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Using Discrete Event Simulation to implement a conceptual model aiming at evaluating the performance of manufacturing lines

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Master in, Management of Services and Technology

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Para a minha avó Celeste e o meu avô Aníbal,

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Resumo

A avaliação dos sistemas de produção de uma organização é uma etapa crítica para a tomada de decisão no que diz respeito à alteração ou melhoria dos sistemas já existentes. Neste projeto foi desenvolvido um método de avaliação das linhas de produção para uma empresa do setor de produção de brinquedos educativos, sendo o foco deste projeto na determinação da eficiência das mesmas. Para tal recorreu-se ao uso de simulações, onde foi possível replicar os sistemas observados num ambiente virtual através da determinação de distribuições estatísticas que permitem mimetizar os sistemas observados e os seus comportamentos. A partir dos modelos criados um conjunto de indicadores foi analisado para determinar quais os fatores que influenciavam a capacidade produtiva das linhas de produção estudadas. Da análise dos resultados verificou-se que a minimização de estrangulamentos de produção e o seu adiamento para jusante do local original permite um aumento da capacidade produtiva dos sistemas. Verificou-se também que a utilização do parâmetro eficiência de utilização, fornece poderosas perspetivas acerca dos sistemas de produção, ao determinar de que forma as linhas de produção se encontram balanceadas.

Palavras chave: Operações, Simulação, Avaliação de eficiência

Abstract

The assessment of an organisation's production systems is a crucial stage in the decision-making process for modifying or improving the existing systems. In this project a method of evaluation of the production lines was developed for a company in the educational toy manufacturing sector, being the focus of this project to determine the efficiency of these lines. For this purpose, it was used computer simulations as a tool to evaluate these systems, replicating the observed systems in a virtual environment through the determination and application of statistical distributions that allow mimicking the observed systems and their behaviour. Based on the models created, a set of indicators was analysed to determine which factors influenced the most the production capacity of the studied production lines. The analysis of the results revealed that the minimisation of throughput bottlenecks and their postponement downstream from the original site allows an increase in the productive capacity of the systems and consequently increase the efficiency of it. It was also observed that the use of the parameter efficiency of utilisation, provides powerful insights into the production systems by determining how the production lines are balanced.

Key words: Operations, Simulation, Efficiency evaluation

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1. Introduction

1.1. Introduction to the project sponsor

Science4you is a Portuguese group that produces and commercializes Scientific, Technological, Engineering and Mathematics Educational Toys for children of ages comprehended between 3 and 14 years old. The products have own design and brand, being its commercialisation the major business activity. The company also provides services such as birthday parties and scientific summer camps. The group is composed by 3 subsidiaries, as follows: Science4you S.A., Science4you Espanha and Science4you UK. Science4you S.A. is located in Mercado Abastecedor da Região de Lisboa, Lisbon, and has conquered the Portuguese market being the biggest toys producer in Portugal, having expanded into 35 strategic markets around the world in 2019, exporting regularly to more than 60 countries. The company was founded in 2008, in a partnership between ISCTE Business School former students and Faculdade de Ciências da Universidade de Lisboa (FCUL). The project that started as a potential valuation of the scientific and educational toys industry was later transformed into a company by its founder and current CEO Miguel Pina Martins.

The company is characterized by having a strongly vertically integrated business model, controlling the product from the design to the production, distribution and sales to the final consumer, allowing the company to manipulate and implement changes rapidly along the production system without being deeply dependent upon external actors.

According to the data provided by Science4you IPO Prospect (Science4you, 2018) it was possible to verify that from 2016 to 2017, the sales and services provided by the company increased from €13.794.494,00 to €20.962.533,00, corresponding this variation to an increase of 52%, being verified a strong growth in the exports sales volume, that from 2016 to 2017 increased 149% from €5.564.106,00 to 13.853.819,00€ when compared with the previous year,

This fast growing trend has distinguished itself from the global average increase in the STEM markets that was highly marked by the bankruptcy of big players in this environment, such as Toys ‘R‘ Us, as it is described in the Science4you IPO Prospect.

1.2. Business Problem

During the period of June and August of 2019, the author had the possibility to participate in an internship opportunity in the main production facilities of the Company, where the presented business project took place, having been all the data collected during this time period.

Before the internship started a meeting between the Company's *Operations & Efficiency Department* manager and the author was held. At the company this department is focused on the production, storage and shipping of different products, being in constant contact with the top management, the financial and the creative department, controlling the manufacturing lines, the warehousing and the shipping process. This department is vital to the success of the company as it is deeply interconnected with other departments and it has the enormous responsibility of coordinating the activities that correspond to the largest portion of the company's revenues.

In this meeting the department leader detailed that it had been verified that an operation segment was as a hindrance for the overall manufacturing process, leading to a decrease of the global efficiency of the activity and delaying all subsequent activities. As previously detailed the commercialization of the manufactured products corresponds to the largest portion of the income stream of the company, directly affecting the company's ability to thrive in a competitive environment that is the Science, Technology, Math and Engineering market. Therefore, any change in this system leading to an identification and correction of inefficiencies would lead to an increase in the overall efficiency of the company.

In a context of high growth in sales, with a high quantity of products to be exported, there is a need for the company to be able to increase its efficiency in all its systems, identifying flaws and correcting them, thus allowing continued and sustained growth. This business project was developed to allow the company to better understand the operation segment in which were identified hindrances, allowing the assessment of the efficiency of this system, identifying the reasons for it to perform badly when compared with other systems and how to improve the efficiency and minimize the associated flaws with it.

