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Process and Layout Design in the Footwear Industry: a Simulation-Based Approach

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Resumo

O paradigma da indústria portuguesa de calçado tem vindo a mudar drasticamente nos últimos anos. Os fabricantes nacionais de calçado estão a mudar dos mercados de trabalho típicos de baixo custo de fabrico, no entanto de baixa qualidade, para uma produção local ou com recurso a fornecedores próximos, devido ao aumento dos custos de energia, transporte e atrasos dos fornecedores.

Os recentes avanços na indústria do calçado levaram ao desenvolvimento do *3D Bonding*, uma tecnologia de produção inovadora baseada na injeção de plástico, não sendo necessário recorrer à costura dos componentes dos sapatos. Embora esta tecnologia seja bastante promissora, viabilizando *lead times* mais curtos e processos de produção menos complexos, só pode ser explorada em todo o seu potencial se forem implementadas as operações corretas de logística e *layouts*.

Esta dissertação propõe uma abordagem baseada em simulação com um duplo objetivo: i) criar um modelo de simulação flexível e parametrizado, e ii) avaliar como o *lead time* de produção pode diminuir através da integração desta nova tecnologia, o *3D Bonding*, no processo de produção. Assumindo uma estratégia de simulação retroativa e utilizando *FlexSim*, um software de simulação avançado, a metodologia proposta, baseada em Simulação de Eventos Discretos, determinará quais as alternativas de *layout* e operações que originam melhores indicadores de desempenho (KPIs).

Além disso, os sistemas complexos de fabrico assumem um elevado nível de incerteza e variabilidade. Esta dissertação utilizará funções probabilísticas de distribuição (baseadas em dados históricos recolhidos) para analisar o impacto da aleatoriedade na variabilidade da produção, considerando, entre outros, a ocorrência de eventos que simulam os tempos de paragem da máquina de injeção.

Os resultados obtidos permitiram tirar ilações essenciais para a incorporação do *3D Bonding* na produção e recomendações prescritivas para aumentar a eficiência do processo de produção a um nível competitivo, reduzindo também o *lead time*.

Abstract

The paradigm of the Portuguese footwear industry has been changing drastically in recent years. The national footwear manufacturers are changing from the typical low manufacturing cost but low-quality labour markets to local production or nearby suppliers due to increased energy, transport costs, and suppliers' delays.

Advances in the footwear industry recently led to the development of 3D Bonding, an innovative production technology based on plastic injection which does not require any stitching of the shoe components. Although this technology is rather promising, opening the door for shorter lead times and less complex production processes, it can only be explored to its full potential if the correct layout and logistics operations are implemented.

This dissertation proposes an approach based on simulation with a twofold purpose: i) create a flexible and parameterised simulation model, and ii) evaluate how the production lead time can decrease by integrating the new technology, 3D Bonding, into the production process. Assuming a backward simulation strategy and using FlexSim, an advanced simulation engine, the proposed methodology, based on Discrete Event Simulation, will determine which layout and operations alternatives originate better Key Performance Indicators (KPIs).

Furthermore, complex manufacturing systems assume a high level of uncertainty and variability. This dissertation will use probabilistic distribution functions (based on gathered historical data) to analyse the impact of randomness on production's variability, considering, for example, the occurrence of events emulating the injection machine' downtimes.

The obtained results provide essential decisive insights for incorporating the 3D Bonding into the production and offer prescriptive recommendations to increase the production process's efficiency to a competitive level and reduce the lead time.

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*“Everybody is a genius.
But if you judge a fish by its ability to climb a tree,
it will live its whole life believing that it is stupid.”*

Albert Einstein

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Abbreviations

APICCAPS	Associação Portuguesa dos Industriais de Calçado, Componentes, Artigos de Pele e seus Sucedâneos
KPI	Key Performance Indicator
3D	3 Dimensional
PU	Polyurethane
RFID	Radio Frequency Identification
DES	Discrete Event Simulation
PCE	Process Cycle Efficiency
VSM	Value Stream Map
WIP	Work In Process
WS	Workstation
ITR	Inventory Turnover Rate
ERP	Enterprise Resource Planning
PO	Production Order

Chapter 1

Introduction

1.1 Context

1.1.1 Footwear Industry

The Portuguese footwear industry has undergone a rapid and intensive transformation in the last few decades. From a traditional and labour-intensive sector, it has transformed into a modern and competitive industry by conquering the global market and making its statement.

As a result of economies of scale, the footwear industry enjoyed rapid growth between 1970 and 1980 due to low labour costs and high volume production. Exports resulted from subcontracted production by international companies to Portuguese manufacturers and sales by the large foreign-owned industrial units installed in the country [15].

However, in the 90s, Portugal started to suffer competition from Asia with the liberalisation of international trade and the entry of China into the World Trade Organization in 2001, resulting in the exit of multinational companies looking for cheaper labour, aggravating the trade imbalance in Europe. Since it was implausible for Portugal to have lower productions costs than Asian competitors, the country pursued a different strategy to face the problem: shifting to quality production, product differentiation and technological innovation and due to the local and cultural proximity, as well as the high purchasing power, the European markets were the preferred choice of the Portuguese industry [16]. These factors allowed Portugal to become a successful case among other international manufacturers.

As the statistical data proves, between 2008 and 2018, exportation, in million pairs of shoes grew from 64.7 to 83.8, a variation of 29.6%. Respectively, in million euros, exports grew from 1,209.9 to 1,902.1, a variation of 47.3% [17]. In 2018, footwear represented 3.4% of the overall national exported goods, a high percentage within the international scenario.

Currently, the footwear industry is concentrated in the north of Portugal, where most companies are located (96% are in the Aveiro, Porto and Braga districts). The footwear cluster is composed mainly of small and medium enterprises. The solid geographic concentration is one of the most interesting characteristics, allowing growth and sharing of qualification, knowledge and development within the cluster, contributing to their innovation and internationalisation [18].

Within the manufacturing industry of the northern region of Portugal, footwear accounts for 12% of the jobs and 6.8% of business volume. For the Portuguese economy, these are, respectively, 6,7% and 2,8% [17].

In 2019, Portugal was the eighth biggest exporter of leather footwear worldwide and was ranked among the world's top 20 leading footwear exporters. It represented 70% of total exportation in 2019 in Portugal [19]. Moreover, Portuguese footwear is considered consecutively by several entities and leaders as an example and a reference in the economy, as one of the largest exporting industries and one that contributes to the country's trade balance the most. However, one of the biggest challenges in the cluster is the search for competitive advantages based on the innovation of equipment, materials, processes, products and business models. The current strategy focuses on speed, flexibility, and high quality to respond to orders in a reasonable time regardless of the size or type of the order. To achieve this, Portugal has invested in technology, innovation in equipment and processes, being one of the strategic plans of the Portuguese Footwear cluster defined by APPICAPS at Footure 2020 [20].

1.1.1.1 Impact of Covid-19 in the Footwear Industry

Global footwear production fell by almost 4 billion pairs in 2020 due to the COVID-19 pandemic. A 15.8% decline in production in 2020 has erased all growth globally over the last ten years, and exports fell by 19%, according to World Footwear 2021 Yearbook. North America and Europe suffered a more significant impact than other parts of the world from COVID-19: the difference between the average number of pairs of shoes purchased per person in North America decreased from 4 pairs in 2019 to just 2.7 pairs in 2020. In spite of that, the pandemic's impact on the footwear industry was less than projected, and Portuguese footwear fared better than the international competitors. In terms of production, Portugal fell 13.2% of the whole production, going to values of 66 million pairs in 2020, around half the loss reported by Italy (26.8% to 131 million pairs) and Spain (26.5% to 72 million pairs) [19].

International data predict a full global recovery of the footwear sector by 2023. However, the results in the last Portuguese quarter of 2021 have exceeded expectations. In 2021, the Portuguese footwear industry grew 12% in foreign markets and exported over 95% of its output to international markets in the last quarter, a record for the sector, surpassing expectations. Additionally, several segments of the footwear industry achieved record export levels, including safety footwear (up by 16%), waterproof footwear (up by 56%), and textile footwear (up by 36%) [21].

1.1.2 INESC TEC

INESC-TEC - Institute for Systems Engineering and Computers, Technology and Science - is an Associated Laboratory that originated from the Porto node of INESC, created in May 1985. Before, it was formerly known as INESC Porto, founded in 1998 by INESC, the University of Porto, and the Faculty of Engineering of the University of Porto. It is a private non-profit research

organization committed to scientific research, technology development, technology transfer, advanced consulting, training, and pre-incubation of new companies based on technology. Currently, it is compound of 13 R&D centres and is affiliated with the University of Porto, the Polytechnic Institute of Porto and the University of Minho. The 13 R&D centres are divided into four areas: Computer Science, Industrial and Systems Engineering, Networked Intelligent Systems and Power and Energy. INESC TEC operates at the interface of the academic and business worlds, bringing together academia, companies, governments, and the general public through technology transfer projects for value creation and immediate social benefit. Dedicated to developing scientific and technological knowledge and implementing it in various sectors, they have become one of the most prominent institutions in the country [22].

INESC TEC began its contribution to the footwear industry in the 1990s with the automation and computerization of existing systems and the development of new equipment. 1992 marked the beginning of the first footwear project aimed to create flexible logistics systems. In 1996, INESC TEC installed the revolutionary LOGICSTORE, innovative storage and an automatic distribution system to seam lines at Kyaia's factory in Paredes de Coura as part of the "Footwear Factory of the Future" project in partnership with the Portuguese Footwear Technology Centre [22].

The "High-Speed Shoe Factory" was another project between INESC TEC and Kyaia Group. A new type of shoe factory was designed, developed, and implemented oriented for single pair production. This model can respond in 24 hours to online orders without stock, restock products in stores, and produce samples and test new products quickly. Other projects implemented at Kyaia to improve flexibility and production speed include the "One Step Production Process" and the "Modular multi-ring system for the flexible supply of workstations". The first project, integrated the entire production process through a single system, from cutting to assembly. The second one, is an innovative logistics system with two rings - one outer ring interacts with machines and operators and an inner ring that allows shoes to bypass major post-operation points. INESC TEC also explored and developed integrated RFID technology in the ShoeID project. The resulting solutions optimize processes and prevent losses in the logistics chain by integrating RFID technology into the initial manufacturing process of footwear [23].

1.2 Objectives

This dissertation aims to develop and evaluate alternative layouts and organise operations for a new production process to increase flexibility and customisation.

The factory in question uses a rotary machine for direct injection, joining the upper (upper part of the shoes) with the outsole (lower part of the shoe) through the injection of PU (Polyurethane). This process replaces traditional stitched seams with an injection process, bonding the shoes in seconds. Implementing this process will allow the simplification of shoe manufacturing, the reduction of lead time and costs.

This work aims to understand how to integrate the new technology with the injection machine in a system without significant stocks, transporting the material through conveyor belts. For this,

it is necessary to design and evaluate layout alternatives for the manufacturing process. As input, a production plan specifies the type of upper, time and position in which uppers are placed on the injection machine. This machine is the bottleneck of the process and has some limitations regarding the available moulds for production, making it necessary to dimension the new production line according to the machine's production plan. Moreover, the objective is also to dimension the buffer length between the manufacturing processes with minimal stock, sufficient to compensate for some variability and uncertainty of the system. Additionally, the purpose is to create a flexible and parametrised simulation model that can be modified by changing input parameters.

The simulation will contribute to better decisions in allocating workstations and operators to the production line. The use of Discrete Event Simulation (DES) is based on evaluating behaviours in a shop floor context and understanding and testing different scenarios of each layout configuration. The simulation will be implemented using *FlexSim* software. To enable an implementable and efficient configuration for the new production line, evaluation of scenarios will consider several important indicators gathered in each iteration. Lastly, it is intended to present future recommendations for the company concerned.

1.3 Motivation

Production systems, more and more, need to respond to distinct orders and sizes, increasing the complexity of the system. Optimised designing approaches are essential to obtain more effective responses, capable of adapting to different production scenarios. Flexibility in production, volume, variety and speed in response time were critical factors in the international success of the footwear industry in Portugal. But despite industrialisation, the sector remains highly dependent on human labour, being complex and laborious, making it one of the highest production costs [24].

One of the many tasks performed during shoe production is the outsole attachment. The advances in the footwear industry recently led to the development of an innovative production technology purely based on plastic injection, not requiring any shoe sole stitching. One of the methods is direct injection, where the outsole is injected directly into the upper. This process typically uses a rotary machine with multiple mould stations, allowing a fast-paced production. In addition to direct injection of the sole, a new technology, 3D Bonding, is being developed to replace traditional seams on the upper shoe with an injection process that fuses the shoes in seconds. This process eliminates the need to import or produce the uppers, creating independence from Asian suppliers and reducing the lead time. It is interesting to highlight the decrease in manufacturing costs which this process implementation could bring and the competitive advantages for the company.

The footwear injection moulding area is a relatively new project for the case study's company. Nonetheless, it has become one of its main focuses due to the cost-effectiveness and innovative features it offers. The company aims to develop methods that allow jetting systems to be used at maximum capacity, ensuring product quality and customer satisfaction. Further, according to the technology patent for 3D Bonding, no information is available regarding machines, methods, and associated manufacturers that utilise these new production processes in real production.

This dissertation has practical relevance based on the simulation of the 3D Bonding process, which allows to reduce lead times and optimize the production processes.

1.4 Methodology

This section introduces the methodological approach adopted in this dissertation. The objectives outlined in section 1.2 served as the groundwork for the methodology's development.

An approach based on simulation was applied to help the company identify the impact of unexpected events on manufacturing operations and assess the feasibility of adding a new process. Discrete Event Simulation (DES), which simulates a system's process as a discrete series of occurrences, demonstrated the possibility of addressing these issues.

In an initial phase, the production of the current system was analysed, comprising two lines: assembly and injection. An assessment of the system requirements, including processing times, available resources, and production plans, was carried out. Different layout designs and scenarios were studied and analysed to select the ones more adequate for the company's reality to integrate the new production process.

The construction of the simulation model using *FlexSim* engine allowed the modelling of the production lines and all the production process characteristics. Initially, a set of parameters allow the automatic configuration of the assembly and injection lines. It uses the data and processes collected by the company to validate the base simulation model. After the validation, the simulation model will also incorporate variability in the production time and the uncertainty of injection machine downtimes.

Finally, in the last phase, using a multi-objective dashboard, the process KPIs derived from the different scenarios will be analysed and discussed. A decision-making model will support the decisive insights for incorporating 3D Bonding into the production process.

Additionally, the methodology and the results will also serve as a base for formulating recommendations for implementing these new processes and studying the potential replication to other companies using the same technology and procedures.

1.5 Document Structure

This dissertation is divided into seven chapters, according to the sequence of the work developed throughout the project.

This first chapter introduces the footwear industry, the objectives this work intends to accomplish, and the motivations for its conception.

In chapter 2, the characteristics of the case study are presented, as well as a more detailed description of the work to be carried out and its objectives.

In chapter 3 and chapter 4, a literature review is presented on the topics fundamental to obtaining the necessary knowledge for the execution of this dissertation project. The first one discusses

the production systems and facility layouts, including their logistics. The second presents a comprehensive overview of the simulation.

Chapter 5 refers to the developed simulation model representing the problem to be solved and addressing the specificities of its application to the case under study.

Chapter 6 presents the simulation model scenarios and configurations results. Furthermore, the results are discussed and compared.

Lastly, chapter 7 presents the conclusions of the work conducted and identifies topics for further work.

Chapter 2

Case Study

The next chapter will provide an outline of the problem that this dissertation addresses. The company, the major characteristics of the plant layout and the existing production system will be presented. Subsequently, the process to be implemented will be addressed.

2.1 Problem Description

The case study is inserted into the footwear industry and intends to develop and evaluate alternative layouts and organise operations for a shoe production process, implementing new technology, 3D Bonding, that at the time of writing this dissertation, this process has not been found implemented in the literature or in the industry.

In order to manufacture a pair of shoes in a traditional way, it takes over sixty processes, making it a very labour-intensive process. Due to the manufacturing complexity, it cannot yet be fully automated, which requires craftsmanship at almost every stage. However, in the last decades, the development of shoe-making machines has reduced the production time and has separated the processes. We can see this progress in the footwear industry, particularly at the company of this case study, which has a direct injection process for the assembly and glueing of the soles, reducing labour costs. Despite this evolution, they do not change the traditional method of stitching the uppers, representing over 50% of the total labour cost. Therefore, although they result in savings, they do not offset the cost of manufacturing the injection mould. The company's production system is unique, specifically developed for the factory, which differs from academic research on production lines.

It is conceivable to reduce the process of sewing the uppers using a newly created technology called 3D Bonding, which will be explored for implementation in the company. This technique is discussed in further depth in section 2.3.1. It is proposed to integrate the new technology with the injection machine in a system without stocks, transporting the material through conveyor belts. Therefore, the main objective is to design and layout a manufacturing process using 3D Bonding. Understanding the characteristics of the existing process is required to develop and design the future production line. The purpose is to understand how the number of workstations, buffer,

conveyor length, and variability/ uncertainty affect productivity based on the scenarios that will be developed.

In a second part, a simulation model will be developed, which aims to simulate the behaviour of the production line over time in order to evaluate the performance of different scenarios developed by comparing the results through KPIs and, finally, present recommendations to the company.

The case study refers to a Portuguese company specialising in technical and safety footwear, AMF Safety Shoes, located in Guimarães, Portugal, that will be introduced in the next section.

2.1.1 AMF Safety Shoes

Founded in Guimarães, Portugal, in 1999, the company "AMF" was formerly known as "Albano Miguel Fernandes, LDA". Initially, the company had 20 employees spread across leather cutting, sewing, and assembly lines. At that time, the daily output was around 250 pairs. Currently, 4000 pairs of shoes are produced every day. Their facilities also include the warehouses, offices and sales departments.

In 2005, the company launched its first brand: "2work4", for workers looking for modern safety shoes with a sports line. In 2009 created a second private label - "Tool'l". The brand presents bold and innovative designs in the safety shoe industry. In 2013, the company changed its name to "AMF SAFETY SHOES" and renamed its main private label "2work4" to "TOWORKFOR". By extending their presence into Europe and recently entering the North and South American markets, "TOWORKFOR" has a global presence in 35 markets [25]. The company, with 22 years of expertise, has more than 150 employees and facilities dedicated to developing high-quality safety shoes and around 80% of its production is for export [26].

The company has invested in technology to reduce the number of shoe production processes. AMF is the first company to industrialise the direct injection process and has an exclusive use in Europe, allowing them to compete with the Asian market. Its success is mainly attributed to its investment in technological innovation, research and development, primarily material technology.

2.2 Current Production System

This section will cover an introduction to shoe components and the manufacturing techniques. It will outline the company's current layout, the methodology of production planning, and the current system constraints.

2.2.1 Shoe Production

The major components of a shoe, as shown in Figure 2.1, are :

- the ***upper*** comprises all parts or sections of the shoe above the sole and covers the foot;
- the ***insole***, located directly beneath the foot, is the part in contact with the foot. It provides cushioning for the foot and also absorbs moisture away;

- the **midsole** is between the insole and the outsole. It cushions and provides the shoe's direct support, one of the most critical components of any shoe. The midsole is an injected component in AMF's production;
- the **outsole** is the exposed part that is in contact with the outside surfaces and must follow the safety requirements. It is a component that can also be injected in the AMF's production.

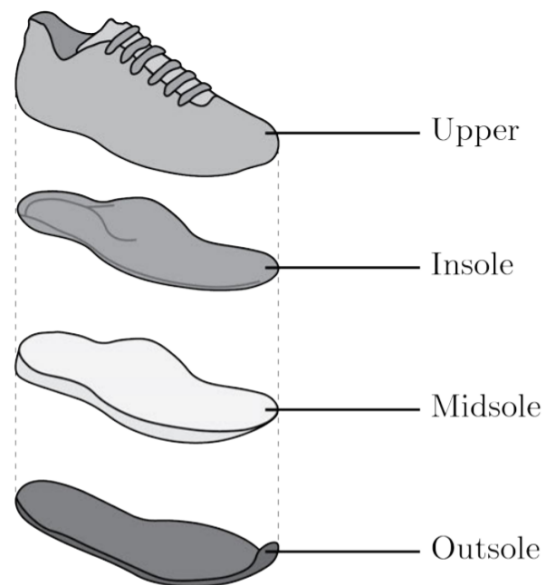


Figure 2.1: Exploded view of a shoe, displaying its major components Retrieved from [1]

Producing a shoe is complex and takes several steps to manufacture. *Mounting and cementing* is the most common shoe-making method. The shoe sole is glued to the upper with a particular machine that reactivates the glue (cement) and applies a high pressure for a few seconds. The main steps for this process are:

1. Cutting

The shoe production process starts with cutting the materials (leather, textile, etc..) to form the upper part. The cut pieces are prepared for the following steps by applying guide marks or temporary unions, among others.

2. Stitching

Upper pieces are stitched together with a sewing machine.

3. Assembly

A heel counter, welt, and toecap are placed on the upper. Some parts are pre-shaped and bonded to the outsole using lasts.

4. Midsole/Outsole Attachment

The *mounting and cementing* method is used for attaching the midsole and outsole to the upper.

5. Finishing

This is the final step, where the product gets the final look. The shoe is cleaned, the insole and lace are placed, and then packaged and stored.

The alternative method, *direct injection*, involves cutting and stitching the upper the same way as *mounting and cementing*. However, an injection machine will create the midsole and in some cases the outsole, permanently bonded to the upper after it is prepared. Usually, the *direct injection* process uses a rotary machine with multiple mould stations in order to allow the placement of the lasted upper [24]. This process will be described in more detail in section 2.2.2.2.

2.2.2 Current Layout Configuration

Two cementing lines, an injection line and a finishing line are part of the AMF's manufacturing area, which spans over 5,000 square meters. The factory uses an RFID system to control and manage raw materials and products on the manufacturing line and in the warehouse. The cementing lines produce shoes with the *mounting-and-cementing* method. This traditional method glued the shoe outsole to the upper using a particular machine to reactivate the glue (cement) and apply a high pressure for a few seconds. The injection process comprises an assembly line and the injection line, processing shoes sequentially from the assembly to the injection line and then to the finishing line. Finished shoes are packed according to specifications and moved to a warehouse for shipping. The processes that the shoes undergo on the assembly line also occur sequentially. A backward scheduling system can schedule the assembly line based on the schedule of the injection machine (injection line).

For the injection process, the assembly line and the injection line will be described in detail in the following sections.

2.2.2.1 Assembly Line

Outsourced uppers arrive at the company and must go through several assembly line steps before being injected with midsoles and outsoles. Eleven employees and a line leader assemble the uppers on the assembly line. Since this is the most crucial supply source for the injection line, the assembly line is organised under the planning of the injection machine. The raw materials are divided between different carts at the material warehouse. Two types of carts are available: the first contains the uppers, and the second provides the insoles and other materials required for the assembly.

There are 10 Workstations (WSs) on the assembly line, where each WS feeds the next, and the Work-in-Progress (WIP) moves between them through a conveyor system. Figure 2.2 shows the first five workstations.

1. A worker in the first WS supplies the conveyor with the respective uppers, toecaps, and insoles based on which article is next on order. Furthermore, he also registers in the company's ERP the pairs that come into production throughout the shift and the consumption of raw materials.
2. At the second WS, the worker inserts the upper in a rotating machine to shape the stiffener to its desired shape, hardening the shoe's base. After completing the operation, he puts the pair of uppers back on the conveyor.
3. Insoles are stitched to the uppers by the third WS. Typically, there are two strobel machines for this operation, one stitching the right foot and the other stitching the left foot.
4. Two workers usually occupy the fourth WS, where a mould is inserted into the uppers to prepare them for the remaining assembly process.
5. The fifth WS's objective is to place the metallic or composite toe cap on the moulded upper, securing it with a pressing machine.
6. During the sixth WS, the employee places the upper in a centring machine, which will seal the top of the shoe over the toecap, ensuring an utterly leak-proof front.
7. During the seventh WS, the upper's bottom is roughened with a carding machine, ensuring excess material removal and uniformity.
8. A steel insole is placed in the eighth WS to ensure resistance to perforations. The insole is placed in the upper with glue and then pressed to ensure its attachment.
9. Ninten WS marks the completion of the assembly process, where an operator removes the mould of the upper and places it back on the conveyor.
10. The tenth WS is dedicated to quality control. Upon conformity, the upper is placed on a cart that will later be transported to the injection line. If any nonconformities are detected, the upper is returned to the conveyor for reworking.



Figure 2.2: Assembly line in AMF. Retrieved from [2]

2.2.2.2 Injection Line

The injection process is carried out on a rotary machine with 24 stations, usually operated by two employees.

Injection carts supply the injection line. Each cart consists of twenty-four racks with a capacity of twelve pairs of uppers, corresponding precisely to the stations of the injection machine. The carts are loaded according to the subsequent ten machine cycles and placed near the buffer zone of the injection machine where an operator is standing (near position 4 represented in Figure 2.3). Polyurethane (PU), used to inject the outsole and midsole, is also supplied for the machine, along with the uppers.

This machine system rotates in a "carousel" style to place several uppers. Figure 2.3 shows the layout of the injection machine. Figure 2.4 presents the device used by AMF, manufactured by one of its partners, Desma. A series of operations are conducted at each station during the machine's rotation to complete the injection process. The principal positions are:

- *Injector 1* is in the first position. This injector is responsible for injecting the outsole.
- The fourth position entails taking off the previously injected shoe and putting on a new upper, ready to be injected. The operator in this position is also the machine manager and records all interventions during his shift, including quality control, maintenance, and mould changes.

