76</td>
</tr>
<tr>
<td>S0700</td>
<td>4-67</td>
<td>5-89</td>
<td>4-85</td>
</tr>
<tr>
<td>S0800</td>
<td>5-81</td>
<td>6-94</td>
<td>5-90</td>
</tr>
<tr>
<td>S0900</td>
<td>6-91</td>
<td>8-101</td>
<td>7-94</td>
</tr>
<tr>
<td>S1000</td>
<td>9-92</td>
<td>11-104</td>
<td>8-103</td>
</tr>
<tr>
<td>S1040</td>
<td>10-98</td>
<td>14-114</td>
<td>9-107</td>
</tr>
<tr>
<td>S1100</td>
<td>16-99</td>
<td>17-114</td>
<td>13-109</td>
</tr>
<tr>
<td>S1200</td>
<td>12-99</td>
<td>20-114</td>
<td>18-109</td>
</tr>
<tr>
<td>S1300</td>
<td>22-99</td>
<td>23-114</td>
<td>29-109</td>
</tr>
<tr>
<td>S1400</td>
<td>27-99</td>
<td>28-114</td>
<td>32-109</td>
</tr>
<tr>
<td>S1500</td>
<td>32-99</td>
<td>45-114</td>
<td>46-109</td>
</tr>
</tbody>
</table>
Table 11 shows that the stations perform a very wide range of tasks, among them many are very rarely performed and are those that are located in the sides of the graphs illustrated in Figure 23. On the other hand, the values confirm that stations located in the middle of the line execute common task in fewer cases, thus can be described as floating stations.

5.5.5 New scenario deduction

The results previously exposed show the values of the system under a total dynamic allocation of the assembly operations, but in order to know the maximum throughput possible it is suggested a scenario where the blocking times, caused by the early finalization of the engines, are deleted.

5.6 Scenario 1.1

5.6.1 Scenario aim

This Scenario attempts to eliminate the blocking times in the last stations of the Scenario 1, in order to obtain the maximum throughput of the production system under a totally dynamic allocation of the assembly operations.

5.6.2 Scenario description

The description is the same as Scenario 1, with the particularity that the engines already finished are directly delivered to the end of the line, thus leaving the station empty and avoiding the blocking times. This can be interpreted as setting buffers or transport the finished engines through a parallel path to the line.

5.6.3 Experimental setup

As stated before, the only difference with Scenario 1 is the delivering of finished engines to the sink. In order to simulate this behaviour, the station logic has been modified, and the logic shown in Figure 24 has been obtained.
The only difference with the previous flowchart, illustrated in Figure 20 is the addition of a new condition to send the finished engines directly to the sink.

5.6.4 Results and analysis

Table 12 depicts results obtained from this scenario.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario 1.1</th>
<th>Scenario 1</th>
<th>Current line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>9.148 Eng./hour</td>
<td>9.084 Eng./hour</td>
<td>8.225 Eng./hour</td>
</tr>
<tr>
<td>Utilization</td>
<td>85.92 %</td>
<td>85,27 %</td>
<td>72.42 %</td>
</tr>
<tr>
<td>Lead time</td>
<td>-</td>
<td>1:23:37</td>
<td>1:37:23</td>
</tr>
</tbody>
</table>

Table 12 Scenario 1.1 results

As expected, there is an increment in the throughput caused by an increment in the utilization of the facilities. The throughput obtained represents the maximum throughput that the system is able reach under the dynamic allocation of tasks, and it represents an increment of 11.3 % in comparison with the scenario Current line 2. The approach implemented in this scenario distorts the values of lead time, since the finished engines are sent directly to the end of the line. Therefore lead time value has not been included in the results of Scenario 1.1.

Figure 25 presents the utilization graph of the Scenario 1.1, where it is appreciated the elimination of the blocking times in the last stations, and the waiting times represented by
grey colour, shows the time during which the stations wait until the previous station finishes the task that is performing at that time.