1.3. Context

The segment that corresponded to a handicap in the system was the final assembly line of products. Any delay in this section of the production process would lead to a necessary decrease in upstream production capacity to avoid the accumulation of work-in-progress items, as well as a decrease in storage and shipping capacity since the final product rate production would decrease when compared with the overall capacity of the system.

In the initial and subsequent meetings was specified that the Company was producing hundreds of different products with very short life cycles. Despite the high number of products to be produced, a general product structure was maintained, reflected in the type of box that was used. It was reported that 90 to 95% of the sales volume was centred on 5 different boxing types, being these the *M, M2, XL, XL2* and *MiniKit* types. Due to top management guidelines the company was moving from one product type to another, increasing the production of product type *M2* and *XL2* at the expense of *M* and *XL*, which would require the modification of the equipment composing the production lines. Therefore, the focus of this master's project is on these 5 product types.

According to Choi (2010), there appears to be a relationship between the success of an organisation's operations and its financial success. Organisations that tend to shift their focus away from their operations also tend to be less successful financially and consequently disrupt the entire operation of the company. Therefore, there is strong evidence between the performance of an organisation's operations and its financial performance, which is reflected in the competitiveness of the market in which they operate.

As described by O'Neil and Sohal (1999), a true world-class organisation, needs to work as a team in all its functional areas. The basis of competitiveness is changing from cost to flexibility, therefore organisations must be able to cope with new market demands, which can lead to significant changes in production systems. It is necessary for the organisation to be able, not only to rapidly change its operations to meet the new consumer demands, but also to promptly evaluate the existent systems. This evaluation of the systems addresses the assessment of their efficiency in the different manufacturing contexts and this requires the employment of different resources, coming from different areas of the company to more quickly adapt the organisation to the new market conditions and consequently to create a sustainable competitive advantage (Barney, 1991). Thus, the use of new technologies that allow a better ability to adapt to a competitive and uncertain market in which new models must be tested and implemented is imperative for the survival of the organisation.

The design of the operation systems is a key component on the success of the organisation on the current paradigm. The design of systems that are appropriate to the existing products and services allow the identification of problems, objectives and outlining problem-solving methodologies and decision-making processes (CIRP 1990) that otherwise could be hidden. These processes are strongly related to innovation processes within the organisation, which must be supported by different management techniques and tools (Du Preez and Louw, 2008).

Simulation techniques allow imitation of a real system, based on a series of characteristics obtained from an original system (Hegselmann, 1996). Based on a preliminary literature review was denoted that the decision-making quality can be improved based on the use of simulations (Schuh, 2014). Therefore, the use of such techniques can lead to the creation of a decision-making tool.

As previously referred, the need to change the final assembly line to meet the new manufacturing needs, enabling the line flexibilization, led to the realization of this business project. It aims to perform the evaluation of different production systems, with different product mixes, thus allowing the characterization and comparison of the different operation systems. Such analysis will allow characterizing each manufacturing system through a set of indicators and parameters, which when compared between the different systems may lead to the deduction of conclusions about the production process. These results can then be used for a more correct evaluation of the existing manufacturing systems in the Company, and consequently for a better allocation of resources in the future. To allow this evaluation a virtual model will be built, using simulation techniques which will allow the analysis of the system in several characteristics. This model will be designed based on the original system, considering a set of assumptions collected or calculated that will increase its reliability and make it more similar to the original system. Stochastic variables will also be added, allowing to model the variability observed in real systems and increasing the model reliability.

1.4. Goals and purpose

As it was introduced in the previous ´Sections, the goal of this business project is to correctly evaluate the manufacturing systems in the Organisation, using a set of parameters and indicators, that allow its comparative analysis and determination of flaws assessing the efficiency of these systems in the process.

The purpose of this work is to provide the Company with new tools for the analysis of manufacturing systems, through the use of simulation, allowing a faster response to changes in the business environment in which the Company operates, and providing the Company with another managerial tool for decision making.

The main goal of this project will be achieved through the creation and implementation of a management tool based on the use of simulation that allows the leadership team to more accurately evaluate its operations, allowing a better decision making when evaluating or changing different physical processes. By doing this it is possible to better display the different factors that affect these operations, identifying the factors that negatively affect efficiency and productivity capacity and boosting the factors that allow the improvement of the systems conditions. Furthermore, the possibility to test new scenarios and conditions allows to increase the amount of information by easily and quickly testing new ideas and suggestions.

Based on the content described in Section 1.3. a thorough literature review was guided by the research questions to be described ahead. First, the *manufacturing sector* was detailed to frame the reader about some of its characteristics, secondly it was defined what system *design* corresponds to, and how it is necessary for organisations to allow the creation of a competitive advantage. In this way is avoided the increase in costs associated with the redefinition of systems and allowing the creation of them based on detailed information of products and services. The main *processes of manufacturing systems* are described thereafter, allowing the match of the production systems in the Company and those described by the literature. Afterwards, it is detailed how the data to be analysed should be collected and processed, using *time study methods* considering the existing production environment, describing a set of good practices and examples to be followed. In addition, it is determined how to *evaluate the performance* of the different systems using different metrics. Finally, a section is dedicated to the exploration of simulation with thoroughly examination of its characteristics that allow the determination for the best use for these techniques and functionalities.