- According to the defined program, a carding robot cards uppers in the seventh position.
- Another worker is in the ninth position, is responsible for checking the neatness of the injection channels and the conformity of the injected outsoles. In the case of rubber or thermoplastic polyurethane (TPU) outsoles, the operator places the outsoles in the moulds.
- In the tenth position, the glue is reactivated on the outsole.
- On the eleventh position, *Injector 2* injects the midsole, as shown in Figure 2.5.
- In the twenty-second position, PU residues are removed from the injection channel of the mould as a robot cleans it and prepares it for the next injection.
- The twenty-third position involves the application of a spray release agent to the mould to ensure that the injected PU does not adhere to the mould during the injection.

The machine has no specific operations between the twelfth and twenty-first positions because this rotation time represents the curing time for the injected PU. In Figure 2.6, it is possible to see a moulded shoe after the cure time. Upon completing this cycle, the obtained product is a pair of shoes with all the major components joined. However, some operations remain to be performed before the shoe is considered a finished item. Further steps are performed on the finishing line, such as inserting applications and laces, packaging, and labelling.

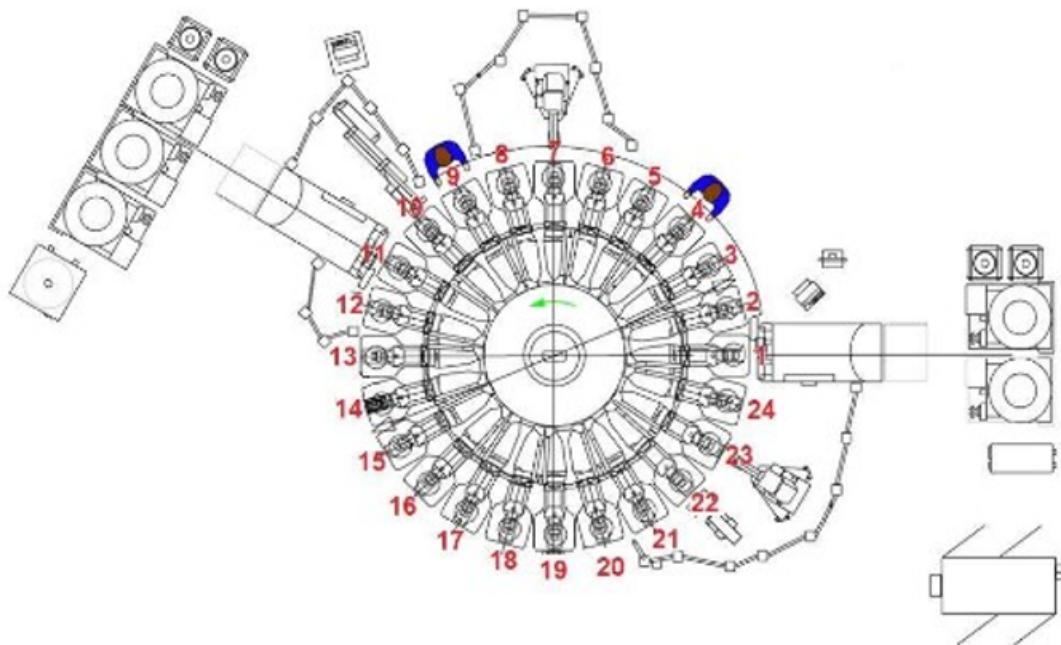


Figure 2.3: Layout of the injection machine. Retrieved from [2]

H]



Figure 2.4: Desmas's Injection rotating machine. Retrieved from [3]

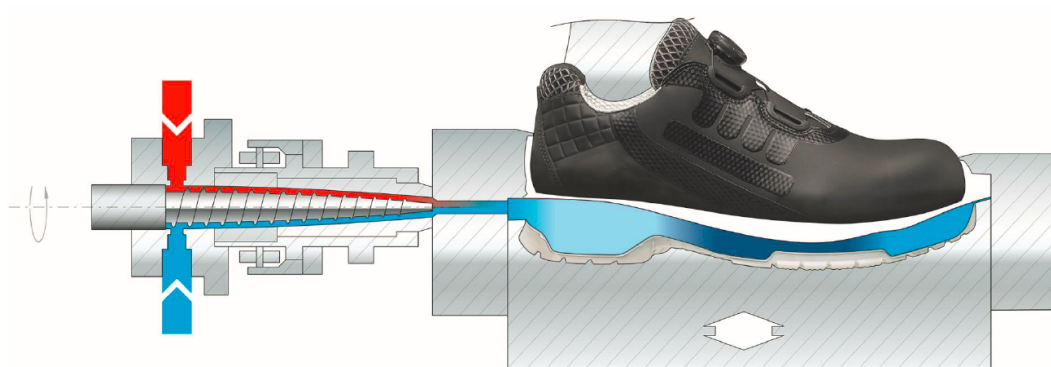


Figure 2.5: Injection of the Midsole. Adapted from [4]



Figure 2.6: Mould of the Desmas's Injection Machine. Retrieved from [5]

2.2.3 Injection Planning Method

AMF, through customer orders and forecasting, integrates these data into an Enterprise resource planning (ERP). This software connects all the data and processes of a company in a single system, making it possible to carry out planning (lot-sizing), thus optimising the quantities to be produced of each production order per week and minimising the costs. The scheduling is carried out using heuristics, where it is possible to sequence the injection machine by batches to be produced per week. After these processes, the production plans are created, obtaining a detailed program for each position in the injection machine. While production takes place, data is collected: current production status, machine occupancy, mould utilisation, and inventory levels, among others, which are fed back to the ERP.

Injection Machine Production Plan

Two principles guide the injection planning process: efficiency of the injection moulding machine and customer service. The variables such as mould type, colour, outsole type, and which uppers are available for injection are considered to achieve a high machine efficiency and apply the

planning to the company's day-to-day operations. In general, an internal AMFs program supports injection planning. Existing production orders, mould availability, changeover durations, and injection moulding machine availability are incorporated into the program. The program complies with a set of rules that fall into three categories:

1. Sorting rules;
2. Selection rules;
3. Mould exchange rules;

The manufacturing orders chosen for the program are ordered using sorting criteria. The user can sort through priorities or by the order in which they are selected. According to the constraints of the injection machine, both selection rules and mould change rules are used to choose the most suitable production order. The rules for the selection are:

1. Same injection colour;
2. Compatible injection colour;
3. Incompatible injection colour;
4. Same reference;
5. Same production order;
6. Split production order;

The algorithm starts by reading the selected Production Orders (POs) and dividing them into kanbans by size. The company uses the term "kanbans" to describe a divided PO, but not for production. It then organises the kanbans according to the sorting rules and reads the initial priority. If the first priority matches any kanbans already in the system, it updates the list of available kanbans and checks if there are any that use the moulds currently in the machine. In this case, it will select a kanban according to the selection rules, update the list, and return to the previous cycle. Otherwise, it will check if there are kanbans that use other moulds within the priority level. If there are, according to the mould change rules, a kanban will be selected and deleted from the list. The mould on the machine at that station will be updated, and the process will restart. The algorithm moves to the following priority level if no kanbans are left in the current priority level. As it moves to the next priority level, it checks if any remaining kanbans are to be sequenced. If there are, another cycle begins; otherwise, the cycle ends.

Algorithm output will include the injection sequence for each shoe size to produce, indicating if mould changes are necessary and when to do so. Various iterations are carried out, with different selection and exchange rules before the production planner selects the plan that best reflects the company's needs.

2.2.4 System Constraints

The system is especially sophisticated, which imposes several limitations. Machine, mould and injection colour constraints are the three primary forms of limitations that will be discussed in the following sections.

Rotary Machine Constraints

The injection moulding machines has 24 stations. In terms of machine cycles, the *transition time* is an interval between two consecutive positions, whereas the *cycle time* is the time for one complete rotation, 24 times the *transition time*. However, the *transition time* can vary depending on which moulds are in the machine, between 18 and 20 seconds.

In some cases, the machine can run moulds with different *transition times* at the same time; in such a situation, the longest possible *transition time* will be considered, meaning the shoes with the shortest processing times spend extra time in the machine than the shoes with the longest processing times. Minimising the variations in *transition times* when different shoe types and sizes are loaded together is crucial.

As the machine requires manual operation, its availability depends on the operator's schedule. The machine can operate with positions not occupied by moulds but only inject when a mould is associated with a position.

Mould Constraints

The six types of moulds available are: "Fusion", "Michelin", "Magnum", "CLS", "Infinity", and "Sika". Apart from their types, moulds are also differentiated by their sizes. In most cases, the mould name carries over to the model name of the shoe - Magnum uses "Magnum" moulds, for example. However, there can be some exceptions. Most of the parts that compound these moulds are designed for specific shoe models and sizes are incompatible with other models and sizes.

Assembly and screwing of an individual mould component in a machine require considerable time and is repeated whenever a new shoe model needs to be manufactured.

The time between mould changes for a machine can be defined in two ways:

- **fixed** for the time between stopping and resuming the machine (2 minutes).
- **variable** the time it takes to remove an old mould and replace it with a new one (estimation of eight minutes).

Moulds are extremely expensive, which limits the quantity available. A model requires several sizes of moulds, with the corresponding right and left feet. Particular sizes differ in production volume according to distribution, as shown in Figure 2.7a. The highest volume is for shoes in the middle of the spectrum, and the lowest is for shoes in the smallest and largest sizes. For the most produced models, the company may have, in some cases, more than one pair of a mould of the same number. Moreover, each shoe model has a specific gender, material and colour, besides

the size, generating a very diversified product range that translates to the demand of moulds, as shown in Figure 2.7b. Consequently, and although direct injection is beneficial, it can only be used for production batches much larger than average, which has been a significant barrier to this technology [27].

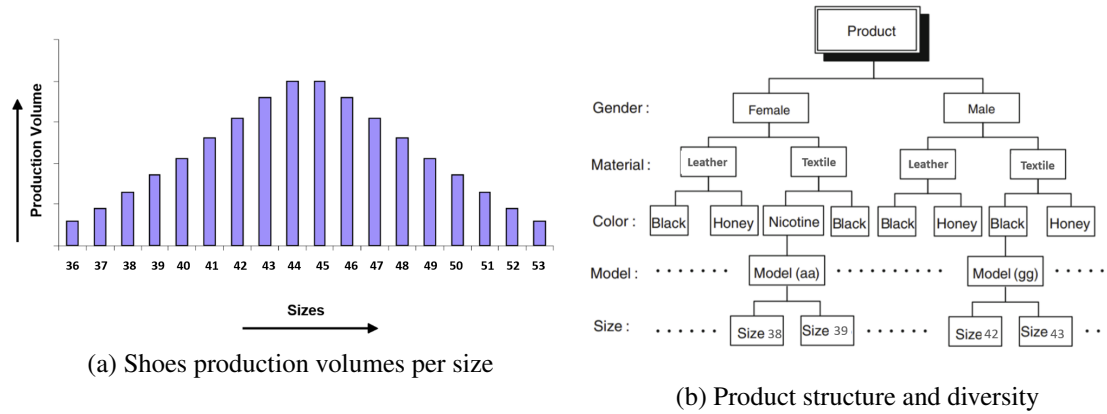


Figure 2.7: Mould constraints

Injection Color Constraints

As previously stated, the machine features two injectors, one for the outsole and one for the midsole. The outsole can be injected, but if it is not, it must be positioned in the injection region to connect to the upper. Between the sole and midsole injections, there are no colour limits. Furthermore, due to the single tank on the injectors, the machine can only handle one pigment colour at a time. Therefore, in the injection process, there are three different situations for the machine's operation regarding the injection colour for the midsole and outsole:

- *incompatibility* refers to the machine's inability to switch between the required colours;
- *compatibility with purging*, i.e., the injection colour can be changed, but the injector must be cleaned, resulting in material waste;
- *compatibility without purging* occurs when there is no colour change between injections for the shoe.

White-other colour and other colour-white exchanges are impossible in midsoles. To inject white midsoles, the injectors must be cleaned entirely, which takes a high set-up time (up to ten hours), and a special production plan is made to run a production just with white colour. As a result, the subsequent midsoles should also be white when injecting a white midsole.

2.3 Production System To Be Implemented

The proposed system aims to evaluate alternative manufacturing processes and identify the best combination of product-process characteristics to integrate 3D Bonding within the constraints

and available processing technology. This new technology, will be discussed in further depth in the next section.

2.3.1 3D Bonding

SimplicityWorks has developed and patented a process called 3D Bonding Technology. The process replaces traditional stitched seams with an injection process, bonding the shoes in seconds. The structural parts are chemically bonded together as pieces of a three-dimensional puzzle.

In the first step, as shown in Figure 2.8, upper components, such as leather, fabric or rubber, are placed in slots separated by narrow channels, and a counter mould is then used to press them into place. In a single shot, the network of channels between the upper components is filled with polyurethane (PU), resulting in a shoe upper held together by a flexible polyurethane skeleton. No seams are stitched, so the overall production process is less labour-intensive, resulting in lower overheads. Material costs are also lower because there are no overlapping areas hence less material waste. 3D Bonding is suitable for creating all kinds of shoes and compatible with synthetic and natural materials.



Figure 2.8: 3D Bonding Process. Retrieved from [6]

In the traditional footwear industry, many complex processes make the process very laborious. The 3D Bonding technology is a paradigm shift due to its simplicity, which engages the industry from the first step resulting in the ultimate simplification of the entire process by requiring fewer production steps thus reducing the labour force, increasing operating benefits and making it possible to produce in Europe at a lower cost than in Asia.

Based on SimplicityWorks's calculations, it was found that producing footwear with a 3D Bonding process in Europe or the United States is more economically feasible than the traditional method in Vietnam. An entirely leather cut shoe with waterproof membrane lining and the same characteristics would cost 16.90 USD in Vietnam and 14.03 USD with 3D Bonding produced in Europe [28]. As a result of this development, the number of tasks goes from 47 tasks in a traditional method and 65,8 minutes to 19 tasks and 21,4 minutes, reducing the labour by about 70%. Another positive aspect of this technology is that it saves approximately 80% of leather used,

0.46 sq. ft vs 2.1 sq. ft traditional methods. Finally, manufacturing in Europe is advantageous since it reduces logistic costs, duty and tariff costs incurred from importing in Asia and reduces the carbon footprint of manufacturing a product [7]. Thus, companies can produce short batches of products on demand, allowing them to dramatically reduce their inventories and out-of-date products, which directly impacts their finances.

From the consumer's perspective, there are additional advantages. With no knitting or stitching lines and no doubling up of materials, shoes have less friction and are similar to socks, producing higher-quality shoes with better comfort and health aspects. Additionally, shoes are waterproof because there are no needle holes or perforated seam lines, as shown in Figure 2.9. An example of a 3D Bonding shoe model produced by SimplicityWorks and AMF Safety Shoes can be found in Figure 2.10.

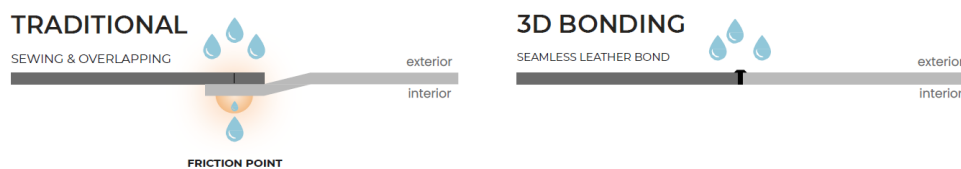


Figure 2.9: 3D Bonding process compared to a traditional. Retrieved from [7]



Figure 2.10: AMF's shoe produced with 3D Bonding. Adapted from [7]

2.3.2 New Production System

After analysing the current production system, it is now possible to identify the general characteristics of the new production process to be implemented.

This new process is based on implementing the 3D Bonding technology, aiming to reduce the shoe production lead time. As mentioned earlier in this chapter, the uppers can be produced directly in the factory or imported from suppliers in Asia, as shown in "Current Production Process" in Figure 2.11. Before entering the injection line, the imported uppers will have to pass through a preliminary process in the preparation line, as described in section 2.2.2.1.

The new technology, described in section 2.3.1, will simplify the process, reducing the operations to cutting the upper parts and assembling them in slots separated by narrow channels with a counter mould, with subsequent injection, as shown at the bottom of the Figure 2.11.

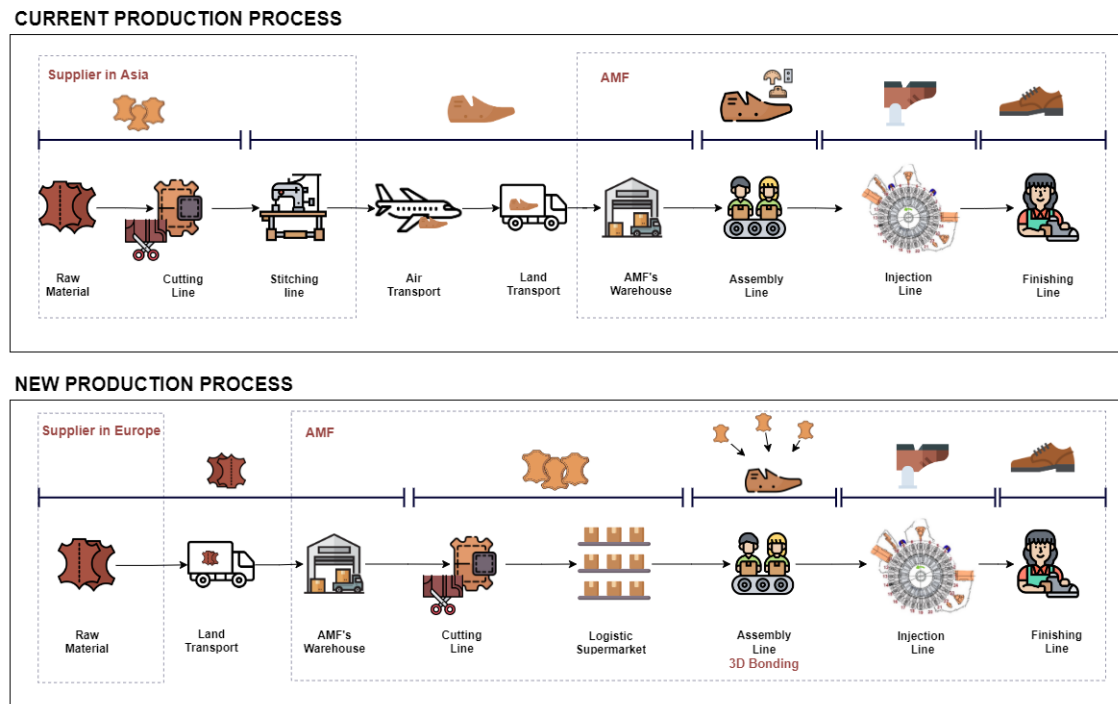


Figure 2.11: Scheme of the production process (current at the top, new at the bottom)

This work focuses on designing, sizing, and synchronizing the assembly and injection lines for the new production system. Since the rotary injection machine is an expensive and relevant asset in the process and emphasized by the company as the bottleneck of the whole operation, the characteristics and solutions generated will be restricted by its takt time, constraints and planning. In terms of the injection machine planning, three production plans differing by the input sequence on the machine will support the injection operation validation and, consequently, the dependent processes.

The new shoe production process would comprise the following work lines:

1. Warehouse

The raw materials for production are kept in the warehouse (imported from Europe).

2. Cutting Line

The shoe production process starts with cutting the materials (leather, textile, rubber) to form the upper part. Cut pieces are prepared for the following steps by applying guide marks or temporary unions.

3. Logistic Supermarket

A *logistic supermarket* is a storage area which supplies a high Inventory Turnover Rate (ITR) goods to manufacturing processes. Since the goods in the supermarket have a high ITR, they should be easily accessible without using a forklift or other equipment. This supermarket would store all the different upper pieces for different models, colours and sizes.

4. Assembly Line

The upper pieces would arrive from the logistic supermarket, according to the manufacturing orders, and are placed in the last, in slots separated by narrow channels. Then a counter mould is used to press them into place.

5. Injection Line

The Injection line would be similar to the one described in section [2.2.2.2](#). A rotary injection machine in a simultaneous action would field the networks of channels between the upper components with polyurethane.

6. Finishing Line

Finishing processes such as inserting applications and laces, packaging, and identifying the packaging are carried out.

For efficient implementation of the new manufacturing system, it will be essential to consider the following factors:

- buffer size (responsible for accommodating production variability and to avoid disruptions);
- length of the conveyor transporting the material from the assembly process to the injection machine;
- assembly line layout (machines' configuration and conveyors connecting them);
- takt time of operations;
- number of workstations in the assembly line (dimensioned based on the injection machine cycle time);
- impact of stochastic data (variation of operations processing time);
- impact of including machine's downtimes (injection machine stoppages based on real historical data).

As a summary of this new process, the company receives material as input (leather, synthetics), cuts it into various pieces, applies 3D Bonding technology and uses the injection machine to join the pieces. After collecting key features of the new production system, scientific research in terms of production system design and simulation methodologies for addressing the problem are presented in the following chapters.

Chapter 3

Production System Design

This chapter provides the fundamental insights from a literature review on Production System Design. The purpose of this topic arises from the importance of developing and integrating a new manufacturing process in the factory.

The first section 3.1, presents a brief overview of the production system design. Section 3.2 introduces the facility layouts, followed by section 3.3, which discusses internal logistics. These principles are closely connected to Production System Design and crucial to the context and process of this dissertation.

Section 3.4 discusses production system analysis methods, which are essential for assessing the current and future processes. Section 3.5 addresses mass customisation in the footwear industry by laying out the framework for developing the production process.

3.1 Introduction

Production system design comprises changes that result in the adjustment of an existing production system or the development of an entirely different one to accommodate products or processes that differ from those now in use [29].

In this regard, creating a production system entails combining the configuration and operation of machines, equipment, materials, people, and information into a unified whole. Production system design requires adjustments or adaptations to current manufacturing capabilities, ranging from incremental improvements to process innovations [30]. The capacity to properly design production systems is a vital competitiveness facilitator, supporting manufacturing industries in overcoming strong competitors, meeting ever-increasing needs for new product varieties, and adapting quickly to evolving technology. The design of production systems is defined as an iterative process that includes requirements analysis, solution formulation, outcomes assessment, and solutions adjustment depending on those results [31].

According to [8], the design of production systems consists of four stages: an informal start, a pre-study, a conceptual design, and a detailed design. Figure 3.1 depicts the stated design process for a manufacturing system, including its stages and operations. [8].

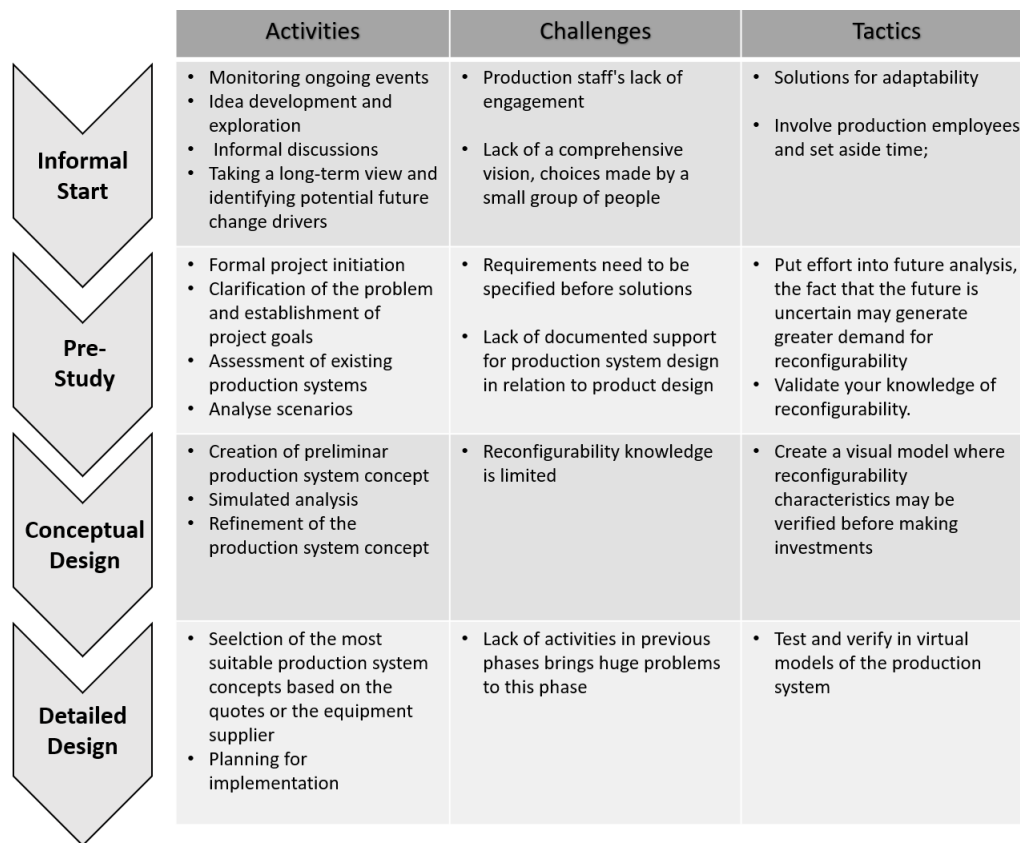


Figure 3.1: Designing a production systems, containing stages and activities. Adapted from [8]

Manufacturing companies cannot expect that developing new production methods and technologies would necessarily result in greater competitiveness. Designing production systems incorporating new production methods or technology is essential for competitiveness if it greatly impacts a manufacturing company's or its structure's competitive advantage [32].

Decisions made during this phase are critical because they affect how a production system will appear and perform. Decisions must be carefully considered throughout the design of the system since commitment to actions and tasks ultimately leads to compromises and trade-offs [33].

The following section will introduce Facility layouts as they are crucial elements of a company's overall operations and maximise the manufacturing process's efficiency.

3.2 Facility Layouts

Facilities layout is the arrangement of activities, features, and spaces according to their relationship. A facility layout problem involves determining the best arrangement and position of facilities on the factory floor, considering specific design criteria and space constraints, to achieve one or more goals. A facility is an entity that helps accomplish a particular task and may include a department, work centre, machine tool, manufacturing cell, machine shop, or warehouse [34].