![Figure 26 Utilization graph of Scenario 1.1](image)

5.7 **Scenario 2**

5.7.1 **Scenario aim**

One hypothesis approach is based in the implementation of a production flow control. The results obtained from Scenario 1 show that stations perform a wide range of tasks when the system is ruled by a dynamic allocation of assembly operations, which causes a huge variation in the workload. In order to control the fluctuations, Scenario 2 provides a new approach of production flow control, and attempts to study the production system under these circumstances.

5.7.2 **Scenario description**

This scenario introduces a limit in the task range of the stations, because on one hand it simulates a more real situation and on the other hand, once analysed the results from Scenario 1 it is possible to know the tasks range of each station, and therefore be able to set limits which encompass the most of the task most frequently performed by each station. The stations operational limit set can be explained as follows “Each station is able to perform tasks of the previous station, its own tasks and tasks of the next station”. The meaning of “tasks of a station” refers to the group of tasks that each station performs in the real system.
Another peculiarity of this scenario is the flow control, which is executed by the last station by means of a signal. **Certain time** before finish an engine; the last station transmits a signal to the rest of the stations. This signal is an advice that all the stations must transfer the engine before the signal time runs out, or in other words, before the last station completes the engine and transfers it. Figure 26 attempts to explain this behaviour. The tasks list of each station is located below the stations.

![Diagram](image)

**Figure 27 Hypothesis description**

As stated in Figure 26, there are assembly operations that have to be done before the engine leaves the station. This is because each station has a group of task at the beginning of it list that cannot be performed by the following stations. This report refers to these groups of tasks as “compulsory tasks”.

### 5.7.3 Experimental setup

With the aim of achieving the desired behaviour, the changes made in the model have been focused in the station logic, which in this case must accomplish with several conditions, resulting in a more complex algorithm. Figure 27 describes the station logic.
In the blue box illustrated in Figure 27, the algorithm performs a comparison between the time of the next task (AVIX time) and the remaining time of the signal. Signal time is a countdown which decreases its value until it reaches zero. Other important aspect in the programming of this scenario is the modification of the table values (Chapter 4 TableFile) that contains the values of station tasks range.

Due to the new implemented approach, it was necessary to change the initialization of the simulation. Therefore the Init method (explained in section 4.2) has been modified to put the system in an initial state, where all the stations are occupied by an engine which reduces the warm-up time needed. Although the warm-up time used in the simulation has remained constant, keeping the value stated in section 5.2.
5.7.4 Results and analysis

As stated in previous scenarios, the main parameter used to compare different results is the throughput value. On the other hand, after the first tests performed with different signal time values, it was concluded that the throughput and signal values are directly related. Thus, an additional experiment was performed in order to obtain the curve that relates throughput and signal values and consequently be able to know the optimal value of the signal. Figure 28 shows the aforementioned curve, where signal values ranges from 0 seconds to 350 seconds, with an increment of 10 seconds between experiments.

![Confidence intervals of selected result values](image)

**Figure 29 Correlation between signal and throughput values in Scenario 2**

The first point of the graph shows the results of the experiment performed with 0 seconds as signal value, the behaviour of the system with this value simulates a line without signal control. Without the signal control, the system behaves as in Scenario 1, with the difference being only that the stations tasks ranges have been modified. As shown in the last graph, the “Value 1” shows the higher throughput value, confirming that the optimal values are obtained without the flow control. On the other hand, under the signal control the system obtains the sub-optimum throughput with a value of 140 seconds and it is shown in Figure 28 as “Value 2”. It is important to clarify that the second value of the graph (obtained with 10 seconds of signal value) is higher than Value 2. This can be explained by a too small signal value.
Therefore, under these circumstances, the signal control is rarely activated. Table 13 shows the results of the two aforementioned situations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Scenario 2 (Value 1)</th>
<th>Scenario 2 (Value 2)</th>
<th>Current line 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>8.980 Eng./hour</td>
<td>8.592 Eng./hour</td>
<td>8.225 Eng./hour</td>
</tr>
<tr>
<td>Utilization</td>
<td>84.62 %</td>
<td>80.54 %</td>
<td>72.42 %</td>
</tr>
<tr>
<td>Lead time</td>
<td>1:25:00</td>
<td>1:34:34</td>
<td>1:37:23</td>
</tr>
</tbody>
</table>

Table 13 Scenario 2 results with value 1 and value 2

The utilization results showed in Table 13 shows significant differences, which are explained in detail in Figure 29.