Such information allows the creation of the knowledge basis to meet the main goals and purposes and to answer the proposed research questions.

The goals of this business project are subdivided into:

1. To identify the baseline level of production for each of product types and manufacturing lines, in the initial conditions as well as the relevant indicators values.
2. To perform a comparative analysis between the performance of the manufacturing lines before and after the updating of the equipment that composed the operation segment.
3. To determine the main issues concerning the assembly line.
4. To transmit the main processes and techniques used in the evaluation of production lines, allowing the managerial team to have new tools for decision making.

1.5. Research Questions

The definition of a research question is a point of utmost importance, which must be done before the research begins. To develop the research questions the author must identify the topic of interest, conduct preliminary research, and use the newly acquired knowledge in determining research questions (Ratan *et al. 2019).*

Thus, and in order to achieve the goals and purpose of this business project, the following research questions were developed:

1. How to measure the efficiency of manufacturing systems applying simulation techniques?
2. Which indicators, or set of indicators, can be used to determine the overall efficiency of a production system?
3. What parameter, or set of parameters, is responsible for the most significant variation in the behaviour of the manufacturing line?

4. How can the organisation use and implement simulation techniques on other operation systems?

1.6. Methodology

In order to achieve the goals previously defined in Section 1.4, a research methodology was defined and made explicit. As described by Sileyew (2019), a research methodology is the path through which the researcher will conduct its research. The path and the methods used for the development of this business project, achieving the proposed objectives, and responding to the defined research questions are defined on this Chapter.

The designed methodology comprises the following steps:

1. Manufacturing facilities study.
2. Data collection.
3. Data treatment.
4. Data analysis.
5. Results analysis.
6. Results discussion.
7. Conclusions.

To start the approach to the research problem, the systems to be analysed will be subdivided into smaller subsystems and the times related to operation times, downtimes and other system characteristics will be collected. These times will consider the Motion and Time Study guidelines (Barnes, 1980), constituting a source of Primary Data. The data collected will be associated with a statistical distribution that will allow the variability to be captured. These statistical distributions will be determined according to the behaviour of the samples collected.

Then a simulation model will be built using the *SIMUL8* software, which will be described later, in which the systems observed will be replicated in a virtual environment. The behaviour of the production systems will be verified after thousands of hours of operation, and the collected data will be treated and analysed as Quantitative Data and furthermore as Descriptive and

Simulated Data. From these data will be extracted the conclusions which will provide the answers to the formulated research questions.

1.7. Business Project structure

The presented business project is divided into seven main sequential chapters.

In the first Chapter, which is the ***Introduction***, general information about the project is presented. Some information about the Company are presented, followed by the business problem, project objectives and research questions.

The second Chapter contains the ***Literature Review***, which was researched to inform the author and the reader about relevant concepts to the topic of this project. This Chapter presents the market sector in which the Company operates and important concepts of the same, the most important production systems of it as well as systems design. Good practices and rules in the study of methods and times are presented hereafter, allowing the author to be trained on how to carry out this process and to inform about innovations in the area. It is also defined what the performance evaluation corresponds to and how it should be performed, and finally it is described what is a simulation and how it was produced.

The third Chapter consists of the ***Conceptual Framework***. On this Chapter a Literature Review synthesis that summarizes relevant collected knowledge from the literature is presented, and what is going to be done to achieve the previously set goals and to answer the research questions is exposed.

The fourth Chapter details the ***Methodology*** used on this business project. The different sources for data collection and the methods that will be used for data treatment and manipulation and results analysis are explained.

The fifth Chapter, ***Case Study***, describes how the methodology defined previously was implemented, describing the characteristics of the model created and defining all the intermediate steps of it. It starts by defining the system as it was studied in the Company, moving on to the way it was replicated in the virtual environment, detailing its characteristics. The validity of the model used according to the existing literature has also been proven. The data obtained through the methodology used are presented, as well as the treatment given to them. Finally, the results obtained through the analysis of the simulation model are presented and analysed.

The sixth Chapter ***Results Discussion***, critically reviews the results obtained and analysed beforehand, drawing conclusions about the patterns verified, defining a new conceptual framework considering the results obtained.

The last Chapter ***Conclusions*** describes a set of conclusions about the project undertaken, also describing its limitations, validating its results in a specific time frame, ascertaining whether the project goals have been met and whether the research questions have been answered, and outlining a set of recommendations for the Company.

2. Literature Review

The literature review is a research tool that allows the reader to share the knowledge highlighted with the topic of interest of the study, describing the most recent findings and information on the subject. It allows creating a framework for the project developed (Creswell, 2013).

To explore the previously defined research questions, the literature review will be divided into 6 sections. It will start with a brief outline of the manufacturing sector, describing different concepts and terminologies related to the sector. Different existing production processes will be described after, detailing those that are more closely related to the processes observed in this project. Afterwards, a review of the literature on manufacturing system design will be presented, and the importance of defining manufacturing systems based on the needs of the organisation. After these topics a review will be presented about the Study of Methods and Times, defining good practices for the collection of data related to time measurements and definition of sub-operations that can be measured, and also describing technological advances and innovations in this area. Hereinafter it will be presented the state-of-the-art knowledge regarding the performance evaluation of a system, identifying some metrics and parameters to evaluate the operations systems. Finally, a section is dedicated to detail what a simulation is, what types of methods to create them exist and how they can be used for the study of operations systems.