The layout also impacts important indicators, such as product flow distance, cycle time, waiting times, flexibility and facility utilisation. Therefore, the facility layout is the most expensive and most important asset for a manufacturer [35, 36]. Moreover, the layout is also crucial since material handling costs are directly correlated with the location of the facilities on the factory floor [37], and it can measure the efficiency of a layout. According to Tompkins, the material handling cost comprises 20 to 50% of the total manufacturing cost and can decrease by at least 10 to 30% with an efficient layout design [10].

When defining a layout, it is essential to differentiate between processes and operations. A process is a sequence of operations contributing to obtaining the final product. Operations are a flow of tasks performed by operators to accomplish a transport, work, or inspection of the product. Additionally, the types of products manufactured serve as a starting point for determining what kind of layout to adopt based on their variety and volume. It is also crucial to consider the possibility of company growth or the need to adapt to future changes, ensure that operators are not remote and isolated, combine material entry and exit points in the layout, placing only the necessary materials within reach of the operator. In this sense, the layout must be flexible enough to absorb such changes without the need for significant investments [38]. However, most layout problems have to deal with many different considerations and are generally NP-hard [39]. Therefore, according to computational complexity theory, the layout's optimisation is quite complex, since no algorithm provides an optimal solution in a reasonable polynomial-time [40].

Koopsmand and Beckmann (1957), Armour and Buffa (1963) were pioneers who investigated this type of problem and developed one of the mathematical models, the classical quadratic model, to optimise the relative location of departments on a single floor [41, 42].

3.2.1 Production Layout Formats

When setting up a layout, the first thing to consider is the manufacturing process, as this will specify the overall flow of work in a facility, influencing the arrangement of departments and machines. In the following section, an overview of different layout formats will be made.

Process Layout

In a process layout, similar equipment and functions are grouped together, as shown in Figure 3.2. Processed parts move from one area to another according to an established order of operations, depending on the location of the machines. This arrangement is suitable for systems with various products and large production volumes. It reduces transportation costs by maximising lot size. However, it tends to accumulate large amounts of work-in-progress, resulting in longer delivery times [43].

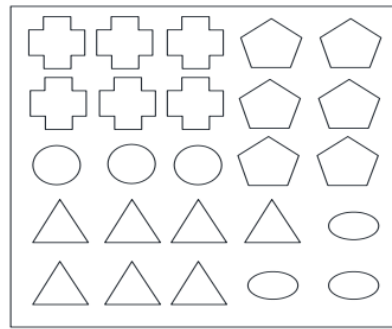


Figure 3.2: Process Layout

Product Layout

The main difference between product layout and process layout is the workflow pattern. Machines and work processes are grouped in a product layout according to the product's manufacturing procedures. Dedicated equipment and departments are employed to focus on a specific product line, duplicate equipment is used to prevent backtracking, and materials can be moved in a straight line, as shown in Figure 3.3. Assembly lines are a particular example of this layout. The proximity between equipment enables the layout to generate an efficient and continuous flow [43].

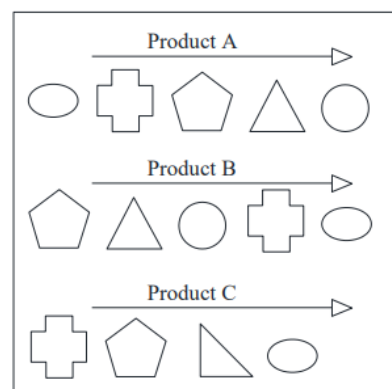


Figure 3.3: Product Layout

Cellular Layout

The cellular layout or group technology is a hybrid between functional and product layouts, as shown in Figure 3.4. As a result, each cell operates autonomously, containing a set of equipment to process the same type of product (or family of products) with similar process requirements, resulting in a reduction in lead time and WIP levels [43].

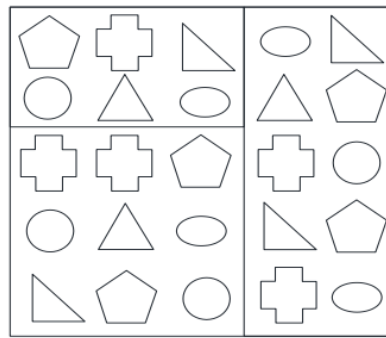


Figure 3.4: Cellular Layout

3.2.1.1 Other Layout Types

Fixed-Position Layout

Fixed-position layouts comprise products (because of their bulk or weight) staying at the same location while manufacturing equipment moves to the product. For instance, construction sites use fixed-position layouts [43].

Fractal layouts

Each fractal cell can produce almost every product type manufactured within an organisation. Fractal layouts are created by grouping multiple different machines into fractal cells. Fractal cells are more or less identical depending on the group of machines, as shown in Figure 3.5. However, in [44] it is argued that, fractal layouts may not be suitable for manufacturing processes with unique machines.

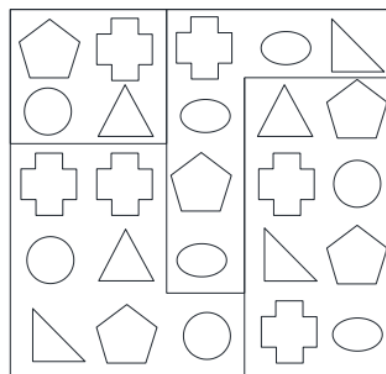


Figure 3.5: Fractal Layout

Maximally distributed layouts/ Holographic

Using maximally distributed layouts, machines or departments are duplicated and strategically spread across the plant floor, providing increased material handling flexibility under variable product mix and volume fluctuations, as shown in Figure 3.6. In this layout, identical machines are maximally distributed across the facility. Holographic layouts offer several efficient routes for specific products and thus allow for increased routing flexibility [45].

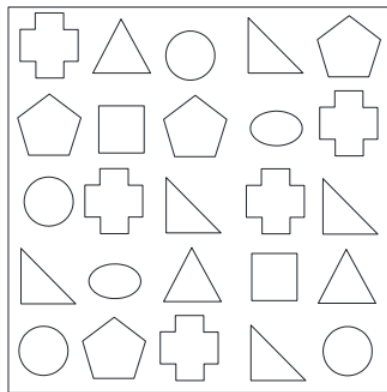


Figure 3.6: Maximally Distributed Layout

Hybrid Layout

In practice, companies tend to use a combination of several of these layouts, based on their individual needs, to become more effective and efficient. For this purpose, modular and fractal layouts can be beneficial based on their flexibility [45]. Manufacturers are now increasingly opting for hybrid layouts, possibly due to their ability to overcome the limitations of specific layout types through combined effects. In other words, a higher level of layout flexibility can be achieved by designing hybrid layouts.

3.2.2 Simulation of Facility Layout Paradigm

Grajo [46] points out that layout optimisation and simulation are both crucial to the process of facility planning and layout study. It has been debated whether layout studies should precede simulation modelling or vice versa to achieve effective layouts.

The Table 3.1, based on work from Aleisa and Lin [12] compares both ways of thought. A facility layout study's approach will depend on the objectives and characteristics of the system under study.

Paradigm	Layout then simulate	Simulate then layout
Belief	Simulation analysis is local, while layout optimization analysis is global	A simulation prior to layout study produces layouts that are efficient and realistic
Benefits	Time efficient	Provides accurate flow estimates for layout optimization using simulation
Application (Best for)	Layout improvements; Resolve congestion and bottlenecks in existing layouts; Minor changes are required only to parameters of the process of the system; The technology adopted requires a special layout type and simulation for verification; Minimizing travel distance is the goal; Insignificant stochastic behaviour;	Designing a new layout for a system that features: sochastic behavior/demand, complex interactions; Major operational policies/technologies that have to be justified prior to layout optimization; A simulation is used to generate the random flow that will be fed into a layout routine; Reducing distances is of greater importance than solving flow congestions and bottlenecks;

Table 3.1: Layout than Simulate or vice versa. Adapted from [12]

3.3 Internal Logistics

Market growth has led to intense competition between organisations, which, in turn, has led to greater consumer demand. The need for more efficient models results from consumer demand for high-quality products at competitive prices while trying to reduce costs simultaneously. To achieve this objective, the strategy should allow the consumer to have the desired product at the right time, at the right location, under the right conditions, but profitably. One way to reach this goal is to reduce logistics costs to a minimum, considering an integrated vision of all activities.

According to the Council of Supply Chain Management Professionals, logistics is the planning, implementation, monitoring, and controlling of the procedures for the efficient and effective transportation and storage of goods, as well as related information from the point of origin to the point of consumption [47]. Therefore, in the perspective of inventory and stock management, logistics is concerned with managing material flows, whether final goods, semi-finished products, or raw materials that are in movement or stopped. This includes controlling both physical and information flows directly and in reverse order [48].

Internal logistics refers to the planning and control of all processes relating to the flow of materials and internal transport within a company [49]. Defining an efficient internal logistics process can be considered a competitive advantage of the company, allowing the company to have a reliable, efficient system for the supply of materials in production to ensure that there is no shortage of materials, production stops and delays [50].

In what follows, some key concepts within internal logistics will be briefly presented. Some of these concepts play an important role in this dissertation.

3.3.1 Logistic Supermarket

A supermarket is a decentralised storage area used as an intermediate warehouse for parts required by the manufacturing system; usually, assembly lines [51]. A supermarket can improve workflow regardless of production type (custom job shops or repetitive manufacturing). Eliminating inventory would be ideal. However, as batch sizes fluctuate between manufacturing lines, suppliers' deliveries are irregular, and quality control is essential, eliminating inventory is unsustainable.

Supermarkets are crucial to a right-sized inventory strategy since they are located at specific points in the production process. These are particularly helpful in businesses with wide variations in customer demand and when production lead times are longer than the takt time. As illustrated in Figure 3.7, the supermarket is located near assembly systems used to replenish the material's stations. The kanban-based continuous supply can be used to feed supermarkets, where the Stock Keeping Unit (SKU) is typically linked to a Kanban card to manage the restocking process [52].

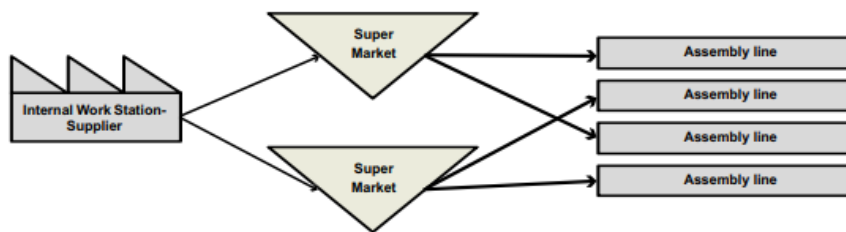


Figure 3.7: Logistic Supermarket positioning

3.3.2 Safety Stocks and Buffers

It's common to use the words "safety stock" and "buffer" interchangeably. Both terms refer to the additional inventory that manufacturing industries keep on hand as a safety net in case of unforeseen demand or supply chain uncertainties. Nevertheless, there is a slight distinction between the two terms.

Safety stocks are kept for each product in the supermarket, from which downstream processes could directly pull. This arrangement enables quick production lead times when demand arrives. It can also serve as a production levelling tool. The upstream processes are responsible for replenishing what is withdrawn from the supermarket. The supermarket replenishment should take place right before the consumption of its last item, but in spite of that, sudden increases in demands, supplier delays and variations in lead time, and other factors often delay the replenishment. When these events happen, safety stocks are essential to continue production. However, just like any other type of stock, it should be reduced as much as possible by cutting production lead times, balancing production and demand, introducing standardised transportation of materials, and increasing the efficiency and accuracy of processes [53].

As a result of the need to reduce machine unpredictability, breakdown diversity, unbalanced processing times, and fluctuations in production requirements, buffer storage emerged. Buffer storage enables machine decoupling and mitigates these variables. Furthermore, it can affect a production system's performance characteristics such as productivity, flexibility, and space usage, making buffer size calculation an important part of design [54]. Figure 3.8 shows a production line with buffer storage, in which the squares are the machines and the circles are the buffers.

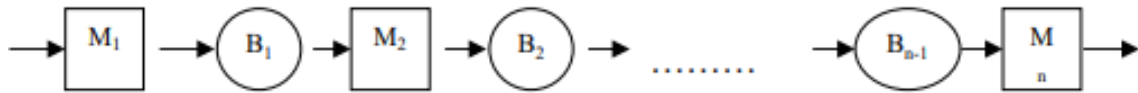


Figure 3.8: Machine flow line with buffers. Retrieved from [9]

Despite their nuanced definitions, safety stock and buffer have the same ultimate objective: ensuring enough inventory is on hand to meet demand and fulfil orders on time.

3.3.3 Picking

Picking orders - pulling products from storage to fulfil a customer's order - is a particularly labour-intensive operation in warehouses using manual systems and a highly capital-intensive process using automated systems [10].

Order picking costs are estimated to be as high as 55% of the entire warehouse operating expense; order picking is the most labour-intensive and expensive activity in almost every warehouse. The order picking process must be robustly designed and optimally controlled to work efficiently to avoid poor service and high operational costs. A poorly designed order picking strategy can negatively impact the company's entire supply chain [55].

According to Tompkins [10] and as can be seen in Figure 3.9, the most significant amount of time spent in satisfying an order is spent by the operator in travelling, the picking route of the article (50%). With 20% and 15%, two other factors address the time needed to identify the pieces and collect them from their locations to the picking aids.

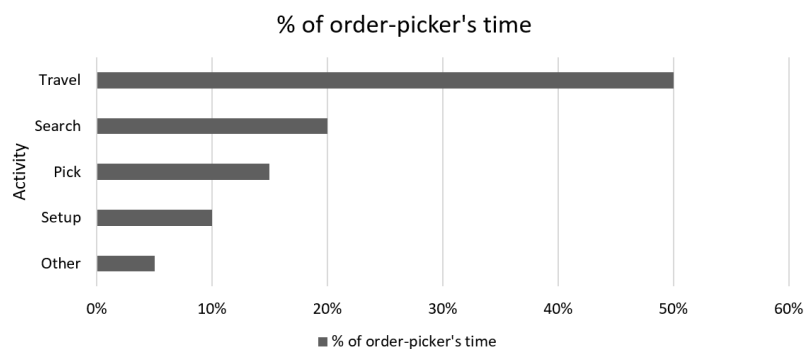


Figure 3.9: Typical distribution of an order picker's time. Adapted from [10]

A significant factor that should be considered is the time taken to get the information. In terms of picking information, this includes reading the article's location, the description of the article code or name, the quantity to be picked, etc. This information must be accurate and precise for the selector to complete the order successfully.

3.4 Methods of Analysis in Production System Development

The competitiveness of manufacturing companies depends on the availability and productivity of their facilities, as noted by Fleischer [56]. In light of this, robust performance measures are necessary to account for the varying aspects of productivity in a manufacturing process.

Bottleneck Analysis

In a manufacturing system, bottlenecks occur when workloads arrive at a given point faster than they can handle. This situation causes unnecessarily large inventories and delays production. In [57], the authors compare several methods using discrete-event simulations to analyse production lines' bottlenecks.

KPI (Key Performance Indicator)

Monitoring industry performance through Key Performance Indicators (KPI) is essential for identifying and improving poor performance. A wide range of performance metrics, including raw materials, control and operation, and maintenance, can be measured for individual equipment, subprocesses, and entire plants [58].

Takt Time

A Takt Time is the time a product needs to be produced (supply rate) to meet demand. This tool brings rhythm to production straightforward, consistent, and intuitively. In [59], a company that manufactures customised products attempted to improve throughput with a combination of takt time and simulation by understanding the relationships between each stage of the process.

Kanban (Pull System)

A Kanban pull system synchronises material and information flow among disconnected processes by replacing what has been consumed at the optimal time. This lean technique helps control the workflow. Kanbans may be used to emulate a pull system application by writing/programming rules that produce electronic Kanbans that perform similarly to physical system [60].

Value Stream Mapping

Value Stream Mapping (VSM) enables quick analysis of the flow of raw materials through the manufacturing process until they are delivered. With VSM, it is possible to visualise the entire process, the flow decisions, and the waste turns easy to identify. In [61] it is presented a concept for creating dynamic Value Stream Maps of a system using DES (Discrete-Event Simulation).

Process Cycle Efficiency

In lean production, Process Cycle Efficiency (PCE) is the ratio of value-added time to the total time required to deliver goods to customers (lead time). This metric measures how efficiently work-in-process is being converted to exits. The system becomes leaner as the PCE value increases as there is less non-value-added time. PCEs of less than 10%, according to George (2005), are typical pre-improvements [13].

Most processes, including manufacturing, order entry, product development, and accounting, have less than 10% cycle efficiencies. PCE differs depending on the application, as shown in Table 3.2, but if lean techniques are applied, the efficiency of a process could be as high as 20% to 25% [13].

Application	Low End PCE (typical)	High End PCE (world-class)
Machining	1%	20%
Fabrication	10%	25%
Assembly	15%	35%
Continuous Manufacturing	30%	80%
Business Processes- Transactional	10%	50%
Business Processes- Creative	5%	25%

Table 3.2: Typical and World Class PCEs. Adapted from [13]

3.5 Mass Customisation in the Footwear Industry

Mass customisation is an emerging market paradigm changing the way consumer goods are created, manufactured, and distributed in today's market. The ongoing and prospective production issues are similar to those of the traditional and handmade production era, but now with benefits and more complicated use of production systems and technology [62].

Industry 4.0 is changing how companies manufacture, improve and distribute their products. The manufacturing industry is integrating new technologies, including the Internet of Things (IoT), cloud computing and analytics, as well as artificial intelligence and machine learning, into their production facilities and operations [63]. As part of this paradigm shift, Industry 4.0 provides consumers with solutions for their interaction, customisation and change in the relationship between consumers and producers [64].

With mass customisation, it is feasible to provide goods and services that suit the individual tastes and demands of diverse clients. This implies we may combine the efficiency and economics of mass manufacturing with the capabilities of small-scale production [65].

This trend has also affected the footwear industry, resulting in the rapid growth of customisation solutions in recent years [66]. It also has the potential to increase the profitability of companies by enhancing the value perceived by the customer and reducing production and logistics costs. However, to achieve a competitive advantage, the organisational structure of the footwear

companies must be updated. For instance, western footwear manufacturers could benefit from mass customisation and product personalisation since the main competitor is Asian producers, where production volume and low costs dominate.

According to Boer and Dulio [62], footwear can be tailored in three ways: style/aesthetics, fit/comfort, and functionality/performance. In terms of complexity, duration, and costs, every one of them affects the shoe lifecycle process (design, production, and sales) differently, with implications in several concrete aspects such as technology, human resources, organisation and the supply chain. The style/aesthetics dimension is the most used by producers and consumers, and it is usually configured through a web configuration tool [67]. The term used to describe this dimension usually is co-design.

In customer co-design, customers specify their product requirements and map these requirements to the physical domain of the product. Therefore, the customer can choose from a finite set of product specifications, a combination that meets their needs [68]. Co-design and mass customization are closely related concepts [69]. To ensure an acceptable service level for customised products, producers may face the challenge of synchronisation of inventory management for all components. The optimisation could be achieved by changing the process layout to an efficient configuration, maximising resources' utilisation and flexibility.

In [66], the authors explore a range of Portuguese footwear companies to assess their perceptions of co-design and mass customisation methodologies, recognising the manufacturers' interest in the application. However, they are concerned with the effort and risk associated with the transition and implementation of the productive approach.

Chapter 4

Simulation

This chapter provides a comprehensive overview of the simulation literature. The characteristics of simulation models, their advantages and disadvantages, as well as circumstances in which simulation is not recommended, are discussed in section 4.1 along with the process of developing a simulation. The most general simulation modelling approaches are described thoroughly in section 4.2. Furthermore, the available simulation softwares are assessed, and the concept of backward simulation is covered.

4.1 Introduction

Simulation is used to experiment instead of direct, costly, time-consuming experimentation and enables the identification of constraints, anticipates problems and obstacles. Therefore, simulations allow exploring distinct possibilities. Nowadays, it is an indispensable tool for many companies, serving as a support for decision-making.

There are several definitions for simulation. According to Shannon (1998) [70], simulation is the process of designing a model of a real system, conducting experiments using that same model to understand the system's behaviour and/or evaluate various strategies for its functioning. Banks (2005) [14] defines simulation as the imitation of the operation and dynamics of a real-world process or system over time. According to Ingalls (2011) [71], simulation is the process of creating a dynamic model of an existing dynamic system in order to either comprehend the system's behaviour or evaluate potential strategies (within the restrictions established by a criterion or collection of criteria) for the system's functioning. From these definitions, it can be concluded that the authors agree that simulating is the act of imitating the behaviour of a model of a real system.

The terms "model" and "system" are central components when defining simulation. A system is a group of interdependent and interconnected elements cooperating to achieve a common goal. The system's behaviour is studied by building a simulation model, which generally takes the form of a particular set of assumptions about the system's workings and from a practical point of view. Simulations are created and designed through a computer, using software to imitate the operations

and characteristics of these systems, allowing to study a wide variety of existing or proposed systems and enabling numerical evaluation to make conclusions.

Every simulation model must be valid and credible [11]. The model should be verified and validated to the extent required for its intended use or application so that the decisions are equivalent to those made if experimenting with the system itself were possible. Credibility refers to the agreement of the correctness of the model by the decision-maker.

4.1.1 Simulation Models Characteristics

We can classify several types of simulation according to various categories. It is then essential to choose a type of simulation based on the model's principal characteristics. A simulation can be categorised as deterministic or stochastic, static or dynamic, and discrete or continuous [14].

In deterministic models, the behaviour is predictable, the inputs are known, and the result is a unique output. Therefore, it can simulate a baseball ball's trajectory, considering the physics laws involved. Deterministic arrivals will occur if all patients arrive in a dentist's office by the scheduled appointment time. A stochastic model has random variables as inputs, and consequently, random inputs lead to random outputs. Thus, the exit result is an estimate of the real model characteristics due to this difference. An example would be the randomness with which a customer could appear on the balcony of a bank.

Simulation models representing the system at a particular point in time are called static. This type of simulation is also referred to as Monte Carlo simulation. For example, a model of a building. Dynamic simulation models represent systems that change over time and can be further categorised into discrete or continuous. Simulating a bank from 8:00 AM to 3:00 PM is an example of dynamic modelling.

Discrete simulation models are appropriate for systems where the states are discrete, and the variables change at a particular time. Subsequently, discrete simulation is divided into time-stepped and event-driven. Time-stepped consists of fixed time increments where alterations occur after a specific time. In the event-driven simulation, which is usually called discrete-event simulation, updates are linked to scheduled events and irregular time intervals. An example of a discrete-event system would be a queue in a store—the number of clients changes when a new client arrives or when a customer is served. In a continuous model, the state variables change continuously over time. For instance, the amount of gas in a car or the room temperature are examples of continuous models.

Considering the discrete-event system, we can conclude that it suits better for our context. Our system is dynamic and discrete, with a stochastic component. Continuous simulation generally requires more complex models based on differential equations. Therefore discrete-event simulation leads to a more straightforward formulation of the problem.

4.1.2 Advantages and Disadvantages of Simulation

A client is intuitively attracted to simulation because it mimics what happens in a real system or what is perceived for a system in the design phase.

According to Pedgen, Shannon and Sadowski [72] these are the major simulation advantages:

- a new hardware design, physical layout, transportation system, can be evaluated without investing in the purchase;
- examine different policies, operating procedures, decision rules, organisational structures, and information flows without disrupting existing operations;
- work in process, information, materials, and so on can be identified by conducting a bottle-neck analysis;
- test hypotheses about the causes and mechanisms of certain phenomena;
- have a better comprehension of the interactions between variables and their significance to system performance;
- compress or expand time to speed up or slow down the investigated phenomena. It is possible to simulate the system for several months or years of experience in just a few seconds;
- beneficial when designing new systems to answer "what if?" questions.

In the same article [72], the author stresses that even though simulation has many advantages, it has some disadvantages, namely:

- model building requires training and experience. Furthermore, if two different competent individuals construct two models, they may have some similarities, but it is doubtful they will be identical;
- most simulation outputs are random variables (since they are based on random inputs), so it can be challenging to differentiate between system interrelationships and randomness;
- performing simulation modelling and analysis takes time and money, and skimping on resources could cause inadequate models or analyses for the task. Simulation cannot compensate for inaccurate information or poor management decisions;
- an analytical solution is sometimes preferable to simulation. This may be particularly true for waiting lines when analytical models can be used.

4.1.2.1 When the simulation is not suitable

This section is based on an article by Banks (2005) and Banks and Gibson (1997), which suggests ten rules, as shown in Table 4.1, for determining when the simulation is inappropriate [14, 73].

Rules	Description
1	When common sense can solve the problem
2	When a problem can be solved analytically
3	When direct experiments are less expensive
4	Simulators should not be used if the savings outweigh the costs
5	When the resources are not available
6	When the time is not available
7	When there is no available data
8	When a simulation model cannot be verified or validated
9	When the power of simulation is overestimated
10	When the behavior of the system cannot be defined or is too complex

Table 4.1: 10 Rules when simulation is not suitable. Adapted from [14]

4.1.3 Simulation Developing Process

To build a simulation model, as shown in Figure 4.1, the following steps should be followed [14, 11, 74, 72]:

1. Problem formulation

The formulation of the problem needs to be clear and clear of doubt. In some cases, a total or partial reformulation is necessary.

2. Collect Data and Construct an Assumptions Document

Data needs to be collected on the existing model, its design, operating procedures, and performance. The more complex the model, the greater the amount of information needed.

3. Conceptual model validation

Perform a structured walk-through of the assumptions document.

4. Programming the model

Program the assumptions document in a commercial simulation-software package.