The conclusion taken from Figure 29 is that the blocking times obtained with the “value 2” are significant, while the graph of “value 1” shows stations with more waiting time but a very low level of blocking. The high values of blocking time showed in the first stations of the “value 2” graph leads to the conclusion that the performance of the system is highly dependent on the delay of the station that has the highest workload at that moment. To understand this, it is useful to consider the next situation, “a **station** receives the signal, but at the same time it has remaining compulsory tasks (compulsory tasks are explained in section 5.7.2) still to be performed, and the total time of these tasks exceeds the signal time”. In this
situation, all the stations located before such station will be blocked for some time after the signal time runs out.

5.7.5 New scenario deduction
As stated before, the system with flow control is highly dependent on workload of the station that is the slowest at that time, which is mainly due to the fixed nature the signal value. In order to avoid the blocking time described in previous paragraph, a new scenario has been suggested, which performs a more flexible flow control, and therefore increase the performance of the system.

5.8 Scenario 2.1

5.8.1 Scenario aim
This scenario was developed in order to obtain a more flexible flow control, which allows more working time in each station by reducing the blockings in the assembly line. For this purpose, this new scenario executes the flow control by means of a flexible signal, which means that the value of the signal time is set according to the current situation of the system. Another motivation to this new scenario was to know whether it is possible to obtain a better performance than the system without flow control.

5.8.2 Scenario description
The difference between this scenario and its predecessor (Scenario 2) lies in the behaviour of signal. In the last section, where the results of the Scenario 2 were described, it was mentioned that the next situation occurs frequently: “A station receives the signal, but at the same time it has remaining compulsory tasks (compulsory tasks are explained in section 5.7.2) still to be performed, and the total time of these tasks exceeds the signal time”. Whenever this occurs in this scenario, the fixed signal time is replaced by the remaining time of the station with the highest remaining compulsory tasks. If the signal time is not exceeded, it retains its fixed value. It is important to clarify that the signal is always activated using the fixed signal time as parameter.
5.8.3 Experimental setup

The logic of the station, showed in Figure 27 has not been modified, but in order to obtain the flexible signal time, it was necessary to use an algorithm which recognize which is the station with the highest remaining time. Figure 30 shows the logic used to achieve this.

![Flowchart of the station logic in Scenario 2.1]

Figure 31 Flowchart of the station logic in Scenario 2.1

To perform the comparison exposed in the last picture, the algorithm needs to recognize different values of each station. Figure 31 shows different parameters that the algorithm uses.

![Station parameters in Scenario 2.1]

Figure 32 Station parameters in Scenario 2.1

In this case station S1100 is presented as an example, the parameters showed are explained as follows:

**act_num1100**: Displays the number of the task under execution.

**Red display**: Show the time of the current activity, after processed by the Johnson SB method, which is described in section 4.4.
S1100_countdown: Remaining time of the current activity.

compul_time1100: Displays the time of the compulsory tasks still to be performed.

total_time1100: Is the time required by the station to finish the current task and the compulsory tasks. This is the time that the algorithm uses to compare with the fixed signal time, as is shown in Figure 31.

5.8.4 Results and analysis
As in the case of Scenario 2, the fixed signal value is strongly related with the throughput value. Therefore, in order to obtain the optimum value of the signal, the graph that shows the correlation between signal value and throughput was obtained using the same parameters as in Scenario 2, and it is shown in Figure 32.

![Confidence intervals of selected result values](image)

Figure 33 Correlation between signal and throughput values in Scenario 2.1

The results obtained show the highest throughput value with a signal value of 100 seconds. Table 14 depicts the results obtained using the aforementioned signal value.
The results obtained show significant improvements in comparison with the Scenario 2 due to the increasing of the facilities utilization. Figure 33 depicts the comparison between the utilization of Scenario 2 and Scenario 2.1.