2.1. The manufacturing sector

According to Jovane *et al.* (2008) the manufacturing sector is a global business that started in the industrial revolution in the 19^{th} century allowing the large-scale production of goods. This sector suffered tremendous changes along the years due to the constant incorporation of new technologies, processes, material, communication, and transportation methods (Mohamed, 2013). A manufacturing system can be described as a set of machines, transportation elements, computers, storage buffers, and other elements that are used together for manufacturing purposes (Gershwin, 1994).

The business environment in which most companies compete, has undergone considerable changes during the past years. With the aperture of previously closed economies to highly interconnected global marketplaces have brought new possibilities, but also new requirements for manufacturing organisations (Bellgran *et al.*, 2004). Now customers demand more than a low price, also demand the best products, with the lowest possible price, with a wide variety and with immediate availability (Jackson, 2000). Therefore, it is necessary that the manufacturing systems are able to handle the increased requirements, in the most appropriate way (Bellgran *et al.*, 2004). As described by Slack *et al.* (1998), the correct adjustments to the new requirements and needs of the market, and a correct use of the available resources are some of the necessary requirements and abilities to maintain a high operational efficiency.

2.1.1. Lean manufacturing

A manufacturing philosophy, related to constant innovation, cost and waste reduction is the *lean manufacturing*. It relies on thorough assessment of each activity of a company with the aim of reducing waste at all levels, allowing the organisation performance to increase, by cutting on non-value-adding processes and focusing on the processes and tasks that create value. Through the lean manufacturing process, the efficiency and effectiveness of each operation are studied including machines, equipment, layouts, and personnel (Mohamed, 2013), and improvements suggested and tested. Under this philosophy, *waste* is defined as an activity or process that does not add any value to it and is usually about 70% to 80% for most process operations (Melton, 2005). According to Hicks *et al.* (2004) there are 7 types of waste in different systems, being:

- *Over-production*
- *Waiting*
- *Transport*
- *Inventory*
- *Over-processing*
- *Motion*

Other important objectives of this manufacturing philosophy are the increase on flexibility and quality of the studied systems, and shorten the delivery time (Cagliano *et al.*, 2004), making organisations more active and able to resist strong changes in the market.

2.1.2. Robustness and agility

The environment in which manufacturing organizations operate is constantly changing, with the decline in product life cycles, the increased demand for product quality and the increase in product diversity (Cho, 1996). For manufacturing organisations to prosper they need to have production systems that can remain working, on a stable and high-performance level, even with hindrances affecting that system being, therefore, *robust* (Bellgran *et al.*, 2004). There is therefore a need for organisations to have systems that can quickly and inexpensively develop and adapt to new products and requirements in order to remain competitive in the ever-changing environment and thus being *agile* (Cho, 1996). *Agility* is, therefore, the set of characteristics of an organisation that allows it to quickly rearrange itself and remain competitive in the face of new demands.

2.1.3. Competitive Advantage

Therefore, for an organisation to prosper in a competitive environment, it needs to be able to have characteristics that distinguish it from other competitors in the market, and at the same time allow them to perform better. Such features may constitute a *competitive advantage* for the organisation. This concept is related with the *Resource Based View* (Barney, 1991) in which it is described that an organisation obtains a competitive advantage when it has one or more resources that are *VRIN*, meaning *Valuable, Rare, Inimitable* and *Non-substitutable,* allowing it to outperform its competitors.

In the manufacturing context are characteristics of systems that are able to perform better than their competitors in a wide variety of scenarios, which can constitute a competitive advantage that can be exploited for the managerial team better enhance the organisation chances of surviving in a constantly changing environment.

2.2. Manufacturing process systems

To allow a better understanding of the different manufacturing processes, the most common production processes are described, according to the different needs of the organisations. These data are described in Figure 2.1. and Table 2.1, below:

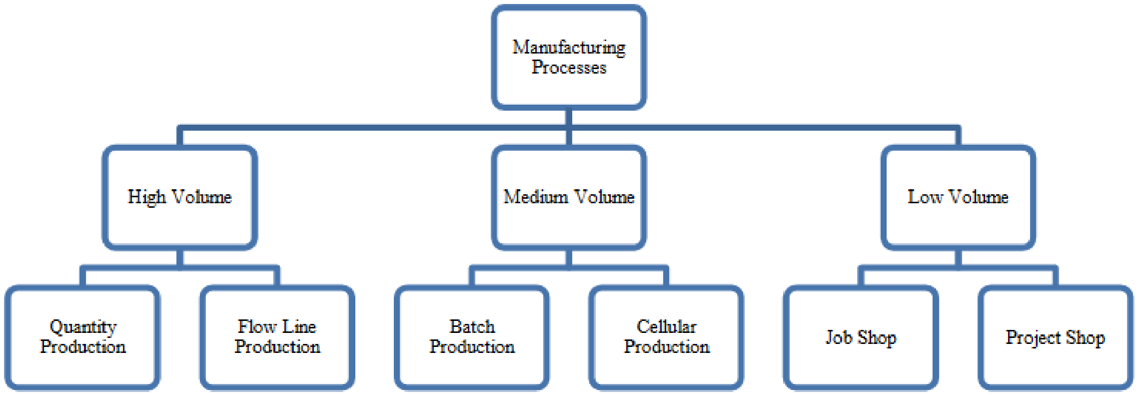

Figure 2.1. Decomposition of manufacturing processes (Mohamed, 2013)

The manufacturing processes can be classified into three categories, high, medium, and low-volume processes. The high-volume manufacturing process, also known as mass production, is a type of process that involves the production of high quantities of product, being only produced a small range of products, decreasing the variability and complexity of the process. This type of process is associated with long assembly lines (Koren, 2017). The low-volume manufacturing processes are normally used for low quantity of specialised, complex, and customised products (Bellgran *et al.* and Aresu, 2003), and requires a highly skilled labour force and maximum flexibility in order to cater for product variations (Synnes, 2016).