5. Program model validation

The simulation model is considered to have face validity if the outcomes are congruent with how people believe the system should work. Sensitivity assessments should be conducted on the programmed model to determine which factors influence the performance metrics and, as a result, must be carefully modelled. In this stage, small adjustments are made to the model to ensure it is a good representation of the initial problem. To this end, the results obtained in the testing phase are analysed.

6. Design, Conduct, and Analyse Experiments

Establish operational aspects such as run length, warm-up duration, and the number of independent model replications for each system configuration of interest. Evaluate the results and determine whether more experiments are needed.

7. Document and Present the Simulation Results

The assumptions document (essential for future reuse of the model), a full description of the computer program, and the outcomes of the present research should all be included in the model documentation (and the corresponding simulation study). Documentation of the simulation is drawn up clearly and precisely, as well as documentation and archiving of the results obtained.

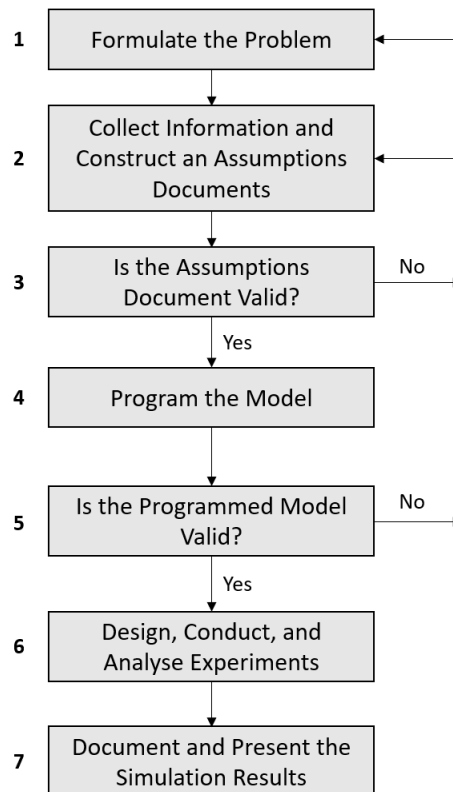


Figure 4.1: Seven steps to a successful simulation study. Adapted from [11]

4.2 Types of Simulation

System Dynamics, Discrete Event Modeling, and Agent-Based Modeling are three commonly used simulation approaches. The following topics discuss the main characteristics of each. Choosing the correct method depends on the system being modelled and the purpose of the modelling.

System Dynamics Modelling

System dynamics is the study of mathematical modelling of dynamic systems and analysis of their responses to understand the dynamic nature of each system and enhance its performance. This method ignores the fine details of the system, such as the particular characteristics of individual elements, and provides an overall picture [75].

The interaction between the system's agents leads to a complex behaviour referred to as dynamic complexity due to the system's nature: dynamic, nonlinear, tightly coupled (everything is connected), and adaptive [76]. This is a strategic modelling methodology with a high abstraction level.

Agent Based Modelling

Agent-Based is a relatively recent method compared to the system Dynamic and Discrete Event. The agent-based modelling (ABM) offered a new perspective: the increasing complexity of systems makes it difficult for modellers to understand how they behave or track the flow of events, but they can gain insights into the behaviour of individual entities [75].

Agents are modelled as groups of autonomous decision-making entities. Each agent analyses its situation and decides how to act based on the rules it has been given. Agents can engage in a variety of behaviours appropriate to the system they represent. The entities are then connected and placed in an environment where they can interact. Global behaviour results from many concurrent individual actions [77]. Agent-based modelling relies on computers' power to explore dynamics out of reach of pure mathematical methods while allowing for repeated competitive interactions between agents.

Discrete Event Simulation

Discrete-event models systems in which the state variable changes only at a discrete set of points in time. A discrete occurrence/state change in these discrete event simulations causes an instant response in the system under study [78]. Some of the basic components of a discrete event simulation are:

- State
- Clock
- Event list

The modeller views the system under consideration as a process or a series of activities carried out across entities. Models are constructed based on inputs, states, and outputs, and the modeller does not need to know how the system works internally. In other words, the modeller programs the model to react to actual observations [79].

The output expected from the discrete event simulation is [75]:

- Bottlenecks
- Waiting times
- System throughput
- Utilization of resources

- Processing costs
- The time spent by an entity within a system or part of it
- Queue length

Through the existing literature, it is possible to find the application of discrete event simulation methods in industry and their use in production lines. In [80] were analysed two configurations of a stitching area in a footwear factory, simulation was used to study 72 scenarios and subsequently evaluated the results by analysing KPIs. This study provided valuable information to the operation managers of the factory. As demonstrated in [81], simulation was used to validate the optimisation of the new automatic transportation systems in a footwear company in Portugal. Similarly, in [82] an assembly line was designed using simulation to maximise one of the key performance indicators in a footwear manufacturing factory. A relevant case is shown in [83], where the aim is to determine the optimal combination of models for daily production schedules when manufacturing men's shoes. This work presents a simulation study using Arena software to see how the changes in the models affect the throughput rate.

4.3 Simulation Software

In order to anticipate the functioning of specific industrial processes, their simulation is performed using dedicated software. The advantages of simulation software are the reduced programming efforts, a natural structure for simulation modelling, conceptual guidance, automatic collection of statistics, graphic symbolism for communication and animation and increased freedom to adjust and update the model [78]. Several parameters of varying types were considered in order to understand which simulation software is most suitable for this dissertation. The essential criteria of comparison were selected:

3D Image

Some software displays the simulation and its elements in 3D, whereas others only display them in 2D.

Direct Manipulation

Describes a type of interaction that represents an object in real-time while quickly, reversibly, and possibly allowing incremental action. This parameter is intended to allow the manipulation of objects.

Data Visualisation

The graphical display of information and data using tools, such as tables and graphs, allows a better understanding of the data, obtained values, discrepancies, and trends.

Import and Export Data

Data can be imported and exported from other platforms and software.

Real-Time Data

This enables the user to understand possible problems in an intermediate process and identify the model's bottleneck faster by obtaining and visualising data in real-time.

For DES modelling, several powerful simulation engines are available, such as *AnyLogic* [84], *FlexSim* [85], *SIMIO* [86] and *SIMUL8* [87].

One of the most popular simulation modeling and analysis tools is *FlexSim*, a robust simulation engine that has undergone years of refinement [88]. Based on this, it is possible to assume that *Flexsim* exhibits potential to deal with the problem requirements. Furthermore, INESC TEC provides a license that allows the complete use of the software, eliminating possible existing restrictions on use. Consequently, for the simulation development of this dissertation, *Flexsim* software was selected.

4.3.1 FlexSim

The *FlexSim* software environment is used to develop, simulate, visualise, and monitor dynamic-flow process activities and systems. The software is a powerful Discrete Event Simulation (DES) tool that can be applied to many fields, from manufacturing and logistics to healthcare.

Having a 3D environment in *FlexSim* makes it simple to drag-and-drop objects into models directly. An object can be edited via a dialogue box once it has been dropped into a model. A hierarchical tree view of the model is also available. Users can create classes and libraries from scratch or customise the existing ones. The *FlexSim* environment is fully integrated with the C++ compiler and utilizes either *FlexScript* (a pre-compiled C++ library) or C++ directly [85].

4.3.1.1 General Concepts of FlexSim

This section presents concepts and general terminology related to *FlexSim*. In the following section, the main objects of the 3D model are discussed, followed by concepts of the process flow.

Objects in the 3D Model

An object is the basic building block of a 3D simulation model. Various types of objects are used in the library, each serving a specific purpose. Some of the most common objects are:

1. Flow Item

These objects are moving (or "flowing") through the simulation model, usually from one station (typically a fixed resource) to another downstream station. Flow items can represent products, customers, or any other item that moves through several stations.

2. Fixed resources

Objects which remain stationary in the model. Each fixed resource performs a specific function. The four most common types of fixed resources are the processor, conveyors, sinks, and sources.

3. Task executers

Objects which can move around in a 3D model and perform tasks, such as moving flow items or operating machines. The simulation model's most common type of task executer is the operator, which represents an employee.

Process Flow

The simulation model's logic is constructed using the Process Flow tool through a flowchart. It is possible to divide the problem into unit activities, which generate blocks of activities that perform specific functions of the model. These activity blocks can also be linked to other individual or group activities. Additionally, the flowchart contains activities that accommodate small segments of pre-programmed logic. A simulation model runs by executing the logic of each activity using small green circles called "tokens". It is possible to edit the activity's properties to link these to the objects in the 3D model.

1. Token

Tokens are objects that flow through the activities (activating them) in a process flow during a simulation run.

2. Activity

An activity represents a logical operation or step in a process flow. Activities are the basic building blocks of any process flow.

3. Shared Asset

Shared assets are finite resources that tokens may claim or release at certain points in the process flow.

4. Connector

A connector is a connection between two activities. During a simulation run, tokens will use connectors to go from one activity to the next downstream activity.

5. Label

The labels play a crucial role in its overall functionality since they can track important information and dynamically change how simulations unfold based on different models and conditions.

The process flow relies on labels to create model logic that can flexibly adapt to changing conditions. The tokens are associated with labels in Process Flow. These tokens move through the process flow, where various activities can create, modify and reference the labels in the token to control the model's logic.

The labels can also be assigned to flow items and 3D objects, such as fixed resources and task executers, and they are used to control how objects are routed from one fixed resource to another downstream fixed resource.

4.4 Backward Simulation

Backward simulation involves starting from the desired state and moving backwards in time to determine the sequential events that lead to the desired state. For years, fields such as artificial intelligence and operations research started with a goal and then worked backwards to identify a path to that goal. The backward simulation aids in identifying and resolving problems with dynamic performance. As a result, it reduces the possibility of costly design adjustments during the final phases of process development.

The backward simulation follows the same concepts as backward scheduling, but the implementation techniques and related semantics differ. For instance, backward simulation can be an effective method for implementing backwards scheduling [89]. Another point is that any problem that can be divided into stages and states can be solved using this method. The solution procedure for this problem generally starts from the last stage, finding the optimal policy, and then moving backwards, stage by stage. Overall, the advantage of the backward simulation approach is its ability to accurately capture resource levels, operational characteristics, and queueing delays [90].

The combined backward-forward simulation will be used. The backward simulation will be used for the injection machine modelling as the starting point and to comprehend the necessary input to the ideal functionality without delays in the production system.

Chapter 5

Developed Methodology

In recent years, it has become fundamental for the footwear industry to develop speed and flexibility in production. The production system design, however, is complex and demands the use of methodologies for calculating Key Performance Indicators (KPIs) to aid decision-making.

A Simulation-based methodology may offer a promising approach, helping assess unexpected events' impact on production operations and understand the feasibility of integrating the new process into the company. Discrete Event Simulation (DES), which models a system's process as a discrete sequence of events, demonstrates the potential for dealing with these challenges.

This chapter mainly presents the developments in the simulation model. Therefore, a set of steps were taken into account to obtain a new optimised production system design. The first step is to evaluate the current production process and general requirements. Next, the phase of scenario design (resource calculation and allocation, buffer length) will summarise the information for model development. After this preliminary work, the modelling phase arises. Applying concepts of backward simulation, the injection machine was first modelled as a starting point to understand the desired input and move backwards to determine the sequential process which can lead to the desired state. The model will be developed incrementally until a faithful system representation is obtained. Additionally, the simulation model was parametrised to enable an automatic configuration of scenarios and designs.

In the end, dashboards and the *Experimenter* are used to analyse the results. The approach is to first validate the injection machine model by analysing expected metrics resulting from the execution of the production plan. Then, it will be possible to analyse the complete model and introduce variability and uncertainty into the simulation model to estimate the feasibility of alternative configurations for the multiple pre-defined plans.

The division of this chapter is sequential, according to the simulation model's development. The first segment will introduce the input data for the simulation. The second section will present the constructed preliminary model of the injection machine, followed by the third section describing the final base model. The final part concludes with a description of the scenarios and parameters.

5.1 Input Data Handling

As input data, the injection machine production plans (previously computed) and the down-times during production (historical records) were used, which will be analysed and discussed in this section. In addition, a matrix of references of the shoes produced and the corresponding available moulds were also obtained.

5.1.1 Injection Machine Production Plan

The production plans that serve as input to the injection moulding machine result from a previous dissertation work with AMF. The developed optimisation model has the capability of generating better solutions than priority sequence rules (planning strategy currently used by the company) in terms of production makespan, number of mould changeovers, and machine utilisation [2].

In order to verify distinct solutions in a stochastic environment with variability and uncertainty, three injection production plans, deviating only in the production sequencing over the same period, were provided.

The production plans, supplied in an Excel file, outlines which model and size will be produced in each lap and the exact placement in the machine throughout a two-week period. It also includes general information: the overall number of laps, the stops for mould changes, the number of utilised moulds, the total production time, and the total number of manufactured pairs. Figure 5.1 displays a production plan for the first ten laps. A shoe reference is associated with the number of the lap and the position to be placed in the machine. The reference "6A51.95-S3 42" for the first lap and position comprises the shoe's model "6A51.95-S3" and size "42". Each lap also has an estimated cycle time. In the instance of 480 seconds, the transition time between positions is 20 seconds.

In figure 5.2, after lap 140, a mould change occurs for positions 11 and 12. The new moulds occupying the positions are "FSN 36" and "FSN 37". The number of moulds which need to be changed and their relative positions determine how long the process will take. In this case, the expected exchange time is 1080 seconds.

Nº Lap	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8	Position 9	Position 10	Position 11	Position 12	Lap Time
1	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
2	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
3	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
4	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
5	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
6	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
7	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
8	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
9	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480
10	6A51.95-S3 42	6A51.95-S3 42	6B51.90-S3 43	6B51.90-S3 43	6A49.50-S3 41	6A49.50-S3 41	6B51.90-S3 44	6B84.20-S3 40	6B51.90-S3 45	6B84.20-S3 39	6C11.20-O2 43	6C11.20-O2 43	480

Figure 5.1: Production plan for the injection machine

N° Lap	Position 1	Position 2	Position 3	Position 4	Position 5	Position 6	Position 7	Position 8	Position 9	Position 10	Position 11	Position 12	Lap Time
135	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
136	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
137	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
138	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
139	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
140	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.90-S3 45	6B51.90-S3 39	6B11.20-O2 43	6B11.20-O2 43	480
141	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.95-S3 45	6B51.90-S3 39	FSN 36	FSN 37	1080
142	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.95-S3 45	6B51.90-S3 39	6B51.90-S3 36	6A49.90-S3 37	480
143	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.95-S3 45	6B51.90-S3 39	6B51.90-S3 36	6A49.90-S3 37	480
144	6B51.90-S3 42	6B51.90-S3 42	6B51.90-S3 43	6B51.90-S3 43	6B51.90-S3 41	6B51.90-S3 41	6A49.50-S3 44	6B51.90-S3 40	6B51.95-S3 45	6B51.90-S3 39	6B51.90-S3 36	6A49.90-S3 37	480

Figure 5.2: Production plan with mould change for the injection machine

The mould matrix displays the company's moulds for each model and size. In addition, as illustrated in Figure 5.3, each shoe model has an associated mould and the minimal transition time required between consecutive positions. The "Michelin" mould with "IDMoldSet" "17" is utilized for the shoe with reference "6A03.10-S3" and has a minimum transition time of 20 seconds.

ID	Reference	IDMoldSet	Description	TransitionTime (s)
1	6A03.10-S3	17	Michelin	00:20,0
2	6A03.12-S3	17	Michelin	00:20,0
3	6A06.20-S3	17	Michelin	00:20,0
4	6A08.11-S1P	1	Fusion	00:18,0
5	6A08.51-S1P	1	Fusion	00:18,0
6	6A09.00-S3	46	Clis	00:18,0
7	6A09.11-S1P	46	Clis	00:18,0
8	6A10.20.3-S1P	1	Fusion	00:18,0
9	6A10.20-S1P	1	Fusion	00:18,0
10	6A11.00-O2	30	Magnum	00:20,0

Figure 5.3: Moulds matrix

5.1.2 Downtime of the Injection Machine

The historical data of the injection moulding machine's downtimes were also provided. This information is crucial, considering that the input production plans do not account for these unpredictable interruptions. Nonetheless, these interruptions can be applied via simulation. The machine operator registers any failures or stoppages that take place. When the situation is rectified, the operator reports what caused the downtime, and the machine resumes the production. This data is stored on an internal platform and is accessible through an excel spreadsheet that comprises all relevant information about the downtimes.

The outcomes are presented in a similar data table of Figure 5.4a. The cause for the downtime, the date and time of the stop and the subsequent restart, along with the time resulting from the downtime, are all available. Figure 5.4b presents a table that categorises the number of occurrences according to the type of downtime (mould changes are also recorded as downtimes). The statistical data obtained from these downtimes will subsequently be employed in the simulation.

Description	BeginStop	EndStop	ElapsedTime
PROBLEM T1	03/01/2022 13:53:43	03/01/2022 13:54:58	1,242481947
TUNING T1	03/01/2022 14:06:48	03/01/2022 14:07:42	0,91023761
TUNING T1	03/01/2022 14:12:50	03/01/2022 14:14:56	2,097070932
LINE STOP ERROR	03/01/2022 14:16:04	03/01/2022 14:21:26	0
PROBLEM T1	03/01/2022 14:37:00	03/01/2022 14:37:49	0,808598816
DELAY T1	03/01/2022 14:40:24	03/01/2022 14:41:05	0,674656808
CHANGE T1	03/01/2022 14:44:54	03/01/2022 14:46:05	1,182604671
CLEAN T1	03/01/2022 15:05:21	03/01/2022 15:06:03	0,690825582
ERROR T1	03/01/2022 15:19:07	03/01/2022 15:21:05	1,965616584
ERROR T1	03/01/2022 15:28:38	03/01/2022 15:30:22	1,735061765
CHANGE T1	03/01/2022 15:41:38	03/01/2022 15:42:41	1,056937099
REQUESTED STOP	03/01/2022 15:52:16	03/01/2022 15:53:07	0,847273946
CLEAN T1	03/01/2022 16:14:07	03/01/2022 16:15:18	1,175786495

(a) Example of the data with downtimes of the injection machine

Total number of stops per description	
Description	Total
ERROR T1	575
CHANGE T1	549
CLEAN T1	504
DELAY T1	293
TUNING T1	280
ERROR T2	253
FAILURE T4	112
TUNING T4	87
MOULD CHANGE	80
SAMPLE INJECTION	77
PROBLEM T1	74
TUNING T3	59
OTHER	52
TUNING T2	50
LINE STOP ERROR	47
CHANGE T2	23
REQUESTED STOP	21
PROBLEM T2	21
FAILURE T3	12
FILL T1	11
PROBLEM T3	7
FAILURE T2	7
MAINTENANCE T1	6
MAINTENANCE T2	6
FAILURE T1	4
POWER CUT	4
CLEAN T2	3
DELAY T2	2
FAILURE T5	2
Grand Total	3221

(b) Total stops by description

Figure 5.4: Example data tables of the downtime of the injection machine

5.2 Preliminary Injection Machine Model

A model of the rotary injection machine was developed in the first phase of work since it was crucial to validate the production plan and for the execution of the other processes. For the modelling, certain assumptions were made, which are detailed in the next section.

5.2.1 Assumptions

The assumptions related to the developed simulation model are:

- The moulds required at the start of a production plan are already on the injection machine.
- The machine may work with positions without shoes to produce.
- Each upper has one assigned mould for being produced.
- The injection machine is fully functional and works 24 hours a day, 7 days a week.
- As shoes are always produced in pairs, it can be assumed that the machine has 12 positions. Each position then corresponds to one pair.

- The transition time between consecutive positions is 36 or 40 seconds, as each position corresponds to one pair.
- Every position has a mould, even when it is not utilised for the subsequent laps.

5.2.2 Implementation of the 3D Model

Considering the rotary machine functioning presented in Chapter 2, the logic of the flow to be simulated passes through a correct representation and similarity to reality. The elements used in the 3D Model of the *FlexSim* for the layout of the injection machine are:

- *Conveyors* transport the items between the various processors, allowing the rotary movement of the injection machine.
- *Queues* work as the racks where the company stores the uppers for each machine lap. It works as an input station for the uppers that are created during the process flow.
- *Rack* is a storage object. It serves to store the moulds that are not currently in use.
- *Processor* simulates the processing of the shoes at each position. A processor allows setting the processing time of the items and the maximum quantity allowed simultaneously.

5.2.3 Implementation of the Process Flow

In Figure 5.5, the Process Flow representing the logic of the injection machine is divided into several flowcharts, forming several groups of activities, each of which fulfils a specific function in the simulation model. The function and operation of each flowchart will be presented next:

Operator Task - Put upper in the mould

This flowchart is used to manage the operator's activities in the upper placement on the machine. A token is created in this flowchart for each upper created in the queue. Therefore, one token corresponds to one upper to be placed in the machine. The upper remains in the queue, waiting for the corresponding mould to arrive at "Processor 1" (first position of the rotary machine). When the upper's "position" label corresponds to the mould's "position" label, the operator places it in the machine.

Operator Task - Remove shoe from mould

A token is created whenever a mould passes, empty or not, in "Processor 1". The token waits for the mould to complete one lap, and when it arrives back at "Processor 1", it verifies if the mould has a shoe. If it has, it gives an order to the operator to remove the shoe. This activity has priority to the placement of uppers.

Operator Task - Change moulds

A token is created for this activity whenever a mould change is required on the "*Control of the Injection Machine*" flowchart. This token verifies the moulds to be changed in the

production plan and in which position. The operator goes to the corresponding position, takes the old mould to the rack, and searches for the new mould by its reference. After the change, the token verifies if other moulds are to be changed. If so, it repeats the process. If not, the activity is finished.

Control of the mould in "Processor 1"

This activity lists the mould currently at "Processor 1" to compare the label "position" between the next upper and the mould.

Mould creation and allocation

This activity set creates the moulds in the 3D model and places them at the corresponding location (injection machine or rack). This activity reads the first line of the production plan, linking the shoe reference to the required mould and places the first uppers of the production plan in the injection machine. The rack is stocked with the remaining moulds. A global table monitors the location and quantity of each type of mould.

Control of the Injection Machine

This flowchart is the main control of the machine's operation. When starting the simulation, a token is created. The token is associated with labels that allow controlling the flow of the production plan.

As shown in Figure 5.7a, the labels "*row*" and "*col*" correspond to the row and column of the production plan, respectively. The label "*lap*" corresponds to the machine lap. When a change of moulds occurs, this label has a value of "0". The "*processTime*" corresponds to the processors' processing time, which will depend on the lap time read on the row.

The token then runs through the production plan. All uppers in the row with references are created in the queue. Each upper in the 3D model has a set of labels used for identification—namely, the shoe reference and the position for the injection machine, as shown in Figure 5.7b.

When the token reaches the end of each line, it checks whether the production plan is finished or not. If not, it increments the "*row*", and "*col*" returns to the initial value and checks whether the processing time has changed. If the following line corresponds to a mould change, the operator does not place uppers on the machine, and all the uppers are removed from the machine, giving an extra lap (without placing uppers). After the change, the "*row*" label is incremented.