The improvements are focused in the increase of the utilization time of the stations located at the beginning of the line, which means that in Scenario 2.1 the line is less dependent on the slowest station and the assembly delays that occurring upstream have less effect in the stations located at the beginning of the line.

On the other hand, as expected, the throughput of this scenario is lower than the throughput of the Scenario 2 without signal control in 1.23 %. Scenario 2 without signal has the highest flexibility, which allows the independent movement of the engines along the line; therefore a better balancing is obtained and the waiting times and blocking are reduced. On the other hand, one important comparison between Scenario 2 without signal and Scenario 2.1 is the workload fluctuation, which tends to be higher in systems with high dynamic behaviour.
Figure 34 shows the fluctuation graph of the Scenario 2.1 in comparison with Scenario 2 without signal.

![Fluctuation graph of Scenario 2.1 and Scenario 2](image)

Figure 35 Workload fluctuations of Scenario 2 and Scenario 2.1 respectively

Scenario 2.1 graph shows a still high fluctuation, but a more smoothly shape compared to Scenario 2.

### 5.9 Results summary

Table 15 presents the summary of the results analysed in this chapter. The last column depicts the improvements in the throughput of the scenarios in relation with Current line 2.

<table>
<thead>
<tr>
<th>Simulation scenarios</th>
<th>Throughput per hour</th>
<th>Utilization (%)</th>
<th>Lead time (time)</th>
<th>Exit Interval (time)</th>
<th>Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current line 1</td>
<td>8.579</td>
<td>68.36</td>
<td>1:51:42</td>
<td>0:06:59</td>
<td>-</td>
</tr>
<tr>
<td>Current line 2</td>
<td>8.226</td>
<td>72.42</td>
<td>1:37:23</td>
<td>0:07:17</td>
<td>-</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>9.084</td>
<td>85.27</td>
<td>1:23:37</td>
<td>0:06:37</td>
<td>10.44</td>
</tr>
<tr>
<td>Scenario 1.1</td>
<td>9.148</td>
<td>85.92</td>
<td>-</td>
<td>0:06:33</td>
<td>11.23</td>
</tr>
<tr>
<td>Scenario 2 (value 2)</td>
<td>8.592</td>
<td>80.54</td>
<td>1:34:34</td>
<td>0:06:58</td>
<td>4.47</td>
</tr>
<tr>
<td>Scenario 2 (value 1)</td>
<td>8.980</td>
<td>84.62</td>
<td>1:25:00</td>
<td>0:06:40</td>
<td>9.19</td>
</tr>
<tr>
<td>Scenario 2.1</td>
<td>8.864</td>
<td>83.30</td>
<td>1:33:06</td>
<td>0:06:45</td>
<td>7.77</td>
</tr>
</tbody>
</table>

Table 15 Results summary
5.10 Summary

Once obtained and analysed the results, it is possible to understand the main features and the behaviour of each scenario proposed, which have been analysed in a normal production situation where values such as frequency of model production or the time of the tasks have been kept constant. Taking into account the features of the systems studied, it is interesting to analyse its response to changes in different parameters such as variants frequency, station task range or tasks times.
6 Experiments

Experiments involve one or more of the scenarios exposed before, and attempts to analyse their response under different conditions, which may occur under the real world environment. In order to simulate these conditions, several parameters that have remained constant in the last chapter have been modified.

6.1 Experiment 1 Task range variation

6.1.1 Experiment 1 aim

The aim of this experiment is to provide the value of the throughput in correlation to the task range. For instance, the company has the possibility to increase the stations tasks range. Due to the fact that the bigger the tasks range, the greater investment is needed (e.g. in material handling or operator training), the company needs to find an optimum value of task range.

6.1.2 Results and analysis

The experiment has been performed from an initial state which corresponds to the scenario Current line 2, in order to start the experiment without dynamic allocation of tasks. Figure 35 shows the relation throughput-station range, where each point shows the result after an increment of 1 in the task range, which means that after an increment the stations are able to do one task more of the next station and one task more of the previous station.