The medium-volume manufacturing process comprehends every manufacturing process in between of the high and low volume manufacturing processes being more closely related to the manufacturing conditions of this business project, so this topic will be developed further. It has two different variants, depending on the product variety, being these *Cellular Manufacturing* and *Batch Production*.

Table 2.1. Typical characteristics of process choices (Mohamed, 2013)

	Low Volume		**Medium Volume**		**High Volume**	
Manufacturing aspects	**Project**	**Jobbing**	**Batch**	**Cellular**	**Line**	**Continuous**
Nature of the process technology	Orientated towards general purpose	Universal	Dedicated	Dedicated	Dedicated	Highly dedicated
Process flexibility	High	High	Low	Low	Low	Inflexible
Production volumes	Low	Low	High	High	High	Very high
Changes in capacity	Incremental	Incremental	Stepped change	Stepped change	Stepped change	New facility
Key manufacturing task	To meet specs/ delivery schedules	To meet spec/ delivery schedules	Low cost production	Low cost production	Low cost production	Low cost production

Cellular Manufacturing – This manufacturing process is used when there is a very small degree of variation between the produced products, allowing machinery and equipment to be easily grouped into functional cells that can be optimized as a whole and increasing the overall efficiency of the system (Drira *et al.*, 2007). Each cell is constituted by one to several machines and equipment that compose one to several workstations that perform a certain set of operations. This type of manufacturing process focusses predominantly in allowing a continuous flow of work-in-progress items without having to wait between operations (Panchalavarapu and Chankong, 2005).

Batch Production – This manufacturing process is used when there is some degree of variety of different products, being produced on that manufacturing line, but in smaller quantities (Kalpakjian and Schmid, 2006). Once a batch of products is finished, the manufacturing system is changed over to produce another batch of different products (Floudas and Lin, 2004). In this type of production process, the machinery and equipment in each workstation is shared between the different batches, leading to loss of production time due to the set-up times during the changeover process and due to scheduling processes (Mohamed, 2013). In this type of manufacturing process, the machinery and equipment are grouped by function, and not by product (Drira *et al.*, 2007), allowing the production of a wide variety of products, in the production facility.

The next step for medium volume manufacturing processes would be the *Flexible Manufacturing System*. For this type of process different computer mechanisms associated to Computer Numerically Controlled Systems would be integrated, which would allow the total control of the production lines, thus enabling a better use of the production times, as well as producing several products simultaneously on the same line (Kumar and Sridharan, 2009 and

Mohamed, 2013). Tools such as these would allow the production system to be much more flexible in the face of market needs, responding to market changes more quickly and efficiently, necessary for the current global demand (Sujono and Lashkari, 2007).

2.2.1. Assembly line

Assembly lines are described as flow-oriented production systems that are still typical in the industrial production of high quantity standardized commodities and low volume production of customized products (Scholl, 2006). According to Maqsood *et al.* (2011), an assembly line is composed by some workstations that consistently perform certain operations on a workpiece in a cycle time (maximum or average time available for each work cycle). This type of systems is present in all manufacturing processes mentioned and is of high importance for the success of the production process.

2.2.2. Operation System

Nevertheless, it is necessary to define what is an operation system. Based on the definition of Wild (2002), is “a configuration of resources combined for the provision of goods or services”, being this type of systems normally a mix between *designed physical systems* – as for example a fully automated manufacturing line – and *human activity systems* – as for example a healthcare delivery system. There are four specific functions identified for operating systems: *manufacture*, *transport*, *supply,* and *service*. These types of systems encompass manufacturing systems, thus covering the processes described in this Section.

2.3. Manufacturing system design

“Here’s the simple truth: you can’t innovate on products without first innovating the way you build them.” - Alex Schleifer, Airbnb

For an organisation become a World Class Manufacturer, manufacturing systems must be adapted to the types of products produced, this being a key point in defining the future performance of the system, and consequently of the organisation.

According to Drira *et al.* (2007) *design* is “an arrangement of everything needed for production of goods or delivery of services”, being the system layout process divided into design, implementation, growth, maturity, and obsolescence phases (Raman *et al.*, 2009b). This design process of a system allows the identification of problems, objectives and outlining problem-solving methodologies and decision-making processes.

2.3.1. Redo or adapt?

For an existing production system there are two approaches that can be followed (Slack *et al.*, 1998): *planning and control* the existing production system or *designing a new one*. The planning and control approach is related with the day-to-day operations, being this approach important on allowing the normal operations of an organisation, but at the same time the organisation itself becomes limited by the system it uses, but these limitations can however be eliminated from the system by creating a new one (Bennett and Forrester, 1993).