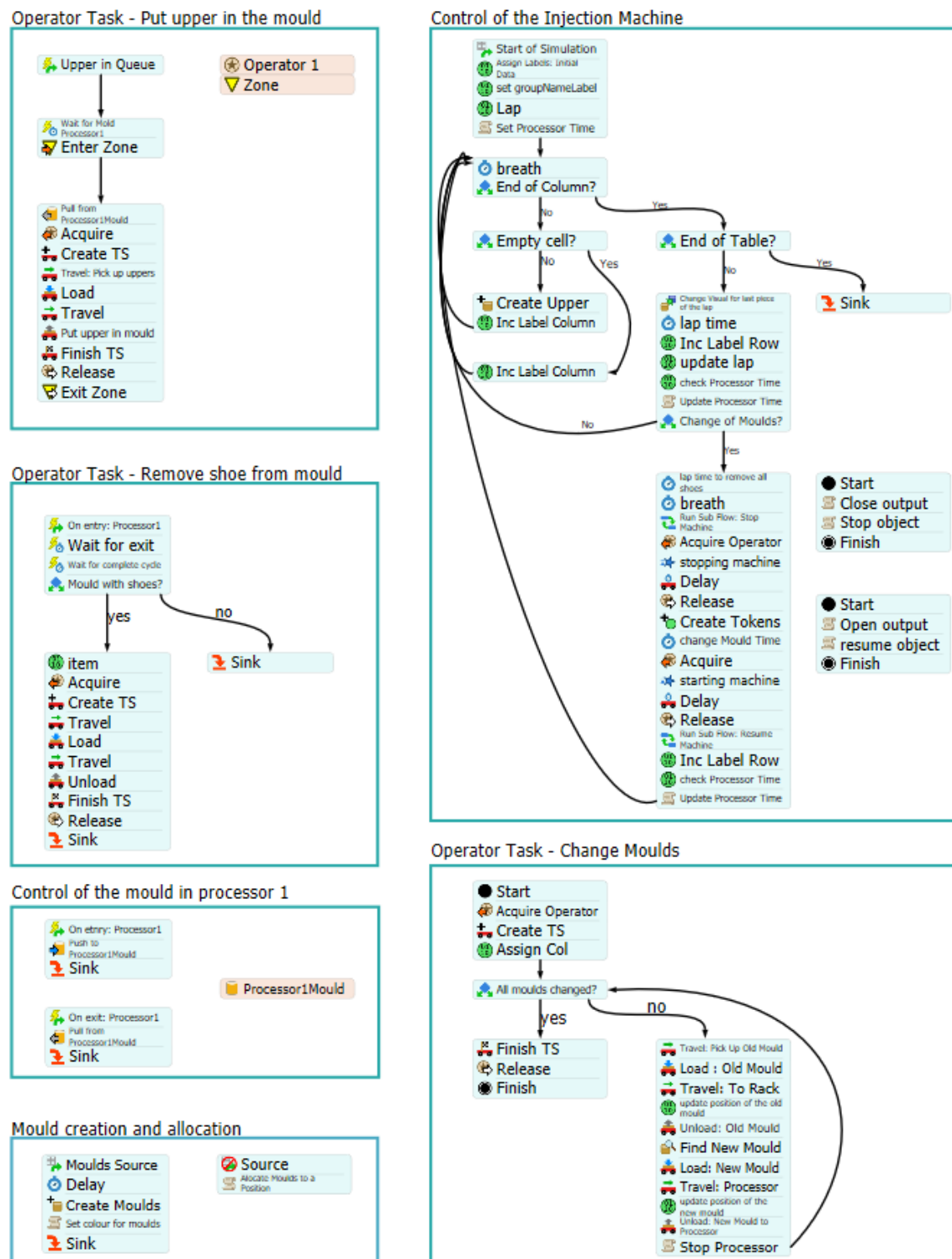


Figure 5.5: Preliminary Process Flow of the injection machine

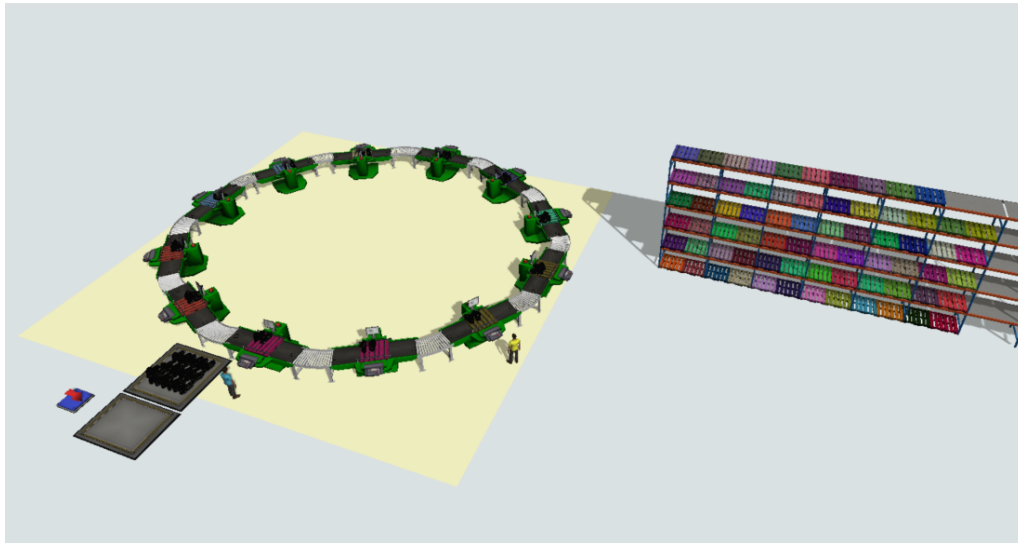


Figure 5.6: Preliminary model of the injection machine

row	260
col	14
processTime	36
numChangeMould	5
groupName	Processors
volta	255
item	/Queue3/Box1~7

(a) Token labels

ID	6B51.90-S3 42
Mold	6B51.90-S3 42
ref_shoe	6B51.90-S3
position_shoe	2

(b) Labels of the "shoe"

Figure 5.7: Different types of labels. (a) for a token and (b) for an object in the 3D Model

5.2.4 Validation of the Preliminary Model

It was possible to obtain results to validate the production plan for the injection moulding machine through simulation. The comparisons between the simulation and the plan results are available in Table 5.1. For production plan 1, it can be seen that the production time obtained in the simulation (137.53 h) was higher than the theoretical plan (133.45 h) by 4.05h. Consequently, the makespan is different in the same proportion. The other two production plans obtained the same differences. In view of the fact that the model was simulated without any variability, the differences between the simulated model and the theoretical plan are significant, hence the need to understand the underlying causes for these differences.

The mould change was the difference after a detailed review of the process and comparison with the production plan. It was considered that the machine had to be empty for the changeover to proceed. So, an additional lap was made to empty the machine and align the mould's position with the processor.

	Planned	Simulated
Total Laps	1040	1040
Mould changes	40	40
Pairs Produced	10187	10187
Makespan (h)	139,89	143,95
Mould Change (h)	6,43	6,43
Production Time (h)	133,45	137,52

Table 5.1: Validation of Production Plan 1

It was accessed that the production plan did not correlate to the actual mould changing process after visiting and confirming the procedure on the factory shop floor. The process occurs without emptying the machine. Additionally, there is an area delimited for that purpose, located between positions 13 and 20 of the machine, as shown in Figure 2.3 on page 13.

Only the positions corresponding to the mould change are left empty at the beginning of the lap, so no uppers are placed when it passes position 4, as described in chapter 2 section 2.2.2.2, so when it reaches the changeover area, the mould is empty. In cases of changing more than one mould, if the positions are close enough to fit all (between 13 to 20 positions), the mould change is carried out at the same machine stop. If they are far apart (outside of 13 to 20), the mould change is carried out one at a time, stopping the machine as many times as necessary.

5.3 Base Model

The final model presented in this section was modelled as the base model and used to run the different parametrised configurations and scenarios. The machine's operation was corrected according to the change of the moulds, and other process flow activities based on time, instead of events, were altered. Subsequently, the assembly line was dimensioned, preparing the various pieces that will form the uppers into a last with slots. Then it was necessary to join the two production lines, injection and assembly, and simulate the synchronisation of both processes to understand whether the dimensioning of the processes allowed it.

5.3.1 Assembly Line

This section outlines the modelling of the assembly line, starting with its dimensioning and layout design in the 3D model and followed by the process flow development.

5.3.1.1 Dimensioning and Layout

A dimensioning analysis was conducted based on the particular characteristics of the problem under study.

The operators of each workstation receive the upper components for assembly in their respective slots in a shoe last. The expected time for assembling the pieces is 120 seconds for each shoe, 240 seconds per pair [91].

The assembly line will be dimensioned according to the assembly process time (240 seconds) and the rotary machine's cycle time per lap. The number of workstations will differ depending on the number of pairs produced per lap at the injection machine, which could be between 12 pairs and one pair. In order to derive the theoretical minimum number of workstations, we employed the following formula:

$$\text{Minimum number of WS} = \frac{\sum_{i=1}^n \text{Time for task } i}{\text{Cycle Time}} \quad (5.1)$$

If the rotary machine works with a processing time of 480 seconds, the number of workstations will correspond to the data in Table 5.2, and for 432 seconds, it will correspond to data in Table 5.3. However, this data table only provides a preliminary indication of the minimum number of necessary workstations since the upper is not always evenly spaced in the rotary machine, creating uncertainty about the exact entry times.

N° uppers per lap (480 s)	Injection Machine C/T per lap	Minimum number of workstations
12	40	6
11	43,63	6
10	48	5
9	53,33	5
8	60	4
7	68,57	4
6	80	3
5	96	3
4	120	2
3	160	2
2	240	1
1	480	1

Table 5.2: Workstations for a cycle time of 480s (C/T - Cycle Time)

N° uppers per lap (432 s)	Injection Machine C/T per lap	Minimum number of workstations
12	36	7
11	38,27	7
10	43,2	6
9	48	5
8	54	5
7	61,71	4
6	72	4
5	86,4	3
4	108	3
3	144	2
2	216	2
1	432	1

Table 5.3: Workstations for a cycle time of 432s (C/T - Cycle Time)

From Table 5.2 and 5.3, it is possible to conclude that the minimal number of workstations required in the assembly line will be seven as the rotary machine occasionally operates with a higher velocity (process time of 432s).

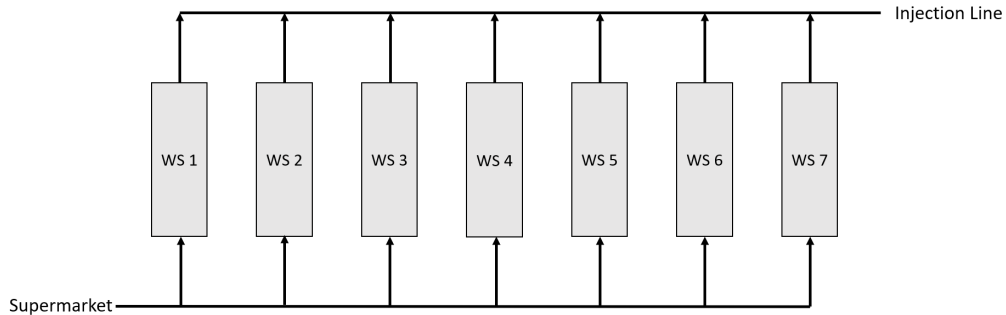


Figure 5.8: Layout of the Assembly Line

A conveyor belt will connect the workstations in a parallel (product) layout, as shown in Figure 5.8. The components for the uppers arrive as input from the logistics supermarket, as was previously indicated. When they arrive at the conveyor, they are sequentially forwarded from workstation 1 to workstation 7. After the assembly, the uppers, ready for injection, are conveyed to the injection machine in the sequential order of the production plan. With the use of sensors and an RFID system it is then possible to control the material flow to ensure the correct order on the conveyor leading to the injection machine, which is a crucial factor for the proper functioning. Then the operator in the injection machine uses the conveyor as FIFO (First-In-First-Out) system. The simulation will be carried out with different scenarios and configurations to obtain results and evaluate the line performance.

Final Layout Implemented in the 3D model

The layout implemented corresponds to Figure 5.8. Seven workstations were dimensioned in a parallel layout, fed by the conveyor belts. The implemented layout in the *FlexSim* is represented in Figure 5.9.

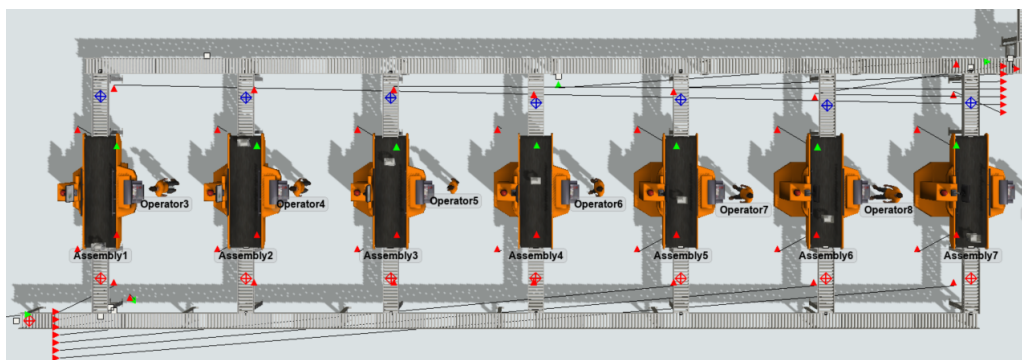


Figure 5.9: *FlexSim* layout of the assembly line

The following section discusses the main assembly line objects and their functions:

Flow Item

A pair of shoes represents the flow item that circulates in the 3D model as uppers and shoes, depending on the stage of the production process, as shown in Figure 5.10. In *FlexSim*, it is possible to dimension the measurements of the flow item.

For a correct dimension representation, the width and length of a pair of shoes were estimated (0,25x0,35x0,30) (the height is not relevant for sizing). These measurements are essential because they directly influence the required conveyor belt's dimension. Then, it will be possible to place the sensors at strategic points on the conveyors.

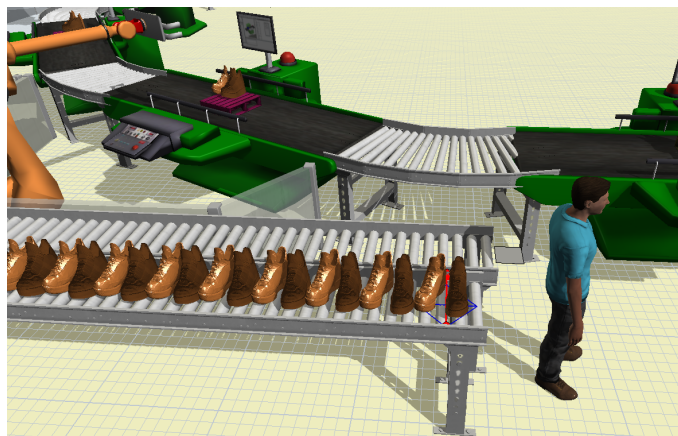


Figure 5.10: Uppers (flow items) in the buffer

Conveyor

The conveyors transport the flow items to the respective workstations and to the injection machine.

Sensors

Statistical data about production can be extracted from sensors on the conveyor that feed the injection machine and control the buffer size.

Processors

The processors represent workstations. They are used for simulating the process time of each operator.

Decision Points

At the beginning of the assembly line, the decision point sends the flow items to the conveyor that corresponds to the number on the flow item's type label, i.e. a destination-based classification is performed.

The decision points at the assembly line exit operate differently. This decision point sorts the flow items based on a simple condition, true or false. If a flow item meets the condition on the property, it will be diverted to the output port of the logical transport object.

5.3.1.2 Process Flow

We can observe in Figure 5.12 the developed process flow. The process flow is divided into three flowcharts, formed by several groups of activities, where each of them fulfils a specific function in the simulation model. The function and operation of each flowchart will be presented next.

Upper Creation

This flowchart allows the creation of the flow items in the incoming conveyor queue of the assembly line. A token is created at the beginning of the simulation. This token will be assigned labels "*row*", "*col*", and "*lap*" that will allow reading the production plan.

The next activity verifies if the "*col*" label is the end of the row, corresponding to the value "13". As long as it is not the end of the row, it advances to the next activity.

Next, it verifies if the cell is empty or corresponds to a mould change. If it is, the label "*col*" is incremented to move forward in the line, and it does not create the upper. If the cell corresponds to an upper reference, it moves on to the next group of activities.

The flow item will be created in this group, and each one of the flow items in the 3D model will contain labels associated. There are six labels representing the information of the shoe, as shown in Figure 5.11:

- ***Id_A***: corresponds to a copy of the reference of the production plan cell;
- ***moldA***: it is used to associate the shoe reference to the necessary mould;
- ***ref_shoesA***: corresponds to the reference without the shoe size, that is the model to produce;
- ***position_shoeA***: corresponds to the position that the shoe will have to occupy in the machine;
- ***order***: is the sequential order number produced. It allows the correct ordering of the uppers on the machine's entry conveyor;
- ***lap***: corresponds to the number of the lap the shoe will have to enter the machine.

ID_A	6A10.20-S1P 44
moldA	6A10.20-S1P 44
ref_shoeA	6A10.20-S1P
position_shoeA	7
order	19
lap	2

Figure 5.11: Labels in the flow item

Token label "*col*" is incremented after the flow item is created. It is checked whether the infeed conveyor to the injection machine is full. In such case, the assembly line stops after processing the parts on the line, and no new parts enter until the conveyor buffer is reduced and the sensor is re-activated.

If it is the end of the lap, it is checked if the label "*row*" is the last line of the production plan. If so, the token is deleted, and the flowchart activity ends. The label "*row*" of the production plan is incremented if more lines are in the plan, and the label "*col*" is set to 2, the column's value at the start of the plan. Additionally, the appropriate number of machines is checked in a variable number of machines scenario.

Assembly Line Exit

This activity group controls the output of the flow items after the assembly to ensure that the uppers are in the correct order to the injection line as indicated in the production plan.

As previously mentioned, there is a "Decision Point" at the exit of each workstation. When a flow item arrives, the item is stopped and it is verified whether this item can advance onto the conveyor to the injection machine.

At the conveyor entrance towards the injection machine, another "Decision Point" checks the label "*cycle*" of the flow item. This label allows the sorting on the conveyor. According to the expected "*cycle*", movement orders are given through the global lists. The "*cycles*" list holds the "*cycle*" value that may move.

Conveyor Sensors

This flowchart allows the control of the buffer on the infeed conveyor to the injection machine. A total of three sensors are utilised.

PE1 determines the maximum size of the buffer. Depending on the scenarios, it will have a distance that allows the accumulation of up to 2 or 4 complete machine laps, i.e. 24 to 48 pairs of uppers. When an upper remains over 40 seconds blocking the sensor, the sensor goes to the "blocked" state, and an alert is then sent to the assembly line to pause the assembly.

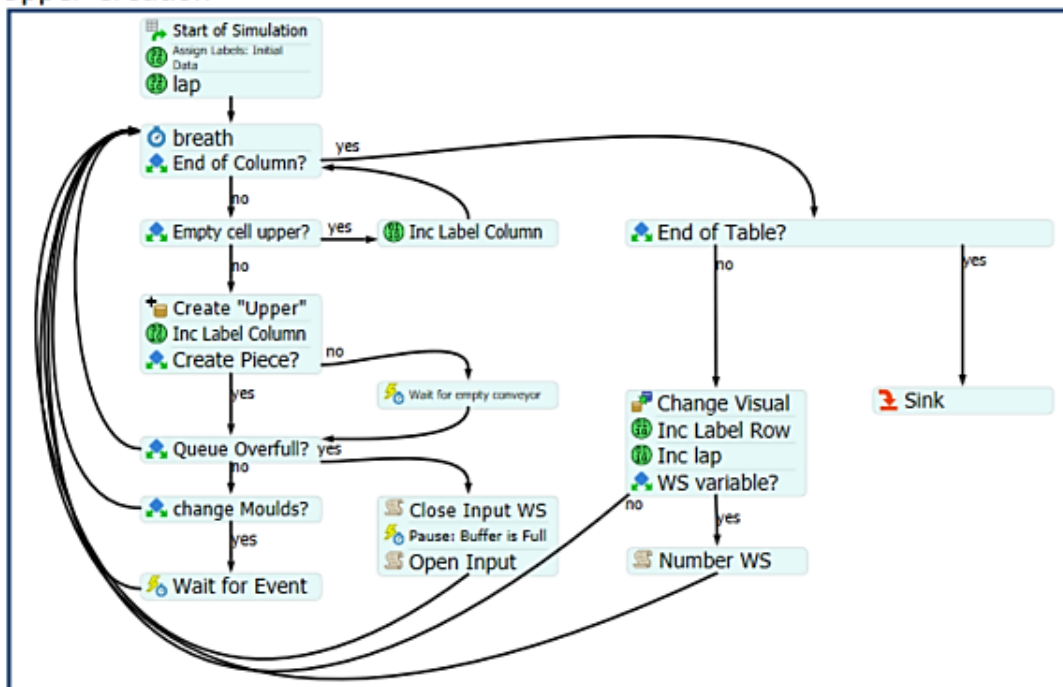
The second sensor, *PE2*, in the middle of the conveyor and at a distance equivalent to one or two complete machine laps of uppers, indicates when the assembly line must restart at the unclear state.

This last sensor, *PE3*, identifies whether an upper is present at the end of the belt.

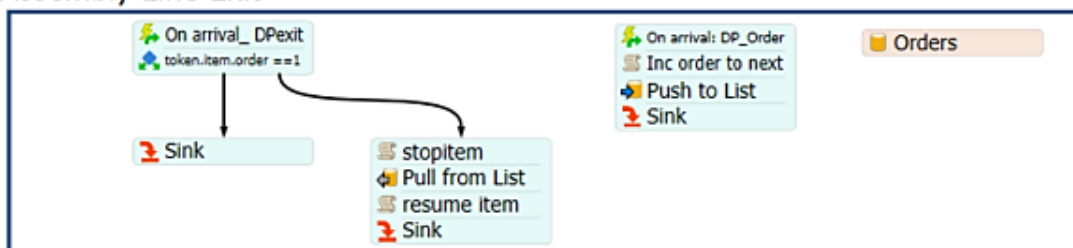
Control of uppers in the conveyor

This flowchart serves as a safety device for the machine's operation. The injection machine stops when no upper is detected on sensor *PE3* until an upper arrives. The aim is that this does not happen and will also serve as an evaluation for different production plans.

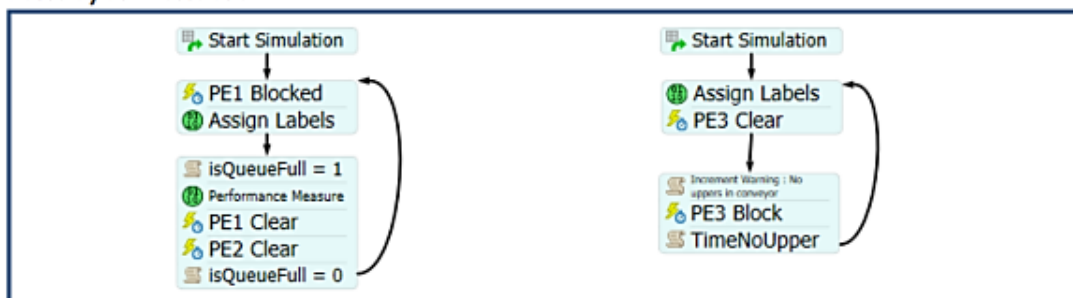
Upper Creation



Assembly Line Exit



Conveyor Sensors



Control of uppers in the conveyor

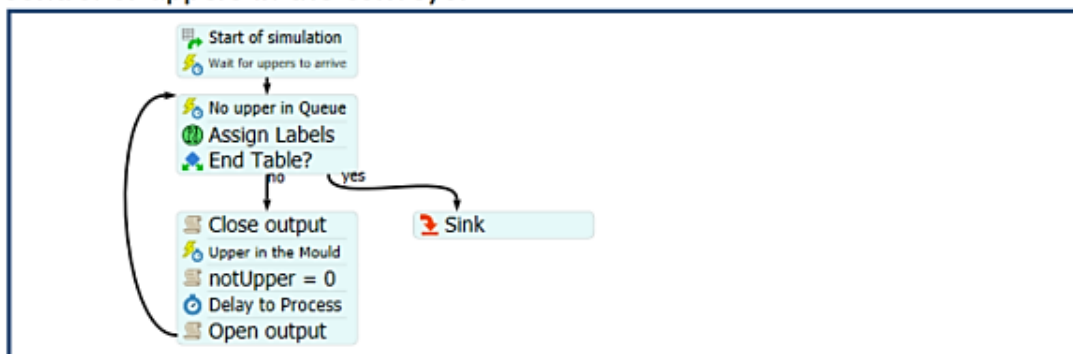


Figure 5.12: Process flow for the assembly line

5.3.2 Injection Line

As described before, the validation using theoretical data and visiting the shop-floor showed a justified inconsistency of the simulation model regarding the mould change. This correction was implemented by modifying the flowchart of the injection moulding machine's central control unit. The modified flowchart is shown in Figure 5.15. It maintains direct and indirect relationships with all the other processes since it is the central control of all production processes.

Main control of the injection machine

The simulation starts with a single token that will remain in the flowchart until the injection moulding machine completes the production plan execution. For this token, some initial labels are assigned:

- **row** and **lap**: correspond to the production plan line that the machine is currently processing. The value is incremented as soon as the first upper of a new line enters the machine.
- **processTime**: every row on the production plan includes a reference to the processing time, which is verified and updated when necessary. It corresponds to the transition speed of the injection machine.
- **numChangeMoulds**: counts the number of mould changes that have occurred.

Next, the token waits for the placement of the first upper to occur. The "row" label verifies if the production plan is complete when starting and whenever it is incremented. This label is only incremented whenever the mould with "position 1" passes the "Processor 1". Additionally, when the row is incremented, it is checked whether the next line contains a mould change. Supposing yes, it is verified for this line which are the positions and references of the mould to be exchanged. In that case, an independent token is created from the main flowchart for each mould. The token representing each mould has information about the position and reference. After completing the previous lap, the current lap will correspond to the effective mould change. Two labels are added to the token (a complete view of the token's labels is shown in Figure 5.13):

- **timeMchange**: is an array that corresponds to the planned time of exchange, depending on the number to exchange and the locations.
- **moldsToChangeArr**: an array that keeps the name of the processors where the exchange will need to be performed.

The mould to be changed is removed from the list once it reaches "Processor 5", and it is verified whether or not more moulds need to be changed within the change zone (in Processors 6, 7 or 8). If so, they are also removed from the list, and mould change operations occur. Verification is done after the change to determine if more mould changes will occur that are not yet within the change zone. The process is repeated until no more changes

are detected. As soon as there are no further changes, the machine returns to its regular operation, in which the "row" label is incremented every time the mould with the "position" label equals to "1" passes through "Processor 1". The transition times are also verified and updated to label "processTime" in case of a change.

row	140
processTime	36
numChangeMou	0
groupName	Processors
lap	140
mold	/Processor1/Palet1
moldsRefArray	Array[0]: {}
moldsPosArray	Array[0]: {}
timeC	Array[0]: {}
timeMchange	Array[2]: {1080, 0}
moldsToChange	Array[1]: {/Processor5}
pulled	id:10087
processorEmpty	/Processor5
resource	/Operator1

Figure 5.13: Token of the main control of the injection machine

Injection Machine Downtimes

The flowchar in Figure 5.14 handles the simulation of the machine stops. By selecting pre-specified parameters, a simulation scenario can include or not these downtimes of the injection machine. If so, a single token executes the flowchart. Two delay activities represent the "Interval between stops" and "Duration of downtime". The first one represents the frequency of downtimes, while the second one represents their durations. When the injection machine stops due to a downtime, the outputs of the processors close.

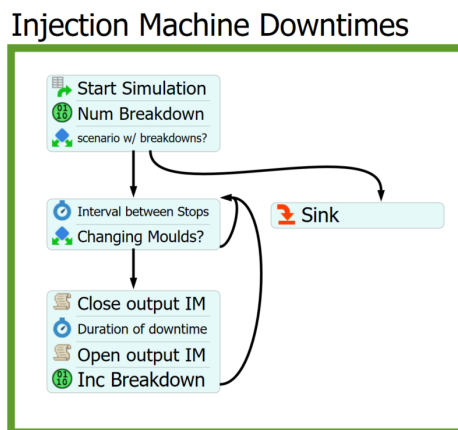


Figure 5.14: Flowchart of the Injection Machine Downtimes

The other flowcharts related to the injection machine will not be detailed since their functioning remains essentially the same, as described in section 5.2.3.