![Figure 36 Correlation between station task range and throughput value](image)
As stated before, the first point of the graph shows the result of the system with the configuration of the scenario Current line 1, while the last point of the graph shows the result of the system with total dynamic behaviour studied in Scenario 1. The optimum sharing value is obtained with a task range of 50 assembly operations, resulting in a throughput of 9,115 Eng./hour. The first points show that the throughput increases its value rapidly in relation with the increments in the range. On the other hand, the intermediate area of the curve shows a decrement in the throughput value, which is due to the blocking of the last stations caused by the finished engines, as it was explained in section 5.5.4. After the decreasing of the values, the curve stabilizes, which mean that the increments performed from that point have no influence in the throughput of the line.

As a conclusion, the last graph provides important information to decide the optimum task range in correlation with the throughput value. It is important to highlight that in this experiment the stations have increased the range in each point in one task of the next station and one task of the previous.

### 6.2 Experiment 2 One station improvement

#### 6.2.1 Experiment 2 aim

Before explain the aim of the experiment it is important to mention a statement of the Theory of Constraints (explained in detail in section 2.4.2), which asserts that “an improvement performed in a non-bottleneck station will not be substantially reflected in the efficiency of the system”.

The aim of this experiment is to compare the results obtained from scenario Current line 2 and Scenario 1, when an improvement is made in a non-bottleneck station, and thereby contrast the behaviour of the hypothesis in relation with the Theory of Constraints. This improvement consists in a reduction in the working time of one non-bottleneck station. For instance: *One operator is able to perform the assembly operations 20% faster than the rest, but he/she is able to work only in a non-bottleneck station, or a Kaizen work improvement of 20% is done on one of the stations that is not a bottleneck. What is the effect of this improvement in the throughput value in the case of Current line 2 and Scenario 1?*
6.2.2 Results and analysis

First of all, in order to know in which station the improvement must be made, the bottleneck stations have been located. The bottleneck analysis has been performed in the scenario Current line 2, because this is the scenario that simulates the real-system and is used be compared with the rest of the scenarios. Figure 36 shows the bottleneck analysis, performed by a tool available in the software.

![Figure 36 Bottleneck analysis of Current line 2](image)

In figure 36, stations are arranged from bottleneck stations to non-bottleneck stations. To carry out the experiment, Station S1100 is chosen to be improved. The improvement consists in a reduction of the 20% in the time of all the tasks performed by the station S1100, and the results obtained from Current line 2 and Scenario 1 are illustrated in Table 16.

<table>
<thead>
<tr>
<th>Throughput before improvement</th>
<th>Current line 2</th>
<th>Scenario 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput after improvement</td>
<td>8,225 Eng./hour</td>
<td>9,084 Eng./hour</td>
</tr>
<tr>
<td>Throughput improvement</td>
<td>0,31 %</td>
<td>1,79 %</td>
</tr>
</tbody>
</table>

Table 16 Experiment 2 results

Table 16 shows a significant difference between the improvements in the throughput obtained in both scenarios. The throughput improvement in Scenario 1 is about three times greater than the result obtained from Current line 2. Figure 37 presents the evolution of the throughput in correlation with the value of the improvement. The graph shows, both for Current line 1 and
for Scenario 1, the throughput (Y axis) in correlation with improvement values (X axis) implemented in station S1100. These improvement values are arranged in X axis and range from 5% to 95% of. The improvement increments between points in the graph are 5%.

![Graph](image)

**Figure 38 Correlation between improvement value (X axis) and throughput value (Y axis) for Scenario 1 and scenario Current line 2 respectively**

As shown in Figure 37 in the left graph, which correspond to Scenario 1, the increment of throughput follows a lineal distribution, which means that the improvements performed in the station always produces the same proportional increment in the throughput. On the other hand the Current line 2 graph (right graph) shows that the improvements do not affect the throughput significantly, and the values almost remain constant.