2.3.2. Robust Design Methodology

Manufacturing systems that are robust and agile may have a competitive advantage in their markets although, to achieve such an advantage is necessary that they are designed, considering the purpose they may serve. The *Robust Design Methodology*, is described by Bellgran *et al.* (2004) as a process and product design, being in this phase that the capabilities of the manufacturing system are largely defined**.**

This design process is based on the core activities and the manufacturing concept of the organisation; and is the result of the conceptualization of the needs of the organisation, aiming to their main objectives (Belgrann *et al.*, 2004). Either the improvement of an existing system, or creating a new one, the goal must be the creation of a robust system, that is able to perform at high levels even in adverse conditions. By designing a manufacturing system without considering their robustness and agility as key characteristics has led to (Bellgran *et al.*, 2004):

- Production disturbances.
- Maintenance problems.
- Capacity change.
- Work and organisation changes

All these situations can affect the quality of the final product, lead to increases in production costs, and decrease the capacity of the system to withstand product diversity. On the other hand, by aiming the robustness of the system as a key characteristic – aiming to create a system that can handle internal and external variations on their operations without losing efficiency, flexibility and speed (Bellgran *et al.*, 2004) – positively influences the product quality, decreasing the time-to-market, time-to-customer, and production costs.

2.4. Study of methods and times

An important element in evaluating the efficiency of a system of operations is the collection of data relating to this system. A set of good practices should be undertaken to subdivide larger operations systems into simpler systems capable of being studied, as well as the methods for collecting the times associated with each of the operations in the systems should be detailed. By following a set of rules and good practices in choosing the systems to be studied, and in collecting the times associated with each of the operations of those systems, it is possible to obtain viable information that can be used and processed to infer conclusions about the systems.

2.4.1. Time study

According to Barnes (1980), *time study* is the analysis of a job for the purpose of determining the time that should take a qualified person, to perform an operation, using a definite and prescribed method, being this time the standard time for the operation analysed. Such studies must be carried out in order to determine the standard times associated with an operation, and thus be able to define the normal rhythm of work.

By designing a correct picture of what the normal rhythm of work is, and consequently of the normal productive capacity for a system, the management team is able to conduct a better production planning, production control, and cost control. (Barnes, 1980). By conducting these studies frequently, it is possible to assess how the performance of the system is changing over time, and how it can increase, being an excellent tool for monitoring and control.

Following Barnes (1980) studies, the *time study procedure* can be summarised in eight phases:

1. Contact the foreman: At the manufacturing facility the time study analyst should contact the foreman in order to show the analyst the place of work and verify if the operation is being performed correctly.

2. Inform the operator: When studying operations that are performed by human workers these should informed. Under no circumstances an operator should be studied if he/she is unwilling to cooperate or is unexperienced on the job.

3. Check the operation method: Adequate the study type method for the operation to be analysed.

4. Obtain all necessary information: All information about the job, machines, and materials should be obtained prior to the time study begins. A draft of the layout should be made, detailing the location of the operators, materials, tools, and other relevant information about the manufacturing lines.

5. Divide the operations into elements: The overall operation should be divided into smaller operations or elements as short in duration as can be accurately timed,

6. Record the time: All foreign elements to the operations process should be detailed for previous evaluations. Should be considered the start and end date of the time study, since operations are flexible on time being determined that during that period the operation was performing in a specific manner.

7. Rate operator's performance: To evaluate the performance of the operator there should be created a scale in which a *normal* operator with no wage incentive would have the classification of 100 points. It is expected that some operators perform better than others. A meticulous description of this concept is detailed ahead. (*vide* Section 2.4.1.1.)

8. Definition of Allowances: Definition of allowances for the times obtained in order to allow the correct determination of the operation time (*vide* Section 2.4.1.2.)

2.4.1.1. Rating

As identified by Barnes (1980), one of the most complex parts of the study of times corresponds to the definition of what rating is. It is known that there are differences in the pace at which people work naturally, so a standard rating should be identified to allow comparisons between different operators. In the same way, this type of rating should also be used in the different equipment that is used in the various operations, so that it can be assessed whether the performance of an equipment is within the expected limits, or whether it is below, or above it.

According to this author rating is the comparison between the observed times and the times that the author considers normal for that work, and a discount or overvaluation factor should be applied to the times obtained in order to equate them to the times that would be expected to be obtained. To allow a correct evaluation of the system a scale must be created to assess the operators, where the value of 100 would correspond to the normal value of an operator.

To determine the normal time of the operation the observed time must be multiplied by the rating factor. In Equation 2.1 the method of calculation of Normal Time is demonstrated for an operator whose observed time for an operation is 10 seconds, and who had a Rating Factor of 110%.

$$Normal\ Time = 10 \times \frac{110}{100} \leftrightarrows Normal\ Time = 11 \qquad (2.1)$$

According to the example given by Equation 2.1, the operator studied with a Rating Factor of 110% is faster than expected, so more time should be given to another operator to perform the operation.

2.4.1.2. Clock Time allowances

According to Barnes (1980), operators will not work all the time without any interruption. In this way the operator will be able to take some time off for personal needs, rest, or other reasons beyond his control. These allowances can be divided into:

1. Personal Allowance: This type of allowance is related to the personal needs of the operator. It varies depending on the type of work to be done, being about 2 to 5% of the total working time (for lighter jobs) and may be more than 5% in case the work requires greater physical or psychological effort, or in case the working conditions are not favourable to the operator (such as high temperature and humidity in the workplace).