Main control of the injection machine

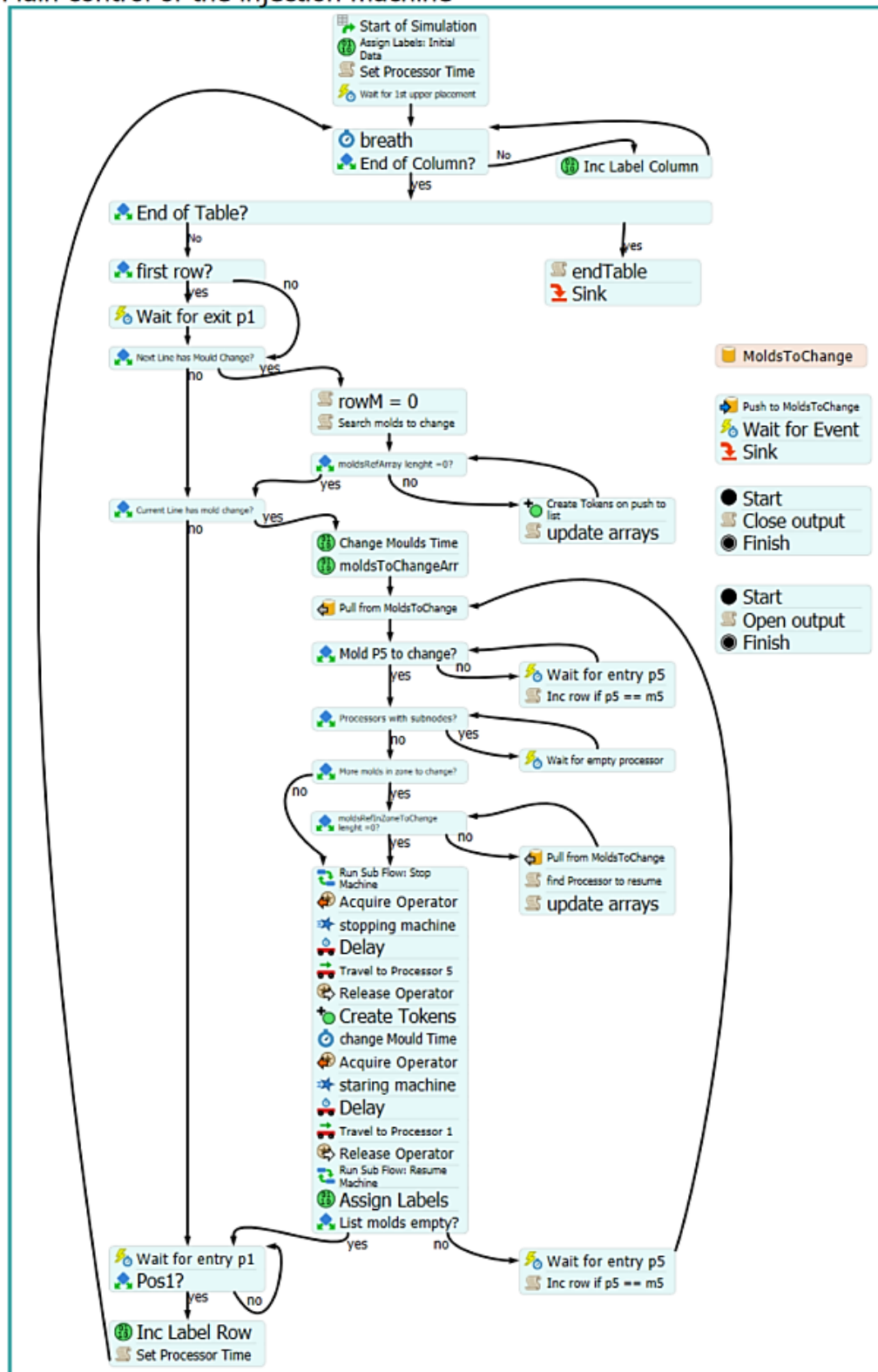


Figure 5.15: Process flow of the main control of the injection machine

5.3.3 Layout and 3D Model

As shown in Figure 5.16, the final *FlexSim* 3D layout includes the assembly line and the injection machine, both connected by conveyors: on the left is located the assembly line and on the right, the injection machine.

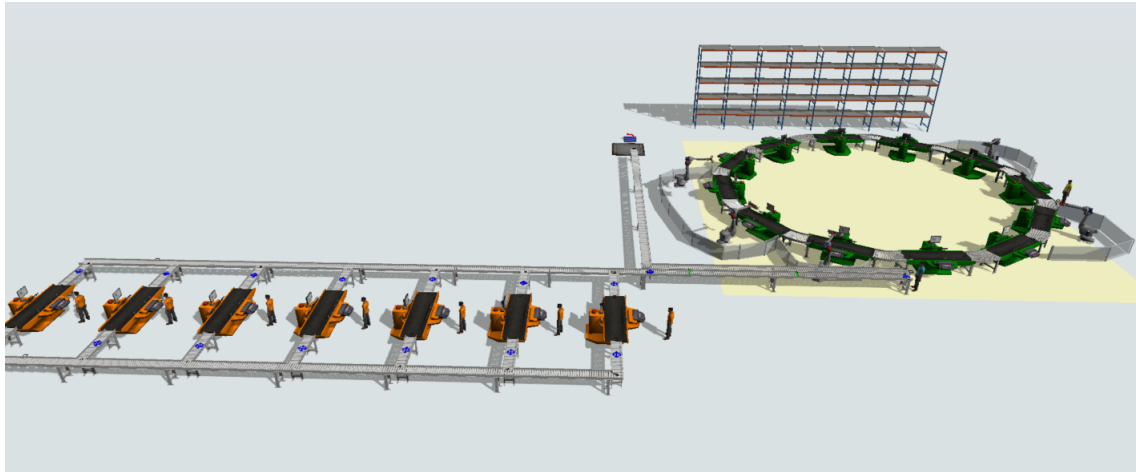


Figure 5.16: FlexSim base simulation model layout

5.3.4 Validation of the Base Model

After the correction of the preliminary model of the injection machine, it was possible to validate the model. The results obtained are shown in Table 5.4. The number of pairs produced is lower due to the adjustment made to the production plan of the mould change. Now, the makespan corresponds to the production plan, with differences due to small operators' travel times.

	Planned	Base Model
Total Laps	1040	1040
Mould changes	40	40
Pairs Produced	10187	10163
Makespan (h)	140,01	140,09
Mould Change (h)	6,43	6,43
Production Time (h)	133,58	133,66

Table 5.4: Validation of the base model.

5.4 Simulations Scenarios

Through the use of *FlexSim* parameters, it is possible to create different scenarios replicating the same properties, but with different values using the same simulation model. Thus, to perform the simulation experiments in *FlexSim*, it was necessary first to define the model's properties to be changed to analyse the response of the performance measures to the changes made in the

properties. The following scenarios, in summary, are shown in Table 5.5, and will be discussed in more detail next.

Scenario	Workstations Allocation	Max. Buffer Length (in laps)
Deterministic	Fixed	2
		4
	Dynamic	2
		4
Stochastic	Fixed	2
		4
	Dynamic	2
		4
Stochastic with downtimes	Fixed	2
		4
	Dynamic	2
		4

Table 5.5: Summary of the scenarios

Deterministic

There are no random variables in the deterministic scenarios, and these scenarios mainly consist of pre-determined values without any degree of randomness. When applied to a model, this conveys the event times being fixed; for instance, the assembly time at the workstation will always be 240 seconds. Similarly, mould changes correspond to the specified time indicated in the production plan. In order to analyse the impact of system variability, this scenario will be used as a base.

Stochastic

Random (stochastic) scenarios present inputs with one or more random variables, which result in different outputs. The impact of the variability of assembly time at the workstations, and the variability of mould change time, based on statistics, will be explored in this scenario. These parameters will be discussed in section 5.4.1.

Stochastic with downtimes of injection machine

Using the stochastic scenario as a basis, the injection machine stops are added using statistical data. It will be possible to analyse how these stops impact the production system and whether they will significantly impact the assembly line modelling. The stopping parameters will also be addressed in the next section.

Workstations

The workstation parameter will analyse the effects of having the number of workstations remain the same, i.e. seven or six workstations, regardless of the speed of the machine (this value was determined and explained in section 5.3.1.1). The other hypothesis is the

dynamic allocation of workstations, which is variable according to the average production volume needed in the following laps of the injection machine.

Buffer length

The influence of the buffer size will also be taken into account. The maximum buffer length affects the number of uppers stacked on the conveyor and will serve as a cushion against variations that may occur. Three different buffer lengths, 2-1, 4-1, and 4-2, were dimensioned for the simulation model, as shown in Figure 5.17. The buffer length represents the extent of the number of uppers on the conveyor. For example, buffer 2-1 means that the conveyor will have a variable buffer between 24 and 12 pairs of shoes (2 to 1 complete laps of the injection machine). The minimum length (in this case, 12 pairs of shoes) corresponds to a "safety stock" for the system's unpredictability.

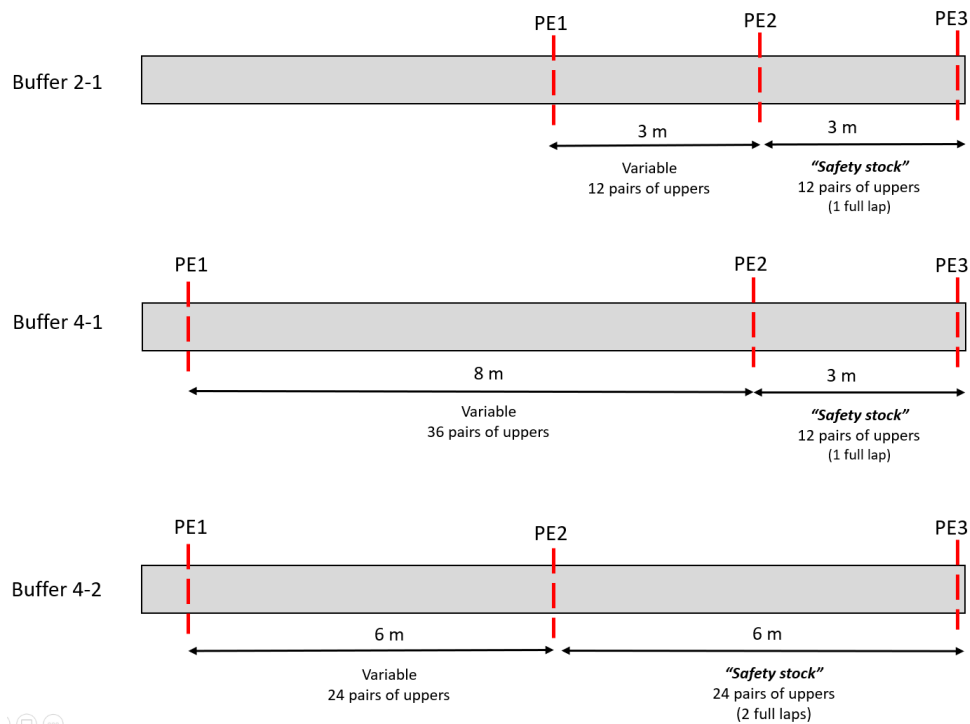


Figure 5.17: Buffer lengths

5.4.1 Parameters Values

FlexSim software integrates the *ExpertFit*, a leading statistical analysis software. This software can automatically and accurately determine the probability distribution that best represents the data set, which makes it a powerful tool. *Expertfit* was used for each parameter, finding the distribution that best fits the historical data [85]. Table 5.6 summarises the parameter's distributions.

Workstation's Assembly Time

The triangular distribution is straightforward; knowing a minimum value (a), a maximum

value (b) and a most likely value (c), it is possible to obtain a triangular distribution that results in a good approximation of the probabilities of occurrence of the event. Considering there are no historical records to use, this distribution was used. The minimum value (a) and the maximum value (b) were considered as 20% of the value (c) of 240 seconds. The distribution is:

$$f(x) = \text{triangular}(192, 288, 240); \quad (5.2)$$

Change of mould

The mould change time distribution function was applied using *ExpertFit*, which determined the best distribution function from the available data set.

For one mould change:

$$f(x) = \text{johnsonbounded}(70.488132, 1143.300881, 0.352562, 1.428629); \quad (5.3)$$

For two moulds to change:

$$f(x) = \text{erlang}(768.017648, 53.991689, 7.000000); \quad (5.4)$$

Lastly, for three moulds to change:

$$f(x) = \text{loglogistic}(751.922006, 1006.203113, 14.495020); \quad (5.5)$$

Interval between stops

The time elapsed between each stop was calculated using the company's records to simulate the machine stops. With the values obtained, the distribution that best fitted was a Pearson distribution:

$$f(x) = \text{pearson}6(40.058912, 2044.471978, 1.340749, 4.512449); \quad (5.6)$$

Duration of the stops

The duration of the stops is similar to the calculation of the interval of occurrence. The distribution function obtained was:

$$f(x) = \text{loglogistic}(5.039889, 81.185502, 2.031209); \quad (5.7)$$

Event	Parameters value
Workstation's Assembly Time	triangular(192, 288, 240)
Change of 1 mould	johnsonbounded(70.488132, 1143.300881, 0.352562, 1.428629)
Change of 2 moulds	erlang(768.017648, 53.991689, 7.000000)
Change of 3 moulds	loglogistic(751.922006, 1006.203113, 14.495020)
Interval between stops	pearsont6(40.058912, 2044.471978, 1.340749, 4.512449)
Duration of the stops	loglogistic(5.039889, 81.185502, 2.031209)

Table 5.6: Parameters values

Chapter 6

Analysis of Results

This chapter aims to present the analysis of the performance indicators of the designed production system. It will be possible to evaluate the model's efficiency and whether it fits reality, taking into account the variability of the processes, the number of resources available and circulating elements, such as the order in which the uppers enter the access conveyor to the injection machine. These variations will have different impacts on the model and may affect its efficiency to a large extent. The scenarios studied are those considered most relevant since, as there are several resources and elements in the simulation, it would be inconceivable to test the model by creating infinite variations.

FlexSim software includes a "Dashboard", capable of analysing the model and generating graphics according to the parameters to be evaluated, thus facilitating both a global and detailed analysis of the model. Moreover, *FlexSim's Experimenter*, was used to run scenario variations to analyse the production system's performance. The *Experimenter* enables the same simulation model to be run multiple times and allows changes in one or more variables to compare outcomes in different scenarios. The *Experimenter* was configured to run five replications for each scenario, with an execution simulation time of 160 hours. Therefore, and to provide a better understanding of the results obtained from *Experimenter*, box plots will be used to represent the variation of the obtained data for the KPIs.

The performance indicators selected for this study are:

- the workstation capacity utilisation rate;
- makespan of the simulated production;
- WIP in the buffer;
- upper shortages for the injection line.

The simulation also allows the observation of other indicators not considered for this study (output of entities, time in queue, number of entities in the queue, among others).

The goal is to minimise the buffer while increasing resource utilisation. Zero buffer shortage is critical because the injection machine is the bottleneck of the production process, and it must be independent of the prior manufacturing rhythm.

This computational model was developed using *FlexSim* software version 22.0.2.

Results will be analysed and presented in the following sections based on how the assembly line operates, i.e. whether the operators are fixed or dynamically allocated to the workstations.

6.1 Fixed Workstations

In a fixed workstation case, the number of stations to be used is pre-determined, and the number is constant throughout the production plan execution. This means that the operator is assigned to the workstation regardless of the production volume.

Twelve scenarios will be tested to assess the functionality of this layout and process configuration. In order to achieve an accurate reflection of the actual operation, these scenarios will be tested, including injection machine downtimes (scenarios 7 to 12) and without (scenarios 1 to 6), in order to explore the viability of reducing stoppages. We will then compare the results using six or seven workstations and evaluate the buffer size influence.

A detailed summary of these scenarios can be found in the Table 6.1 below:

	Scenario	Configuration		Downtimes
		Assembly Line	Buffer	
Fixed workstation without downtimes	1	Fixed 7 WS	2-1	no
	2		4-1	
	3		4-2	
	4	Fixed 6 WS	2-1	
	5		4-1	
	6		4-2	
Fixed workstations with downtimes	7	Fixed 7 WS	2-1	yes
	8		4-1	
	9		4-2	
	10	Fixed 6 WS	2-1	
	11		4-1	
	12		4-2	

Table 6.1: Scenarios with fixed workstations

The KPIs that enabled quantitative comparison between scenarios were chosen from the Experimenter's results. The following sections will go into further depth on each of those KPIs:

Makespan

Regarding the production makespan, the scenarios with and without downtimes maintain a similar average, as shown in Figure 6.1, as the injection machine stops create the most considerable difference between them. Internal variations (in cases with or without downtimes) result from the assembly line stoppages due to a full buffer, upper shortages and mould changes. This means that regardless of the scenario, the makespan remains similar within the group, and is not a weighting

factor in the choice of scenarios, i.e. the process performance over time does not have outliers for the makespan.

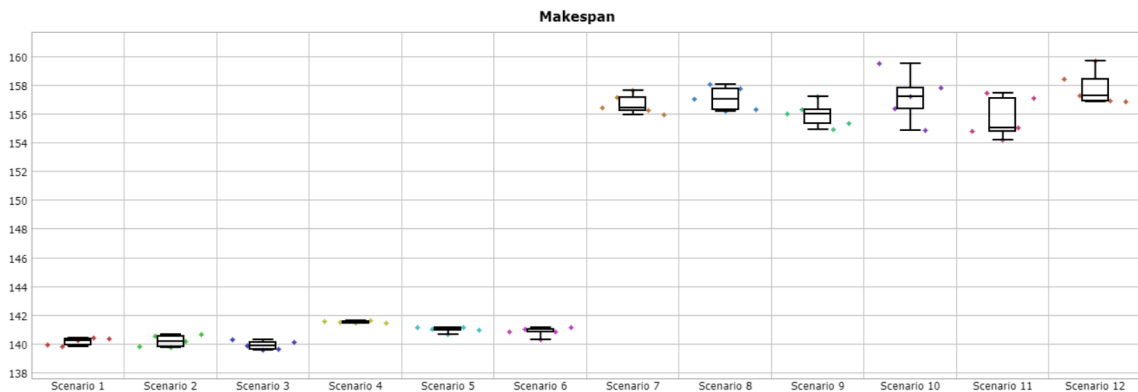


Figure 6.1: Makespan (in hours) for scenarios 1 to 12

Upper shortages

As for the shortages of uppers in the buffer, the scenarios with seven workstations (i.e. scenarios 1, 2, 3, 7, 8 and 9) did not present any failures, as shown in Figure 6.2. As for the scenarios limited to six workstations: scenarios 4, 5 and 6 presented a significant number of failures (between 80 to 200) depending on the buffer size. These configurations are therefore inadequate for implementation. Scenarios 10 and 11 presented fewer upper shortages (between 2 and 58). In spite of this, the shortages caused significant downtime, which made them unviable scenarios. However, scenario 12 presented in just one of the replication six upper shortages with a corresponding downtime of 1.8 minutes.

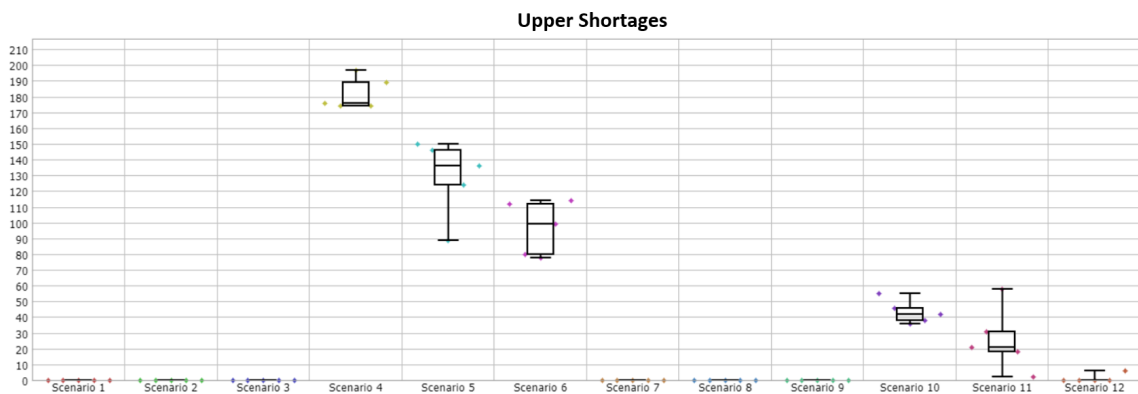


Figure 6.2: Number of upper shortages for scenarios 1 to 12

Buffer Length

As for the buffer length, scenarios 1 and 7 (which both confer a 2-1 buffer) present several assembly line stops due to a full buffer (between 100 and 150 stops), translating into significant

line stoppage time. In the case of scenario 7, this stoppage corresponds to an average of 65 hours, an increase of almost three times compared to scenario 12. Furthermore, scenario 1 likewise presents increased line stoppages compared to the other scenarios', as shown in Figure 6.3.

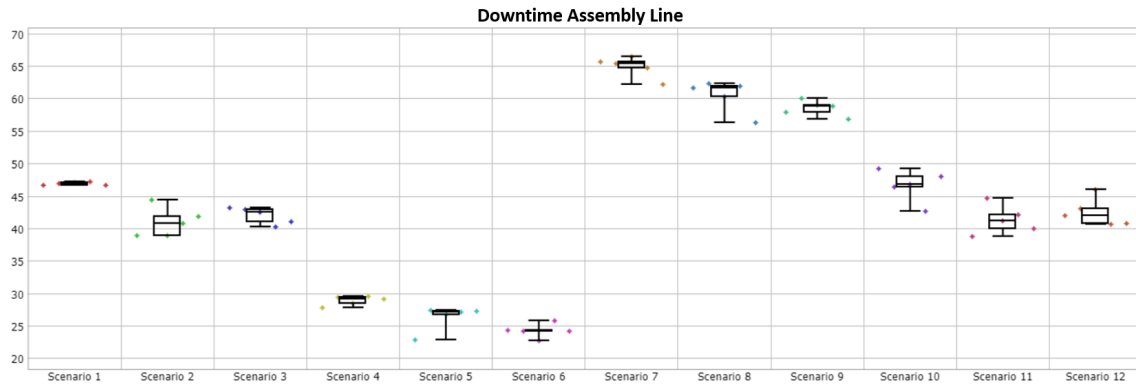


Figure 6.3: Total time assembly line on wait for scenarios 1 to 12

Assembly Line Stoppage

The remaining feasible scenarios 2, 3, 8 and 9, presenting the seven workstations configuration, and scenario 12, with 6 workstations, comprise buffer sizes of 4-1 and 4-2. Considering the total stop time of the assembly line, the configuration scenarios with buffer a 4-1 present less stopped time (on average one hour less than with buffer a 4-2).

Summary of KPIs obtained from fixed workstation scenarios

Therefore, assuming a scenario with a fixed allocation of operators to the workstations, the current design of the injection machine and considering the current stops in the injection machine, it would be recommended to configure scenario 8 for the case with machine downtimes and scenario 2 for one without since they did not demonstrate any upper shortages. Table 6.2 presents a summary of the average values obtained from the five replications of each scenario.

Scenario	Makespan (h)			Downtime Injection		Stoppage Assembly		Upper Shortages	
	Global	Assembly	Injection	Nº	Time (h)	Nº	Time (h)	Nº	Time (h)
1	135,82	140,15	139,95	0	0	106,4	46,95	0	0
2	134,89	140,18	139,98			46,6	40,96		
3	133,65	139,88	139,69			64,4	41,98		
4	136,99	141,51	141,31			41	28,86	182	1,12
5	134,87	140,96	140,76			18,8	26,27	129	0,75
6	135,4	140,81	140,61			25	24,26	96,6	0,56
7	151,79	156,7	156,5	591,8	20,93	148,6	64,91	0	0
8	149,64	157,08	156,88	587,4	21,19	66	60,54		
9	149,39	155,96	155,76	586,2	20,37	89,6	58,53		
10	153,08	157,16	156,97	578	20,92	86	46,63	43,4	0,27
11	148,97	155,72	155,53	566	19,77	38	41,35	26	0,13
12	151,43	157,85	157,65	566,2	21,46	52,4	42,52	1,2	0,01

Table 6.2: Summary of scenarios with fixed workstations

6.2 Dynamic Workstations

In the dynamic allocation of the operators, the number of workstations operating is determined by the production volume and the number of stations to be used is adjusted accordingly during the production plan. As in the previous section, twelve scenarios will be tested to verify the operation of this scenario and configuration.

A detailed summary of these scenarios can be found in the Table 6.3 below:

	Scenario	Configuration		Downtimes
		Assembly Line	Buffer	
Dynamic workstation without downtimes	13	Dynamic 7 WS	2-1	no
	14		4-1	
	15		4-2	
	16	Dynamic 6 WS	2-1	
	17		4-1	
	18		4-2	
Dynamic workstations with downtimes	19	Dynamic 7 WS	2-1	yes
	20		4-1	
	21		4-2	
	22	Dynamic 6 WS	2-1	
	23		4-1	
	24		4-2	

Table 6.3: Scenarios with dynamic workstations

The KPIs that enabled quantitative comparison between scenarios were:

Upper Shortages

As for the shortages of uppers on the conveyor to injection machine, as shown in Figure 6.4, it was found that the scenarios without downtimes and limited to only six workstations presented more failures (scenarios 16, 17 and 18). However, it should be noted that with the injection machine downtimes, scenarios 19, 20 and 21, corresponding to seven available workstations, did not present any upper failures.

Scenarios 22, 23 and 24 provided better results than those without downtimes with the same configuration (16, 17, 18).