### 6.3 Experiment 3

#### 6.3.1 Experiment 3 aim

In all the previous experiments, it has been assumed that the production mix levels are constant. In a realistic environment, the customer demand is constantly changing, which leads to changes in the variants production levels. The aim of this experiment is to test the response of the scenario Current line 2 and Scenario 1 to changes in the production mix levels.

Before start the experiment, it is useful to study the balance of the line for each engine variant, in order to know which variant has the worse line balancing. Figure 38 shows the line workload for each variant.
As illustrated in Figure 38, there are significant differences in the workload of the stations, which depend on the engine variant. In order to have a parameter to measure the smoothness of the line balancing of each variant, it is used the Smoothness Index (SI). This index describes relative smoothness for a given line balancing. It is calculated with the following formula (Grzechca, 2011).

\[
SI = \sqrt{\sum_{i=1}^{K} (ST_{\text{max}} - ST_i)^2}
\]

Where: \( ST_{\text{max}} \) – Maximum station time \( ST_i \) – Station time of station i

Using this formula, the results showed in Table 17 have been obtained.

<table>
<thead>
<tr>
<th>Variant</th>
<th>SI</th>
</tr>
</thead>
<tbody>
<tr>
<td>€5</td>
<td>173.68</td>
</tr>
<tr>
<td>€3-€4</td>
<td>313.83</td>
</tr>
<tr>
<td>P3520</td>
<td>497.87</td>
</tr>
</tbody>
</table>

Table 17 Smoothness index by variant

Taking into consideration that a perfect balance is indicated by smoothness index 0. As illustrated in Table 17, P3520 is the variant with the worst line balancing. On the other hand,
€5 is the variant with the best line balancing. This is logical because the most common variant produced is €5, and therefore the assembly line is designed to have a good performance for this variant.

### 6.3.2 Results and analysis

The experiment simulates scenario Current line 2 and Scenario 1 with two different production mix levels. On one hand, the scenarios have been tested with the mix level that has been used in all the previous experiments, which represents the real mix level of the assembly line, which values are shown in the column “Mix 1” in the Table 18. On the other hand, the scenarios have been tested with another mix level (shown in the column “Mix 2” of Table 18) with an increment in the production rate of the variant P3520, which is the variant with the worst line balancing.

<table>
<thead>
<tr>
<th>Variant</th>
<th>Mix 1</th>
<th>Mix 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>€3-€4</td>
<td>11%</td>
<td>11%</td>
</tr>
<tr>
<td>€5</td>
<td>72%</td>
<td>32%</td>
</tr>
<tr>
<td>P3520</td>
<td>17%</td>
<td>57%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>100%</td>
</tr>
</tbody>
</table>

**Table 18 Production mix levels tested**

The throughput values, obtained from scenario Current line 2 and Scenario 1 (using the mixes shown in the previous table), are illustrated in table 19.

<table>
<thead>
<tr>
<th>Type</th>
<th>Throughput Mix 1</th>
<th>Throughput Mix 2</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current line 2</td>
<td>8.226</td>
<td>7.917</td>
<td>- 3.75%</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>9.117</td>
<td>9.175</td>
<td>+ 0.636%</td>
</tr>
</tbody>
</table>

**Table 19 Experiment 3 results**

Table 19 confirms that when an increment in the production of the variant P3520 occurs in scenario Current line 2, the throughput decreases due to the worse line balancing. On the other hand, in case of the Scenario 1, the throughput value remains stable although in this case it is appreciated a slight increase. This can be explained by the fact that the P3520 variant has a lower total production time (1h 25m 14s) than variant €5 (1h 26m 52s).
7 Discussion

This chapter attempts to clarify the results obtained, providing a discussion where several facts are questioned and interpreted. Moreover, the chapter presents several questions that the readers might have, and the corresponding answers.

7.1 Discussion of findings

The hypothesis on which this thesis has focused on is studied from a dual perspective. On one hand, using total dynamic allocation of assembly operations (Scenario 1 and Scenario 1.1) and on the other hand, using dynamic allocation of assembly operations under the action of a production flow control (Scenario 2 and Scenario 2.1).