2. Fatigue Allowance: This type of allowance corresponds to that which has been constantly minimised and controlled in order to increase the working capacity of operators. Reductions in the number of working hours per day and also in the number of working days per week have made it possible to drastically reduce fatigue levels, thus making this allowance obsolete. In addition, minimising accidents at work significantly reduces the stress associated with it, thereby reducing

fatigue. There is no viable way to check the time needed for a worker to rest, as it depends on different conditions that are difficult to test and proves, however a common practice is the determination of break periods throughout the day, which can go from 5 to 15 minutes (commonly). This type of allowance does not need to be applied to light factory work as the existing breaks have been proven to be sufficient for the worker to rest, avoiding this type of fatigue.

3. Delay Allowance: For this type of allowance we are considering the times when a delay in operation occurs for uncontrolled motives, rather than voluntary reasons by the operator. The delays that the operator intentionally makes are not considered when determining the operating times, however any delay caused by a breakdown in an equipment, or shortage of components must be considered in order to be able to quantify what percentage of the operating time is being consumed in non-productive time.

To apply the allowances, the percentage allowance determined should be added to Standard Time (*vide* Section 2.4.1.1). Equation 2.2. describes an example of the calculation of this parameter considering a Standard Time of 11 seconds for an operation and a Personal Allowance of 5%.

$$Standard\ Time = 11 + (11 \times 5\%) \leftrightarrows Standard\ Time = 11.55 \quad (2.2)$$

2.4.1.3. Determining the number of samples

According to Barnes (1980), the number of samples to be taken should be estimated according to the Confidence Level and the Precision intended for the study in question. The Confidence Level corresponds to the percentage of the elements of a sample that correctly represent the characteristics of a given population (Dekking, 2005). Precision refers to how close estimates from different samples are to each other (Precision, n.d.).

As such, the following equation is listed, which makes it possible to check whether the number of samples taken is in line with the specific features of the study carried out.

$$N' = \left(\frac{Y\sqrt{N\sum X^2 - (\sum X)^2}}{\sum X}\right)^2 \quad (2.3)$$

In Equation 2.3. *N'* represents the minimum number of samples, *N* represents the actual number of samples obtained and *X* represents the value recorded on the observations for an operation. For a Confidence Level of 95% with a Precision of ±10% Y should be equal to 20, whereas for a level of Precision of ±5% Y should be increased to 40. The specifications of the formula will not be detailed here, as they are not directly part of the scope of the project. Its most common uses involve the use of a Precision level of ±5% or ±10% and a Confidence Level of 95%.

2.4.1.4. Time Study – Final Remarks

As described by Barnes (1980) time study is used to measure work, being the result of this process the time that a person or equipment is suited to a specific job. Some commonly study methods are *Stopwatch*, *Motion Picture,* and *Electronic Times*.

2.4.2. Work study

Work study is divided into two methods (Work Measurement Techniques, n.d.) The first one is related with the simplification of the job and determine a more ergonomic way of executing the job, whereas the second one is related with the work measurements, used to determine the time required to develop an operation.

One of the most common methods to measure work in the industry is the stopwatch time study. This method is part of the work measurements methods and allows the determination of the time an operator takes to complete an operation, being this operator considered to work at a normal pace (Work Measurement Techniques, n.d.). From the time of the development of this method by Frederick Taylor in 1881, the method did not change considerably, although there was replaced the analogical stopwatch with digital stopwatches, computers, and barcodes, improving the time count process.

There are two methods of timing using a stopwatch approach (Work Measurement Techniques, n.d.):

Fly back method: The stopwatch is started at the beginning of the first element, and as soon as the operation for that object is concluded, then the stopwatch is set to zero, being the elapsed time recorded.

Continuous method: The stopwatch is started at the beginning of the first element, being the watch ran continuously during the study. When an object is processed by some operation then the time that is presented on the stopwatch is recorded. The times that each operation takes is then calculated by subtracting the total time to the last time registered, doing this process sequentially.

2.4.3. Innovations on the field

Although the studies described by Barnes (1980) are still quite up-to-date, the methods used to collect times of operations and segment the steps that compose the operations into smaller activities in which times can be studied have been a field of great innovation. Technological advances have been integrated into the business environment, such as the use of the software *Tecnomatix Motion Capture* by Siemens (Siemens, n.d.) in the capture of images of operators performing their functions, thus allowing the construction of a virtual model of the movements, and the consequent collection of the times of each of the operations. The use of Motion Capture and Virtual Reality techniques allows the movements mapping of an operator, creating a real-time model of human activities. By coupling motion capture technology with human modelling, it is possible to interact directly with the virtual environment, and thus design systems that are suitable for the work to be performed.

As described by Siemens, human modelling and simulation enables increased safety, efficiency, and comfort in the workplace. By considering the operator as the centre of the operation to be performed, one can create an environment more appropriate for the work to be performed, and at the same time analyse its performance. With the use of this type of software and techniques can also be created models appropriate to the age and characteristic of a population, allowing a more ethical, correct, and efficient use of existing human assets.

2.5. Performance Evaluation

"To win in the marketplace you must first win in the workplace."

Douglas Conant – Former CEO Campbell Soup Company

To enable the correct evaluation of operations systems it is first necessary to define what we understand by "evaluating the performance" of these systems and how can one evaluate it. In this way, and based on the researched literature, it will be possible to determine a set of parameters to be used to evaluate the performance of the systems to be studied in this business project, and how they should be used.

2.5.1. Performance: a literature overview

Performance measurements is defined as the process of quantifying the efficiency and effectiveness of an action (Tangen, 2003). Different authors consider different aspects for what performance should be looked at and what factors should be considered to improve the efficiency of a system. Some conclusions based on the reviewed literature are described in Table 2.2. below.