It is noteworthy to mention that scenario 24 provided interesting results. Two replications suffered upper shortages over a specific production period, showing that when a configuration operates with six workstations, the buffers and the downtimes compensate for the speed under the fastest rhythm (432 s per lap).

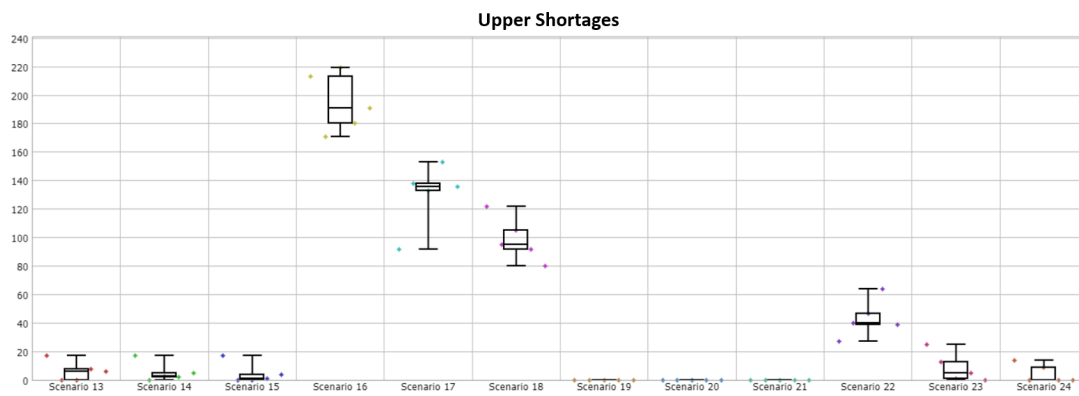


Figure 6.4: Upper shortages for scenarios 13 to 24.

Buffer Length

The buffer length explains the highest number of stops because of a full buffer in scenarios 19 and 22 (with a buffer of 2-1), as shown in Figure 6.5. The reduced buffer size does not accommodate the system's significant variability and uncertainty, translating into a need to stop more times the assembly line. On the other hand, scenarios 20 and 23 with the buffer size of 4-1 accumulate more uppers, translating into fewer stops. However, in terms of assembly downtime, they are very similar since the more significant the accumulation in the buffer, the longer the waiting time until resumption. In contrast, the assembly downtime will be shorter with smaller buffers (2-1).

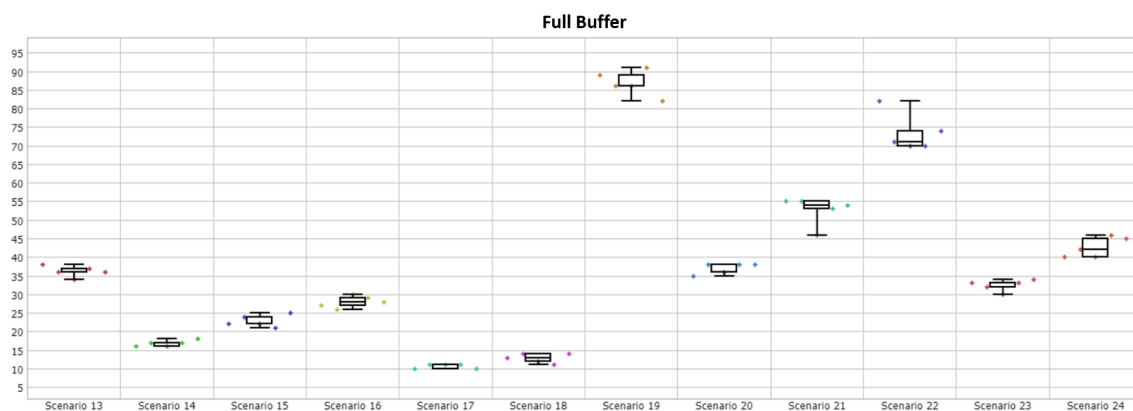


Figure 6.5: Full buffer for scenarios 13 to 24.

Summary of KPIs obtained from dynamic workstation scenarios

Among the configurations with operators dynamically assigned to workstations, scenario 14 stands out as a scenario with no machine faults, although it presented upper failures. Scenarios 19, 20, and 21 revealed no upper shortages. Despite the fact that scenario 24 had some upper shortages, it may have potential.

Table 6.4 presents the average values obtained from the 5 replications of each scenario.

Scenario	Makespan (h)			Downtime Injection		Stoppage Assembly		Upper Shortages	
	Global	Assembly	Injection	N°	Time (h)	N°	Time (h)	N°	Time (h)
13	140,23	138,12	140,04	0	0	36,20	16,99	6,20	0,03
14	140,16	137,16	139,97			16,80	14,86	5,40	0,02
15	140,32	135,36	140,13			22,80	13,43	4,40	0,02
16	141,66	139,55	141,47			28,00	14,39	194,80	1,24
17	140,98	137,83	140,79			10,60	11,50	130,40	0,81
18	140,81	136,04	140,61			12,80	9,75	98,80	0,64
19	156,75	153,72	156,56	544,20	19,99	86,80	36,10	0	0
20	155,39	151,01	155,20	543,00	18,81	37,00	29,74		
21	156,74	150,67	156,55	550,20	19,85	52,60	30,32		
22	156,43	153,35	156,24	551,80	19,40	73,40	32,02	43,40	0,26
23	157,06	152,68	156,86	572,60	20,46	32,40	27,59	8,80	0,05
24	155,59	149,58	155,39	554,60	19,20	42,60	25,89	4,60	0,02

Table 6.4: Summary of scenarios with dynamic workstations

6.3 Validation of the Best Configurations Scenarios

It is not possible to predict success from a scenario analysis. However, the analysis helps anticipate what is possible within the existence of constraints and uncertainties, thereby increasing the chance of success.

Results without downtimes of the injection machine are essential to demonstrate the impact of reducing the current frequency and duration of the stoppages. Some configurations may not be suitable for reducing machine downtime. Nonetheless, considering the injection machine's downtime, which is currently the company's reality, the configurations to be analysed in detail are based on the scenarios that take this characteristic into account. Therefore, according to the previously analysed configurations and scenarios, the configurations using seven workstations did not present any upper shortages, presenting the most interesting results for analysis. However, for this configuration (7 WS), between using a fixed or dynamic allocation, the dynamic uses fewer resources since the operators are allocated conform to the production volume.

In order to test the viability of the selected configurations and increase the reliability of measures, three production plans will be applied, and 50 replications of the scenario will be conducted for each plan. Furthermore, box plots and dashboards of the KPIs will be presented for a detailed analysis. The selected configurations scenarios are the 20, 21 and 24.

6.3.1 Validation of Scenario 20

Although configurations 19, 20 and 21 did not suffer from uppers shortages, scenario 20 was selected based on other KPIs that maximised production and resources. Configuration 20 had a lower average makespan of 1 hour compared to 19 and 21 (a relative difference of about 1%).

In this configuration, seven workstations are configured with a 4-1 buffer, and fifty replications of the three production plans were conducted. However, the results were not the expected ones, it showed upper shortages in 5 replications out of 150 (3.33%), as shown in Figure 6.6. Despite the maximum delay time of the entire makespan being only 42 seconds, the aim is to obtain zero

shortages. These outliers correlate with the injection machine's downtime, i.e. if there are fewer stoppages in a critical period of production (for example, when producing at a higher speed), the assembly line may not be able to respond promptly. The results provide confirmatory evidence that the buffer dimensions are essential and that uncertainty of the injection line converges to the need to maintain a minimum buffer greater than one complete cycle. Therefore, in order to increase the accumulation of the minimum buffer, configuration 21, presenting a buffer of 4-2, will be tested.

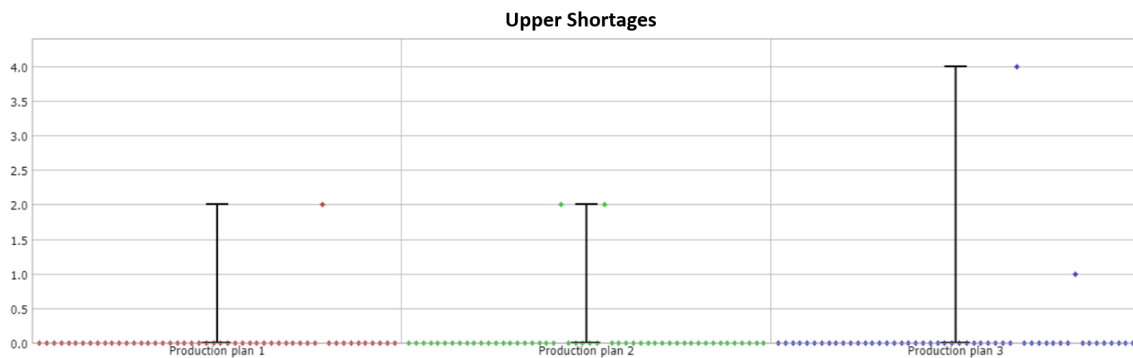


Figure 6.6: Buffer shortages for scenario 20 with three different production plans

6.3.2 Validation of Scenario 21

Based on the scenario 21 results, with different production plans, it was shown (Figure 6.7) that a larger minimum buffer of two complete cycles would ensure no upper failures. However, although 150 replications of this configuration are a reasonable sample size, caution must be applied, as the findings may have a possible bias due to the sample size.

It can be seen from the data in Figure 6.8 the resource utilisation rate of the workstations. The capacity utilisation rate for this configuration is 61,85%. One of the advantages of *FlexSim*'s dashboards is allowing the creation of Gantt charts of workstation usage throughout the production plan execution, enabling the visual representation of the allocation of operators, as shown in Figure 6.9.

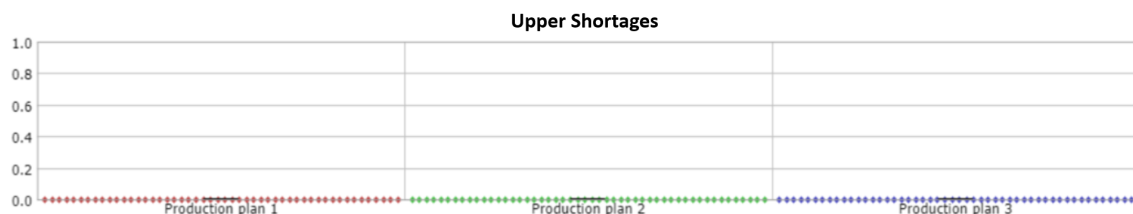


Figure 6.7: Buffer shortages for scenario 21 with three different production plans

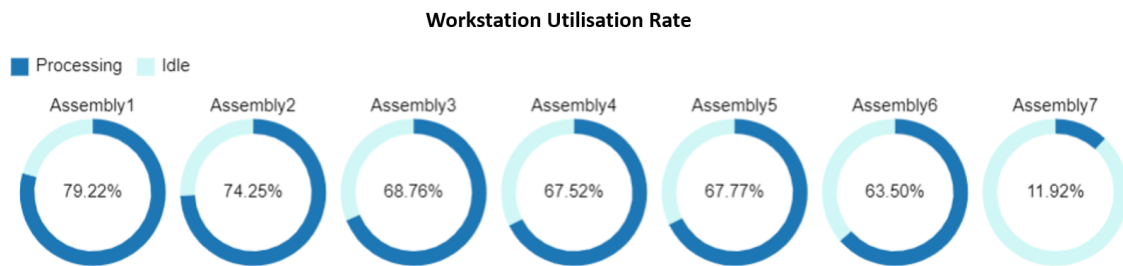


Figure 6.8: Resource utilisation rate of the workstations for scenario 21

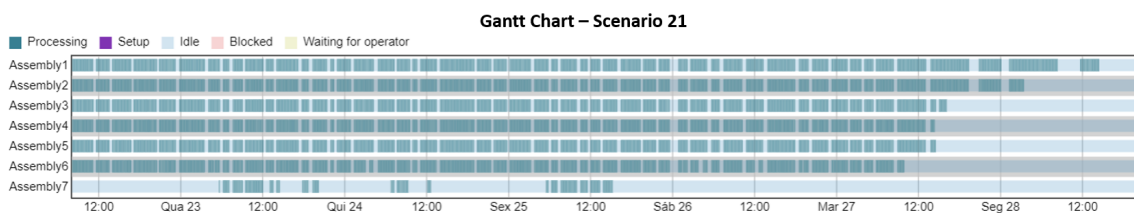


Figure 6.9: Gantt chart for scenario 21

Although the present results are promising, with no input failures to the injection line, the capacity utilisation rate could potentially provide better outcomes.

Considering that strategic planning can improve this rate, and ensuring the most efficient use of current resources, reducing the number of workstations appears to be a reasonable approach for improvement. For instance, using a hypothetical case of the elimination of all machine stops, an improvement of 7.07% is achieved in capacity utilisation for this scenario (68,92%).

The chart in Figure 6.8 shows that the seventh workstation has a low utilisation rate (11,92%) and that the other workstations could also be utilised more effectively. Therefore, further configurations should be analysed to develop a comprehensive study and understand the impact of reducing the layout for six workstations.

6.3.3 Validation of Scenario 24

This configuration features six workstations with a 4-2 buffer. Similarly to what was done before, this configuration will be tested with three production plans, with 50 replications per plan. In Figure 6.10, it is possible to observe the upper shortage for the different production plans.

A probability of 69.33% of zero upper shortages was obtained. Nevertheless, it is possible to observe that the production plan influences the probability of an upper shortage when using six WS. This configuration, however, has the potential for better results if the plan is adjusted to minimise the number of cycles in which the machine runs at the fastest pace (432 seconds per lap) and intercalate regularly with the pace of 480 seconds per lap.

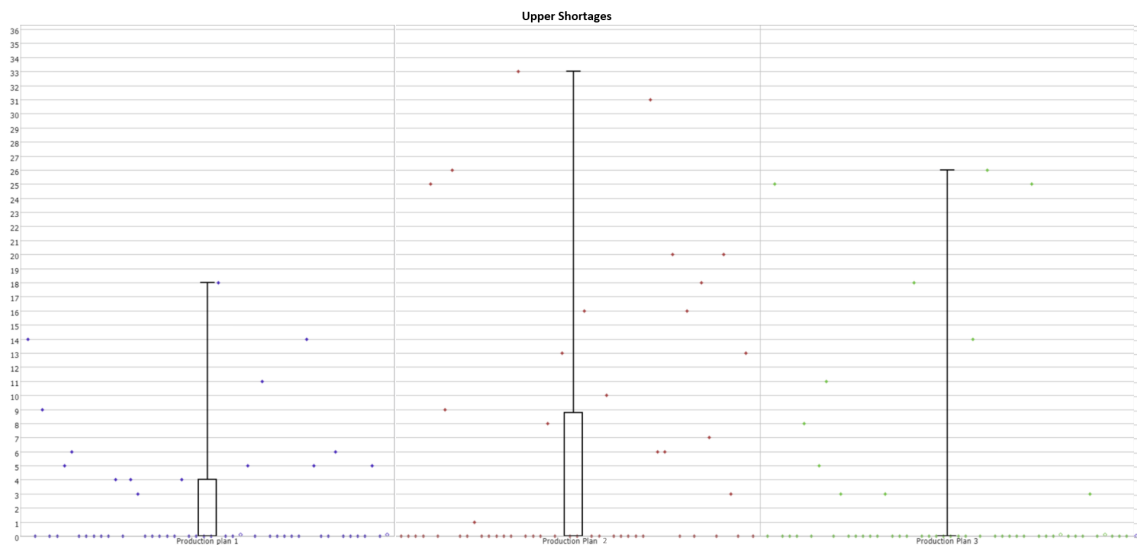


Figure 6.10: Buffer shortages for scenario 24 with three different production plans

In Figure 6.11, it is possible to observe the average resource utilisation rate of one of the replications. This configuration presented better resource utilisation than the previous ones, saving one resource in comparison. The capacity utilisation rate for this scenario is 72.7%, an increase of 11% in contrast to scenario 21.

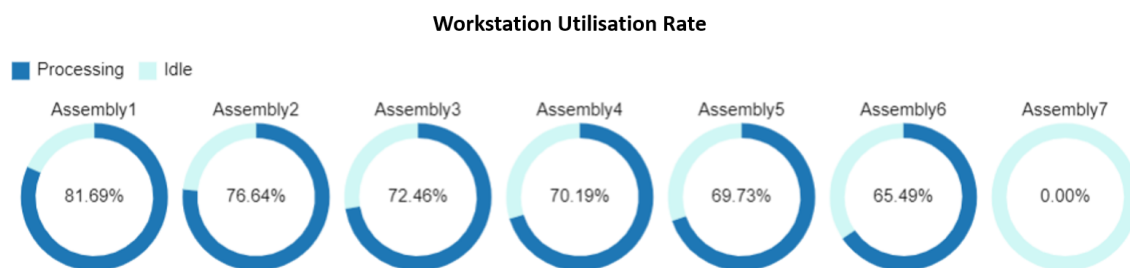


Figure 6.11: Resource utilisation rate of the workstations for scenario 24

In Figure 6.12, it is possible to analyse the WIP of the buffer during the simulation of the production plan execution. It can be seen that there were no failures in the supply of uppers to the injection line. The Gantt chart in Figure 6.13 shows the operator's allocation during the production plan.

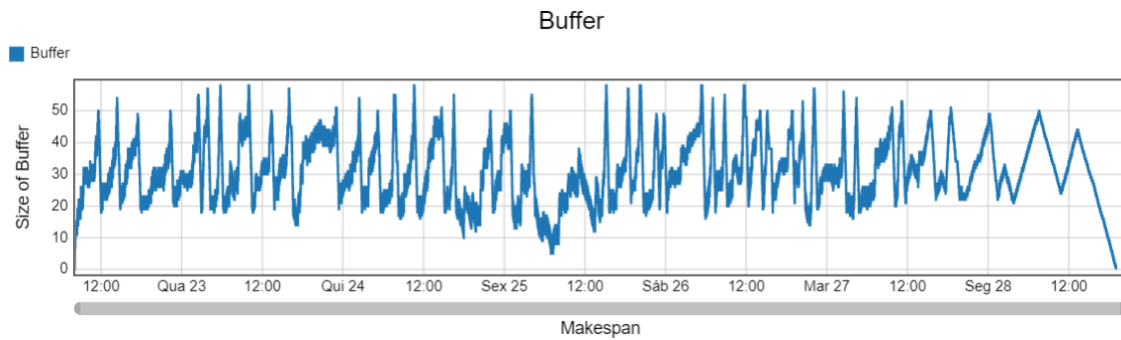


Figure 6.12: Buffer for scenario 24 without shortages

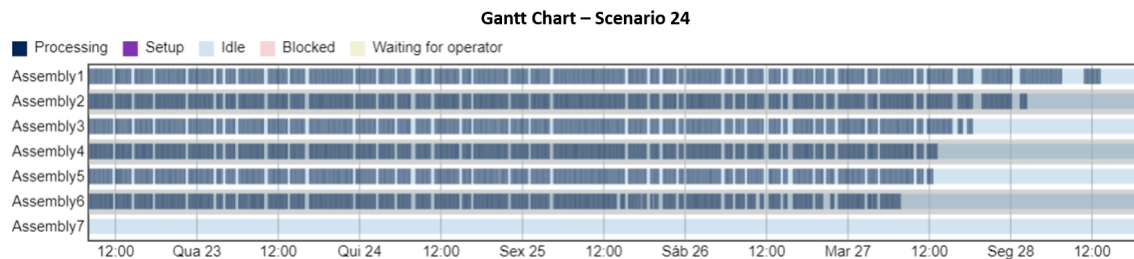


Figure 6.13: Gantt chart for scenario 24

6.4 Final Results Assessments

FlexSim's Experimenter was used to test several configurations with different scenarios. In order to reflect the actual situation of the company, we considered the scenarios with downtimes of the injection machine. The degree of decrease from downtimes to no downtimes had to be conducted in order to comprehend the feasibility of configurations.

It was necessary to choose relevant KPIs to assess how the process configuration affected production. The selected metrics were the workstation capacity utilisation rate, makespan, WIP in the buffer, and upper shortages for the injection line.

With scenario 20 with a buffer 4-1, for which no failures were observed in 5 replications, the total upper assembly time for the injection line was lower on average than with scenarios 19 and 21. Nonetheless, after testing a wider range of replications, we obtained failures in 3.33% of the replications conducted. Upon verification, it was determined that the minimum buffer size was insufficient for the system's variability and uncertainty and that configuration 21 with a 4-2 buffer had to be tested.

This configuration 21 attained the desired result due to the absence of upper shortages (0.00%) during the production plan execution. However, due to the potential of an increased resource utilisation rate, the configuration 24 with a 4-2 buffer was analysed despite the upper failures encountered during the preliminary analysis.

The capacity utilisation rate increased (72,7%) as one resource was spared. Moreover, it was also possible to determine a correlation between the failure probability and the production plan.

A summary of the scenarios tested and the metrics obtained can be found in Table 6.5.

Scenario	WS	Buffer	Upper Shortages
20	7	4-1	3,33%
21	7	4-2	0,00%
24	6	4-2	30,67%

Table 6.5: Summary of scenarios results

In the next section, a Value Stream Map was employed to examine the current and future production processes (considering configuration of scenario 21) in order to analyse the impact of the new manufacturing process.

6.4.1 Value Stream Map Analysis

With Value Stream Map (VSM) is possible to visualise the current flow of materials and information. This technique was chosen because it provides a view of the value chain, identifies the origins of waste along the chain, employing a simple, intuitive, and standardised language that enables the performance of processes to be seen, aids in the sequence and interactivity of activities, and, finally, represents the current state. A comparison between the current process and the future one will be presented.

Current Value Stream Map

Based on the information provided by the company, the VSM of the current manufacturing process was developed, as shown in Figure 6.14.

The uppers take 3 to 4 months to arrive at AMF after the original order is placed. A pair of uppers is processed in 143 seconds on the assembly line, and it takes an average of 2100 seconds to enter the injection line, where they are processed in 432 or 480 seconds. Once it is shared with other production lines (cementing), the finishing line has a higher waiting time of 7200 seconds, with a processing time of 220 sec.

The total processing time (value-added time) is of 843 seconds with a lead time of 10143 sec (non-value-added of 9300 sec). The Process Cycle Efficiency (PCE) (or value added-ratio) of the process is 8,31%, and as presented in section 3.4, this value is towards the low-end of PCE.

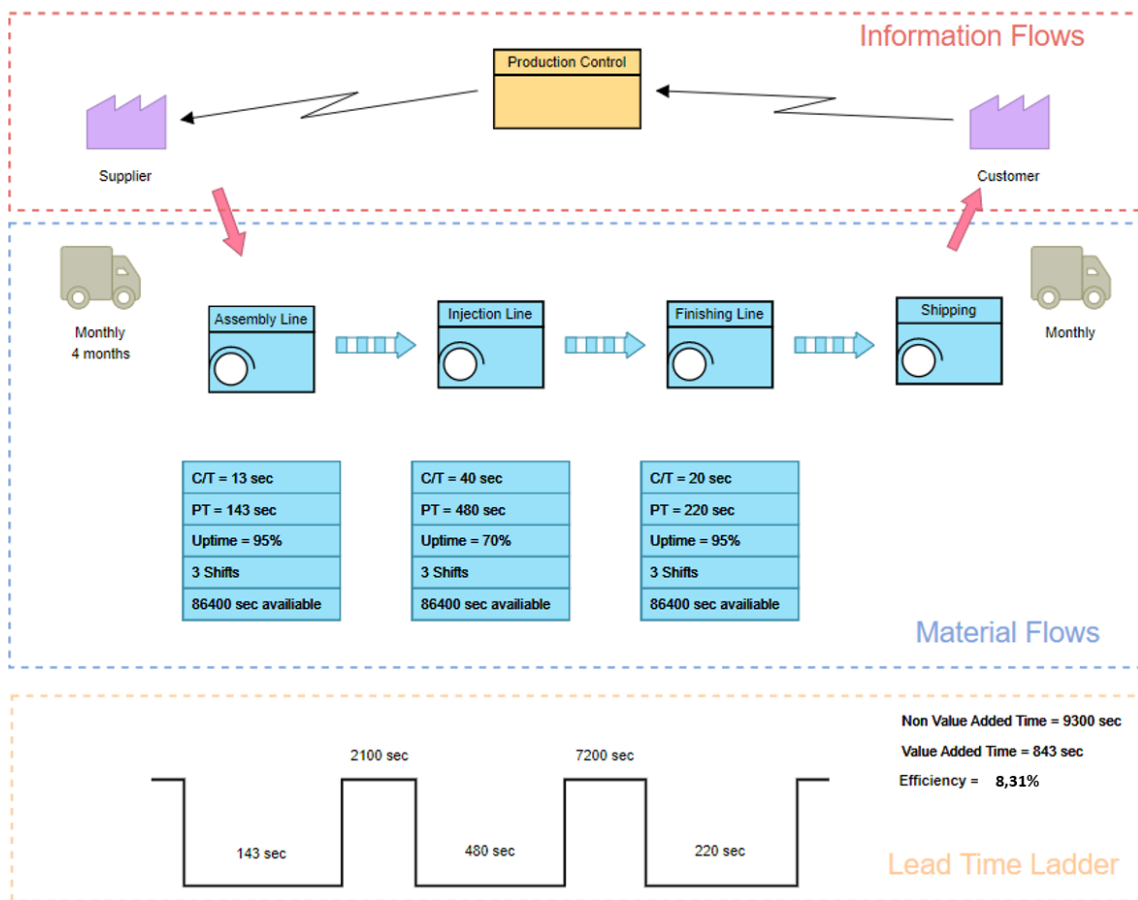


Figure 6.14: Current Value Stream Map

Future Value Stream Map

The developed VSM of the future manufacturing process (Figure 6.15) only refers to the section that has been simulated and for which data could be acquired through simulation (scenario 21), in order to make the comparison with the actual process simpler. The process, on the other hand, is designed to have an exclusive finishing line for this system.