The first approach yielded significant results concerning the performance of the system. The improvement in throughput and other values is mainly caused by the increase of the utilization of facilities. The dynamics of the system allow stations to perform any step in the assembly process as long as the precedence order of assembly operations is fulfilled. In the real world, this factor leads to a reduction of the operator specialization and thereby efficiency, due to the high number of different activities that the worker must be able to perform, among which, many are very rarely performed. Thereby, the worker specialization and training become a problem which may be difficult to solve. On the other hand, the results showed significant fluctuations in the stations workload, which may occur due to the fact that during the assembly process, engines with a high number of assembly tasks performed alternate with engines with less assembly steps done.

One important fact to be highlighted is the relation between the range of station tasks and throughput value. The curve provided by the Experiment 1, Figure 35, depicts that when the task range is progressively expanded, the throughput increases rapidly until reaching a steady state. Using this curve it is possible to determine an optimum range of tasks, which on one hand reduces the number of assembly operations performed by the workers, and on the other hand provides an optimum throughput. Another important finding is that an optimum range of station tasks reduces the workload fluctuations.
One of the most important statements of a lean manufacturing approach is continuous improvement; on the other hand, TOC asserts that improvements should be focused on the system constraints. The results of Experiment 2 demonstrated that due to the dynamics of the system, an improvement performed in any non-bottleneck station produces higher increase on the throughput in comparison with the current system. The latter provides more options for system improvement, due to the fact that it is not necessary to focus all the effort on improving the bottleneck stations. Remember that there are occasions when an improvement on the bottleneck station is not justified due to that it might require a too high economical investment.

The combination of mixed-model production and the changing demand leads to assembly lines which are very difficult to balance. This means that the assembly lines performance is highly dependent on the variant mix level required by the customers at that time. The results obtained have proven that with the implementation of the new approach, the production system performance is not much affected by these fluctuations in the demand, since the dynamic allocation of assembly operations provides a flexible balancing.

Regarding the results of the assembly line using production flow control, even after the improvement of the hypothesis approach developed in Scenario 2.1, the throughput obtained is lower than the throughput of the same system without production flow control. This means that the system operates more efficiently when its flow is not controlled. However, it has been noted that the production flow control produces a smoother fluctuation graph, and due to the fact that the difference in the throughput between scenarios both with and without flow control is not very high (1.23 %), the smoother fluctuation graph may become an important advantage to take into account, since this factor is strongly related with the operator efficiency.

Through the simulation of the system ruled by a flow control, the signal time arises as an interesting parameter, which optimum value turns out to be a characteristic parameter of the line and has a particular value for each possible line configuration.
7.2 Research questions

What are the main disadvantages of the dynamic allocation approach?

The disadvantages found are related with the wide operational range of the stations, which accentuates the operator variability. On the other hand, other important disadvantage is the high investment effort required to implement the approach in the real world facilities, as well as the complex study needed to be able to share tasks between stations.

What are the main advantages of the dynamic allocation approach?

The advantages brought by the dynamic allocations are significant, and largely reduces the effect of the most common assembly line problems.

**Line balancing:** The workload distribution along the line is one of the most important facts when designing an assembly line. The new approach allows a smooth distribution of the workload, thereby increasing the utilization of the facilities.

**Sequencing:** The dynamic allocation of operations allows the system to have better response to changes in the production volumes of different models, and reduce the effect caused by the production sequence.

**Restrictions of TOC:** With the implementation of the hypothesis, the production system improves its performance with any improvement. Regardless if the improvement is implemented in a constraint of the system.

How scenario 1 can be improved?

It is possible to improve the performance of the Scenario 1 through the installation of buffers. Nevertheless, this option implies an increment in the work in process (WIP), which goes against the lean principles. This action should be justified by long or short term benefits.

What is the improvement that could introduce the flow control approach?