Unlike the current process, which relies on imported Asian uppers with a long delivery time, this approach simply requires the raw material for the uppers, which would be imported from Europe with a two to three week shipping time. Since the material cutting operations and the logistic supermarket were not considered and simulated, they are not included in this VSM. A pair of uppers is assembled in 240 seconds, and it takes an average of 1750 seconds for them to enter the injection line, where they are processed in 480 seconds. The estimated entry time to the finishing line will be the same as between the assembly and injection line, 1750 seconds, with a processing time of 220 seconds.

The total processing time (value-added time) is of 940 seconds with a lead time of 4440 sec. The PCE of the process is 21,17% and as presented in section 3.4, this value is a high-end PCE, considered as the internationally competitive level.

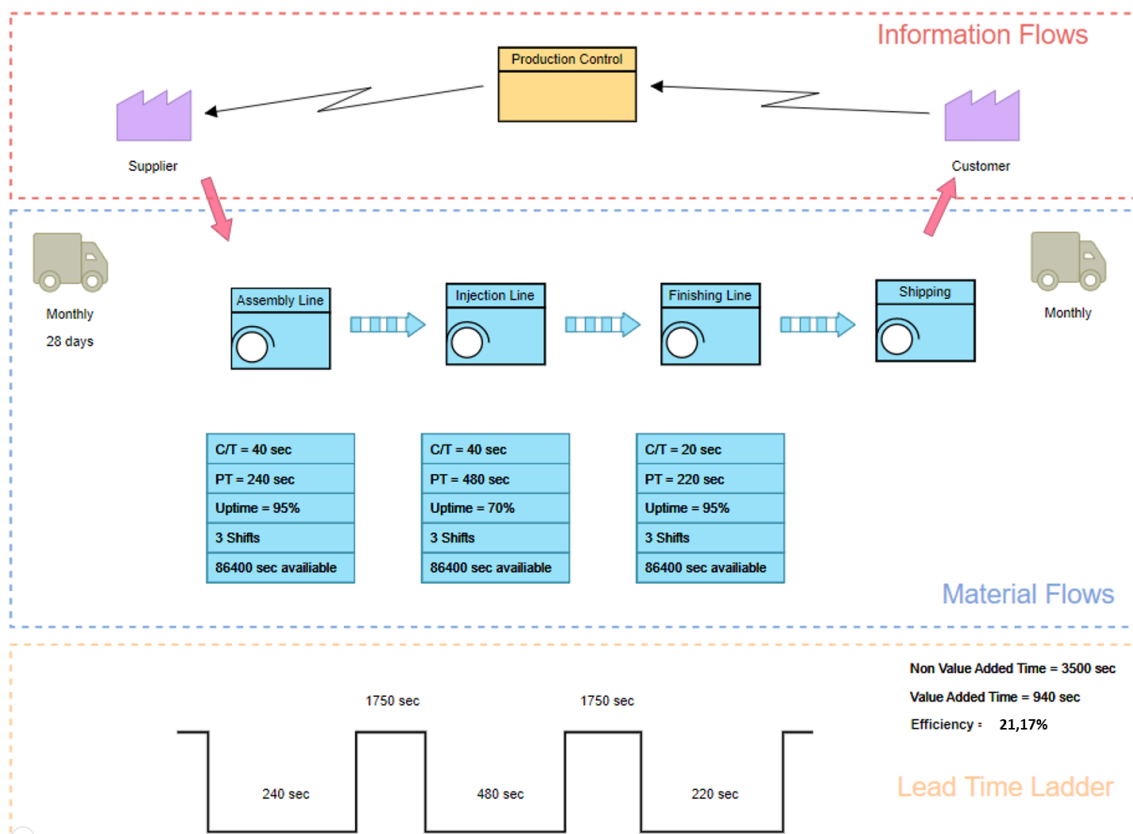


Figure 6.15: Future Value Stream Map

Taken together, these results provided further evidence that the new production process reduced the lead time and increases the process cycle efficiency by 12%, from a low-end to a high-end PCE.

Chapter 7

Conclusions and Future Work

This chapter describes the conclusions concerning the work developed throughout the project that gave rise to this dissertation. In addition to illustrating the contributions and assessing whether the initially proposed objectives were met, some suggestions for future work are also provided.

7.1 Conclusions

The main objective of this dissertation project was to design a new production process for a footwear factory through a simulation-based approach to increase flexibility and customisation. The production process uses a new technology, 3D Bonding, which eliminates the need to stitch the shoe components through plastic injection. The model, once completed, would be used to assess and evaluate the different configurations and scenarios.

The strategy began by creating a preliminary simulation model for the injection machine. Upon implementing the adjustments, the analysis of the results confirmed that the model accurately represented the case under study, respecting the performance indicators specified by the injection machine production plan. Next, the assembly line was dimensioned and modelled through simulation, aiming to synchronise the injection and assembly processes. To fully achieve the objectives set for this dissertation, the injection machine's downtimes were modelled using probabilistic distribution functions that best fitted the historical data, in order to understand its impact on the new production system. Furthermore, to accommodate the production system variability and ensure the injection machine's maximum utilisation, the minimum buffer size was determined, resulting in at least two complete laps (24 pairs of shoes).

Additionally, solutions with fewer resources and workstations were analysed. When implementing six workstations, a correlation between the probability of an upper shortage and the sequencing of the production plan was assessed. Given the current data and taking into account the injection machine downtimes, the scenario (21) with a configuration of seven workstations and an accumulation buffer between 24 and 48 pairs of shoes (buffer 4-2) successfully demonstrated no upper shortages. In terms of overall results, through a VSM analysis, the new production process

appears to be able to reduce lead time and increase the Process Cycle Efficiency (PCE) by 12%, from a low-end to a high-end PCE.

In light of the fact that 3D Bonding seems to be a new revolutionary method which will help the manufacturing processes to be more flexible, it is relevant to mention that this method has not yet been fully implemented by the industry, and that the study's scope was constrained by the information available. Despite its limitations, the study certainly adds insights into the potential of evaluating new production processes, opening the door for shorter lead times and less complex production processes.

Thus, and by way of conclusion, it can be stated that the objectives proposed for this dissertation project were met, and it was also possible to go beyond them, identifying scenarios of improvement to further implement in the physical system.

7.2 Future Work

As part of a more comprehensive ongoing project, future work is foreseen to enhance the simulation model by implementing the complete production system, introducing the cutting and the picking process, and dimensioning a logistic supermarket.

This dissertation considered 240 seconds as the average time for assembling the components constituting an upper, with a variance of 20%. The assembly process, however, could differ in reality. It would be essential to undertake physical experiments in further research to acquire exact data and adapt the simulation model through parameters. Moreover, assessing the results of the developed model for other injection machine production plans may provide further insights and prove the selected configuration's suitability for the problem.

After the physical implementation of the process, it will also be necessary to record historical data of assembly-line disruptions and potential assembly errors so that they can be incorporated into the simulation and comprehend their influence on the production and sizing of the line.

It will also be crucial to optimise the allocation of operators to workstations using heuristics and meticulous planning.

Machine utilisation levels are one of the factors to be improved. In the last laps, the machine works with only a couple of positions, resulting in low machine utilisation and increasing the time required to finish the plan, resulting in wasted energy. The same view applies to the new production process, as it relies upon the injection machine production plans.

In addition, understanding the impact on the production system of reducing the downtime rates of injection machines would be of interest, as it impacts the new assembly line.

References

- [1] Charlotte Méry Folinus et al. *Stiffness prediction methods for additively manufactured lattice structures*. PhD thesis, Massachusetts Institute of Technology, 2020.
- [2] André Moreira. Master thesis. Master’s thesis, Instituto Superior de Engenharia do Porto, 2021.
- [3] Welcome to desma shoe machinery. URL: <https://www.desma.de/en/machines/direct-soling/>.
- [4] Desma msi technology, the new frontier for the safety customizable shoes, Oct 2017. URL: <https://arsutoriamagazine.com/desma-msi-technology-new-frontier-safety-customizable-shoes/>.
- [5] The fit station project is put at the centre, May 2018. URL: <https://arsutoriamagazine.com/desma-fit-station-simac-2018/>.
- [6] Serma.net. News, technical, new-system-for-shoe-manufacturing, Jan 2019. URL: <https://www.serma.net/news/technical/new-system-for-shoe-manufacturing>.
- [7] The simplest method for joining pieces. URL: <http://www.simplicity.works/bond> [last accessed 18.04.2022].
- [8] Carin Rösiö and Jessica Bruch. Exploring the design process of reconfigurable industrial production systems: Activities, challenges, and tactics. *Journal of manufacturing technology management*, 2017.
- [9] Tolga Tezcan and Abhijit Gosavi. Optimal buffer allocation in production lines using an automata search. In *Proceedings of the institute of industrial engineering conference, Dallas*. Citeseer, 2001.
- [10] James A Tompkins, John A White, Yavuz A Bozer, and Jose Mario Azaña Tanchoco. *Facilities planning*. John Wiley & Sons, 2010.
- [11] A. M. Law. How to build valid and credible simulation models. In *2019 Winter Simulation Conference (WSC)*, pages 1402–1414, 2019. doi:10.1109/WSC40007.2019.9004789.
- [12] Esra E Aleisa and Li Lin. For effective facilities planning: layout optimization then simulation, or vice versa? In *Proceedings of the Winter Simulation Conference, 2005.*, pages 5–pp. IEEE, 2005.

- [13] ML George, D Rowlands, M Price, and J Maxey. Lean production six sigma pocket tool book, 2005.
- [14] Jerry Banks. *Discrete-event system simulation*. Prentice-Hall international series in industrial and systems engineering. Pearson Prentice Hall, Upper Saddle River, N.J., 4th edition, 2005. 2004053354 Jerry Banks [and others]. illustrations ; 24 cm. Includes bibliographical references and index. Prentice-Hall international series in industrial and systems engineering.852 T57.62 .D53 2005.
- [15] APICCAPS. Footwear, components and leather goods – statistical study 2009. *Monografia Estatística*, 2010, 2010.
- [16] DGAE. Indústrias do couro e do calçado sinopse 2017, 2017.
- [17] APICCAPS. Facts & numbers 2019, 2019.
- [18] Giacomo Becattini. The marshallian industrial district as a socio-economic notion. *Industrial districts and inter-firm co-operation in Italy*, 2, 1990.
- [19] APICCAPS. World footwear 2021 yearbook, 2021.
- [20] APICCAPS. Footure 2020 plano estratégico - cluster do calçado, 2013.
- [21] APICCAPS. Facts & numbers 2021. *Facts & Numbers 2021*, page 1–24, Apr 2022.
- [22] INESCTEC. Footwear industry, Aug 2017. URL: <https://www.inesctec.pt/en/success-stories/footwear-industry>.
- [23] Kyaia apresenta projecto high speed shoe factory, Oct 2016. URL: <https://logisticamoderna.com/kyiaia-apresenta-projecto-high-speed-shoe-factory/>.
- [24] Jorge Borrell Méndez, David Cremades, Fernando Nicolas, Carlos Perez-Vidal, and Jose Vicente Segura-Heras. Conceptual and preliminary design of a shoe manufacturing plant. *Applied Sciences*, 11(22), 2021. URL: <https://www.mdpi.com/2076-3417/11/22/11055>, doi:10.3390/app112211055.
- [25] Amf shoes. URL: <https://marca.guimaraes.pt/membro/fab-calcado-tecn-pro/amf-shoes/>.
- [26] History. URL: <http://www.amfshoes.com/index.php/en/about-afm/history>.
- [27] Adrian Hernandez Hernandez. Mould, machine and method for manufacturing three-dimensional items and manufacturing plant associated with same, February 3 2022. US Patent App. 17/278,945.
- [28] Roxana Mihaela Cobzariu. International marketing plan of simplicity works. Master's thesis, Universitat Jaume I, 2021.
- [29] David S Cochran, Joseph T Foley, and Zhuming Bi. Use of the manufacturing system design decomposition for comparative analysis and effective design of production systems. *International Journal of Production Research*, 55(3):870–890, 2017.

- [30] Yuji Yamamoto and Monica Bellgran. Four types of manufacturing process innovation and their managerial concerns. *Procedia CIRP*, 7:479–484, 2013.
- [31] Yoram Koren and Moshe Shpitalni. Design of reconfigurable manufacturing systems. *Journal of manufacturing systems*, 29(4):130–141, 2010.
- [32] Iván Andrés Arana-Solares, César H Ortega-Jiménez, Rafaela Alfalla-Luque, et al. Contextual factors intervening in the manufacturing strategy and technology management-performance relationship. *International Journal of Production Economics*, 207:81–95, 2019.
- [33] Alireza Pooya and Mohammadali Faezirad. A taxonomy of manufacturing strategies and production systems using self-organizing map. *Journal of Industrial and Production Engineering*, 34(4):300–311, 2017.
- [34] Kazi Shah Nawaz Ripon, Kyrre Glette, Kashif Nizam Khan, Mats Hovin, and Jim Torresen. Adaptive variable neighborhood search for solving multi-objective facility layout problems with unequal area facilities. *Swarm and Evolutionary Computation*, 8:1–12, 2013. URL: <https://www.sciencedirect.com/science/article/pii/S2210650212000442>, doi:<https://doi.org/10.1016/j.swevo.2012.07.003>.
- [35] Nurul Nordin, Zaitul Zainuddin, Sutinah Salim, and Raja Rajeswari Ponnusamy. Mathematical modeling and hybrid heuristic for unequal size facility layout problem. *Journal of Fundamental Sciences*, 5:87–89, 01 2009. doi:[10.11113/mjfas.v5n1.290](https://doi.org/10.11113/mjfas.v5n1.290).
- [36] Serkan Altuntas. Application of an aggregation technique to facility layout design selection. *Journal of Thermal Engineering*, 3:1078–1078, 2017.
- [37] Berna Ulutas and A. Attila Islier. Dynamic facility layout problem in footwear industry. *Journal of Manufacturing Systems*, 36:55–61, 2015. URL: <https://www.sciencedirect.com/science/article/pii/S0278612515000205>, doi: <https://doi.org/10.1016/j.jmsy.2015.03.004>.
- [38] Amine Drira, Henri Pierreval, and Sonia Hajri-Gabouj. Facility layout problems: A survey. *Annual Reviews in Control*, 31(2):255–267, 2007. URL: <https://www.sciencedirect.com/science/article/pii/S1367578807000417>, doi: <https://doi.org/10.1016/j.arcontrol.2007.04.001>.
- [39] Michael R. Garey and David S. Johnson. *Computers and Intractability; A Guide to the Theory of NP-Completeness*. W. H. Freeman & Co., USA, 1990.
- [40] Jerzy Grobelny and Rafał Michalski. A novel version of simulated annealing based on linguistic patterns for solving facility layout problems. *Knowledge-Based Systems*, 124:55–69, 2017.
- [41] Tjalling C Koopmans and Martin Beckmann. Assignment problems and the location of economic activities. *Econometrica: journal of the Econometric Society*, pages 53–76, 1957.
- [42] Gordon C Armour and Elwood S Buffa. A heuristic algorithm and simulation approach to relative location of facilities. *Management science*, 9(2):294–309, 1963.
- [43] F Robert Jacobs, Richard B Chase, and Nicholas J Aquilano. Operations management for competitive advantage. *Boston: Mc-Graw Hill*, 64:70, 2004.

- [44] Boris Goldengorin, Dmitry Krushinsky, Panos M Pardalos, et al. Cell formation in industrial engineering. *Springer Optimization and Its Applications*, 2013.
- [45] Gayathri Perera and Vijitha Ratnayake. Qualitative analysis on layout flexibility of machine layout configurations. *Journal of Business and Management (IOSR-JBM)*, 2015.
- [46] Eric S Grajo. Strategic layout planning and simulation for lean manufacturing a layopt tutorial. In *Proceedings of the 27th conference on Winter simulation*, pages 510–514, 1995.
- [47] Council of Supply Chain Management Professionals. Supply chain management terms and glossary. *Illinois*, 2010.
- [48] Alcibíades P Guedes, Amílcar JM Arantes, Ana L Martins, Ana PB Póvoa, Cristina A Luís, Eurico Brilhante Dias, João CQ Dias, João CR Menezes, José C Carvalho, Luís MDF Ferreira, et al. Logística e gestão da cadeia de abastecimento. *Lisboa: Edições Sílabo, Lda*, 2010.
- [49] Harald Gleissner and J Christian Femerling. It in logistics. In *Logistics*, pages 189–223. Springer, 2013.
- [50] Gurinder Singh Brar and Gagan Saini. Milk run logistics: literature review and directions. In *Proceedings of the world congress on engineering*, volume 1, pages 6–8. WCE, 2011.
- [51] Maurizio Faccio, Mauro Gamberi, Alessandro Persona, Alberto Regattieri, and Fabio Sgarbossa. Design and simulation of assembly line feeding systems in the automotive sector using supermarket, kanbans and tow trains: a general framework. *Journal of Management Control*, 24(2):187–208, 2013.
- [52] C Sendil Kumar and R Panneerselvam. Literature review of jit-kanban system. *The International Journal of Advanced Manufacturing Technology*, 32(3):393–408, 2007.
- [53] Yuan Zhong et al. *Improved inventory and production control on a multi-product production line: seasonality analysis, inventory supermarket, and Kanban design*. PhD thesis, Massachusetts Institute of Technology, 2009.
- [54] Shine-Der Lee and Siu-Hwa Ho. Buffer sizing in manufacturing production systems with complex routings. *International Journal of Computer Integrated Manufacturing*, 15(5):440–452, 2002. URL: <https://doi.org/10.1080/09511920110118786>, arXiv:<https://doi.org/10.1080/09511920110118786>, doi:10.1080/09511920110118786.
- [55] René De Koster, Tho Le-Duc, and Kees Jan Roodbergen. Design and control of warehouse order picking: A literature review. *European journal of operational research*, 182(2):481–501, 2007.
- [56] Jürgen Fleischer, Udo Weismann, and Stephan Niggeschmidt. Calculation and optimisation model for costs and effects of availability relevant service elements. *Proceedings of LCE*, pages 675–680, 2006.
- [57] Michal Leporis and Zdenka Králová. A simulation approach to production line bottleneck analysis. In *International conference cybernetics and informatics*, pages 13–22, 2010.

- [58] Carl-Fredrik Lindberg, SieTing Tan, JinYue Yan, and Fredrik Starfelt. Key performance indicators improve industrial performance. *Energy Procedia*, 75:1785–1790, 2015. Clean, Efficient and Affordable Energy for a Sustainable Future: The 7th International Conference on Applied Energy (ICAE2015). URL: <https://www.sciencedirect.com/science/article/pii/S1876610215012424>, doi: <https://doi.org/10.1016/j.egypro.2015.07.474>.
- [59] Jun Duanmu and Kevin Taaffe. Measuring manufacturing throughput using takt time analysis and simulation. In *2007 Winter Simulation Conference*, pages 1633–1640. IEEE, 2007.
- [60] Richard P Marek, Debra A Elkins, and Donald R Smith. Understanding the fundamentals of kanban and conwip pull systems using simulation. In *Proceeding of the 2001 Winter Simulation Conference (Cat. No. 01CH37304)*, volume 2, pages 921–929. IEEE, 2001.
- [61] Petter Solding and Per Gullander. Concepts for simulation based value stream mapping. In *Proceedings of the 2009 Winter Simulation Conference (WSC)*, pages 2231–2237. IEEE, 2009.
- [62] Claudio Boer and Sergio Dulio. *Mass Customization and Footwear: Myth, Salvation or Reality?* Springer Science & Business Media, 08 2007. doi:10.1007/978-1-84628-865-4.
- [63] Li Da Xu, Eric L Xu, and Ling Li. Industry 4.0: state of the art and future trends. *International journal of production research*, 56(8):2941–2962, 2018.
- [64] Vasja Roblek, Maja Meško, and Alojz Krapež. A complex view of industry 4.0. *Sage open*, 6(2):2158244016653987, 2016.
- [65] Ralf Reichwald, Frank Piller, and Kathrin Moeslein. Information as a critical success factor for mass customization or: Why even a customized shoe not always fits. *ASAC-IFSAM 2000 Conference*, 01 2000.
- [66] Nelson Oliveira, Joana Cunha, and Helder Carvalho. Co-design and mass customization in the portuguese footwear cluster: an exploratory study. *Procedia CIRP*, 84:923–929, 2019.
- [67] Hugo Emanuel Branco Rodrigues. *Bespoke E-Commerce-Customização em Massa no Calçado: Estudo de Caso Múltiplos*. PhD thesis, Instituto Superior de Gestão, 2017.
- [68] Frank Piller, Petra Schubert, Michael Koch, and Kathrin Moeslein. From mass customization to collaborative customer co-design. In *ECIS*, pages 1497–1509, 01 2004.
- [69] Pamela V Ulrich, Lenda Jo Anderson-Connell, and Weifang Wu. Consumer co-design of apparel for mass customization. *Journal of Fashion Marketing and Management: An International Journal*, 2003.
- [70] Robert E. Shannon. Introduction to the art and science of simulation. In *Proceedings of the 30th Conference on Winter Simulation*, WSC ’98, page 7–14, Washington, DC, USA, 1998. IEEE Computer Society Press.
- [71] R. G. Ingalls. Introduction to simulation. In *Proceedings of the 2011 Winter Simulation Conference (WSC)*, pages 1374–1388, 2011. doi:10.1109/WSC.2011.6147858.

- [72] C.D. Pegden, R.E. Shannon, R.P. Sadowski, and Systems Modeling Corp. *Introduction to Simulation Using SIMAN*. Computer science series. McGraw-Hill, 1990. URL: <https://books.google.pt/books?id=T-AmAAAAAAAJ>.
- [73] Jerry Banks and Randall Gibson. Simulation modeling: some programming required. *IIE Solutions*, 29(2):27–32, 1997.
- [74] Jerry Banks. Introduction to simulation. In *Proceedings of the 31st conference on Winter simulation: Simulation—a bridge to the future-Volume 1*, pages 7–13, 1999.
- [75] I. Grigoryev. *AnyLogic 7 in Three Days: A Quick Course in Simulation Modeling*. CreateSpace Independent Publishing Platform, 2015. URL: <https://books.google.pt/books?id=22YyrgEACAAJ>.
- [76] John Sterman. Business dynamics, system thinking and modeling for a complex world. [http://lst-iiiep.iiiep-unesco.org/cgi-bin/wwwi32.exe/\[in=epidoc1.in\]/?t2000=013598/\(100\),](http://lst-iiiep.iiiep-unesco.org/cgi-bin/wwwi32.exe/[in=epidoc1.in]/?t2000=013598/(100),) 19, 01 2000.
- [77] Eric Bonabeau. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the national academy of sciences*, 99(suppl 3):7280–7287, 2002.
- [78] Anu Maria. Introduction to modeling and simulation. In *Proceedings of the 29th conference on Winter simulation*, pages 7–13, 1997.
- [79] Fevzi Belli, Christof J Budnik, and Lee White. Event-based modelling, analysis and testing of user interactions: approach and case study. *Software Testing, Verification and Reliability*, 16(1):3–32, 2006.
- [80] James C Chen, Aryka Pradhana Putra, Nikita Anggono, Jeff Chen, and Yung-Sheng Su. Simulation modeling and analysis for stitching line of footwear industry. In *Proceedings of the 2014 International Conference on Industrial Engineering and Operations Management Bali, Indonesia*, 2014.
- [81] Parisa Sadeghi, Rui Diogo Rebelo, and José Soeiro Ferreira. Balancing mixed-model assembly systems in the footwear industry with a variable neighbourhood descent method. *Computers & Industrial Engineering*, 121:161–176, 2018. URL: <https://www.sciencedirect.com/science/article/pii/S0360835218302213>, doi: <https://doi.org/10.1016/j.cie.2018.05.020>.
- [82] Quang-Vinh Dang and Khoa Pham. Design of a footwear assembly line using simulation-based alns. *Procedia CIRP*, 40:596–601, 2016. 13th Global Conference on Sustainable Manufacturing – Decoupling Growth from Resource Use. URL: <https://www.sciencedirect.com/science/article/pii/S2212827116001554>, doi: <https://doi.org/10.1016/j.procir.2016.01.140>.
- [83] Muhammed Eryilmaz, Selman, Ali Kusakci, Haris Gavranovic, and Fehim Findik. Analysis of shoe manufacturing factory by simulation of production processes. *Southeast Europe Journal of Soft Computing*, 1, 02 2012. doi:10.21533/scjournal.v1i1.81.
- [84] Simulation modeling software tools & solutions for business. URL: <https://www.anylogic.com/>.
- [85] Home, Feb 2022. URL: <https://www.flexsim.com/>.

- [86] Simio LLC. Simulation, production planning and scheduling software. URL: <https://www.simio.com/>.
- [87] Simul8: Fast, intuitive simulation software for desktop and web. URL: <https://www.simul8.com/>.
- [88] Luis M. Dias, Antonio A. Vieira, Guilherme A. Pereira, and Jose A. Oliveira. Discrete simulation software ranking — a top list of the worldwide most popular and used tools. *2016 Winter Simulation Conference (WSC)*, 2016. doi:10.1109/wsc.2016.7822165.
- [89] Sanjay Jain and Stephen Chan. Experiences with backward simulation based approach for lot release planning. In *Proceedings of the 29th conference on Winter simulation*, pages 773–780, 1997.
- [90] Edward F Watson, Deborah J Medeiros, and Randall P Sadowski. Generating component release plans with backward simulation. In *Proceedings of 1993 Winter Simulation Conference-(WSC’93)*, pages 930–938. IEEE, 1993.
- [91] Romain Girard Adrian Hernandez. 3d bonding: Transforming the footwear complex business | wolves summit 12. URL: <https://www.youtube.com/watch?v=afCSZJR37kk&t=645s>.