Flow control attempts to reduce the fluctuations, although the throughput obtained is lower than the system throughput without flow control. Nevertheless, flow control provides an interesting approach to reduce fluctuations, and with corrections in the logic implemented, may reach the throughput value of the system without control.
8 Conclusions and Future Research

This chapter aims to provide the reader with a brief and concise description of the work carried out, as well as to present the main findings and conclusions achieved. Moreover, several research opportunities are suggested to be studied in the future, in order to continue with the process needed to implement the ideas exposed in this report.

8.1 Conclusions

The purpose of this study was to test, in a real production system, a hypothesis which provides a dynamic allocation of the assembly operations, thereby seeking to solve the most common problems that affect the assembly lines performance. Before carrying out the study, two hypothesis approaches were set, on the one hand an approach with a total dynamic allocation of the assembly operations, which was expected to produce problems caused by a wide station operation range. On the other hand, this expected and confirmed problem is the motivation of the second approach, which has the aim of providing a solution for the aforementioned problem by means of a control in the production flow.

The study has been developed through the simulation of several scenarios based on a real-world production line. The results show a significant improvement of the performance, when the system runs with a total dynamic allocation of operations. In this case the improvement in the throughput reaches 11.2%, representing an increase of 30 engines more per day. This improvement is caused by the increasing utilization of the stations, minimizing losses generated by a starving and blocking the stations. Moreover, several experiments which simulate different feasible situations states that the system ruled by a dynamic allocation presents several advantages over the most important mixed-model assembly line issues, such as line balancing, sequencing or the limitations set by the Theory of Constraints. On the other hand, the problem of the wide station tasks range has been analysed, and the correlation between task range and throughput is obtained. The results demonstrate the existence of an optimum point, where with the smallest task range, the maximum throughput is obtained. With this important result it is possible to set limits to the task range and at the same time maintain the throughput value close to its maximum.
The second hypothesis approach, which attempts to control the fluctuations in the flow, has not provided better performance results. In terms of throughput, the system ruled by flow control has worse performance than the system without control. Nevertheless, with the flow control implementation a reduction in the fluctuation of the workload is obtained. Due to the fact that the difference in the throughput between the system ruled by flow control and the system without flow control is not very significant, about 1.23%, the reduction in the workload fluctuation could be an interesting fact to take into account, and promote an in-depth study of the flow control approach.

8.2 Future Research

The study carried out in this project has provided several research paths to be studied in the future. The results have shown that there is a significant potential for improving the performance of the studied system.

Technical feasibility of the hypothesis: This issue is one of the limitations of this project. However, in order to be able to implement the hypothesis logic, it is imperative to analyse the feasibility of the dynamic allocation of the operations, which is supposed that requires an important investment effort and an extensive study of several aspects (economy, design etc.).

Enlargement of the studied area: This study has been focused in one parallel branch, with only 13 stations arranged in a serial manner. Nevertheless, in order to obtain more accurate simulation results, it is necessary to develop a study which encompasses the whole extension of the final assembly line, as well as take into account several parameters that this study has omitted or simplified.

Optimum station tasks range: One of the most significant conclusions of this study is the attainment a graph which shows the relation throughput-station task range. This may be the motivation of a future research to determine the optimum task range for each station.

Flow control approach: The results obtained shows that the flow control provides a reduction of the workload fluctuations. The latter open a new research path, which may attempt to reduce the workload fluctuation by debugging the logic of the flow control implemented in this study or introducing a new approach of flow control.
Conclusions and Future Research

Sequencing: Experiment 3 has proven that there is a significant difference between the workloads caused by the different variants. Experiment 3 has also proven that the production system performance is affected by these variations in the workload. The development of a sequencing algorithm is an interesting research path, which may provide performance improvements with low investments requirements.

Worker training: The flexible dynamic approach involves that the workers must be able to perform a wide number of assembly tasks, which leads to a more complex and intensive worker training in order to ensure a fast and quality work. This factor is one of the main disadvantages of applying the dynamic approach and must be studied in detail.
9 References


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10 Appendices

10.1 Appendix 1: Layout of the production line at Volvo Powertrain
10.2 Appendix 2: Sample of Avix data
10.3 Appendix 3: Histograms Hypothesis 1

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Appendices

Final Year Project

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