Table 2.2. *Concept review on what aspects should be considered when evaluation the performance of a manufacturing system.*

Author	*Article*	*Concept*
Slack (2001)	Slack, N. (2001). *Operations Management* (2nd ed.), London: Pearson Education.	Performance objectives should be based on cost, flexibility, speed, dependability, and quality
Tangen (2002)	Tangen, S. (2002). A theoretical foundation for productivity measurement and improvement of automatic assembly systems. *Licentiate Thesis, The Royal Institute of Technology, Stockholm*.	Performance measure criteria must be driven by strategic objectives and the measurements must provide timely feedback
Goldratt & Cox (1986)	Goldratt, E.M. and Cox, J. (1986). *The Goal* (3rd ed.), North River Press.	The goal of a factory is to make money, and there are three important measures, being the throughput, inventory and operation expenses, being all these measured as monetary units - the first should be maximized whereas the last two should be minimized

Desrochers (1990)	Desrochers, A.A. (1990) *Modeling and Control of Automated Manufacturing Systems*, Washington, DC: IEEE Computer Society Press.	The objectives of a factory should be: - Minimized total time required to complete all jobs; - Minimized set-up costs; - Meeting the due date; Minimized mean flow time; - Minimized machine idle time; - Minimized mean number of jobs in the system; - Minimized percentage of jobs lateness; - Minimized mean lateness of jobs; - Minimized mean queue time.

The topic of performance measurement and evaluation is of great interest to organisations. It is also a subject of great debate about which should be the focus of organisations to achieve a competitive advantage and thus a good performance (Tsou and Huang, 2010). The biggest challenge for the management teams of any company will be to identify the features of the systems that need to be improved in order to enhance their performance, as well as to define the priorities and weaknesses of the systems (Tseng, 2009).

2.5.2. How to evaluate performance

Gu *et al.* (2010) describes performance evaluation as a tool that provides feedback on the quality of an operational policy, and how to improve it. Three different approaches are identified for performance evaluation being:

Benchmarking: The process of constantly assessing the performance of a system, identifying inefficiencies and propose improvements. It is always done by comparing one system with another or with itself at a different time. It is considered to be a helpful tool in assessing the strengths and weaknesses of an organisation, being a strong and effective management tool for continuous improvement practices. There are different types of benchmarking methods, some of the more important, considering the scope of this master project are (Sekhar, 2010): *Performance benchmarking* - Comparing the organisation own performance with other organisations - *Process benchmarking* - Comparing methods and practices for performing processes – and *Internal benchmarking* - Comparing units and departments inside the same organisation.

Analytical Models: According to (Lin, 2018) the most common analytical models for performance evaluation of manufacturing systems are the *Queueing Theory* – that is concerned with the mathematical formulation, study and analysis of queues, allowing to analyse the requirements needed for that system to meet the desired goals (Peter, 2019) - and *Markov Chains* – which is a mathematical model that describes a sequence of events, in which each subsequent event is determined by the immediately previous one, based on stochastic behaviour (Gnagniuc, 2017).

Simulation: A simulation is a model, based on an existing system, that aims to correctly represent the original system. It creates virtual environments in which new scenarios can be created and tested and that is one of the most common techniques on manufacturing facilities to evaluate and predict performance (Jain, 2017). The components of simulations and their characteristics will be described in higher detail in the following chapters.

The following are some parameters and concepts described in the literature that allow the analysis of a manufacturing system, that can be used on the current business project.

2.5.2.1. Relative Efficiency

The concept of performance of a manufacturing line is normally associated with *relative efficiency* concept (Leachman, 2005), in which is based on the ratio of weighted outputs to weighted inputs. This concept is closely related with the concept of productivity that expresses the relationship between the quantity of goods and services produced (output) and the quantity of labour, capital, land, energy and other resources to produced it (input) (Smith, 2001).

2.5.2.2. Throughput

As described by Li (2009), *throughput* is the number of objects that leave the system, although due to randomness in production, such as breakdowns, causes this number to be modelled stochastically, therefore the *throughput* is the rate to which the objects are produced on a system. This variable greatly influences the performance of the system and should be analysed and evaluated based on their impact on the system.

2.5.2.3. Throughput bottleneck

A factor that greatly influences the performance of a system is the *throughput bottleneck*, which is defined as the workstation or machine that is most sensitive to the overall performance of a manufacturing system. As so, is a point in the system where it presents the most reduced capacity of the line, determining so the pace in which operations occur in that system. So, identification and control of bottlenecks in the system is a useful tool for performance evaluation and improvement.

2.5.2.4. Efficiency of utilisation

The *Assembly Line Balancing* (ALB) problem is a decision-making problem of grouping tasks required to assemble a product among set of workstations with respect to some constrains and objective (Khlil, 2020). It can be classified as *Simple* – when the assembly line only processes one type of product at a time - or *General* – when the assembly line processes more than one type of product at a time - *Assembly Line Balancing* (SALB/GALB). Based on the scope of the master project there will only be analysed the SALB problem. As described by Khlil (2020), the heuristic method to solve the SALB problem is given by Equation 2.4. below:

$$\eta = \frac{\sum_{i=1}^{m} t_i}{c \times m} \tag{2.4}$$

The equation 2.4. presented allows to answer to the Simple Assembly Line Balancing (SALB) problem, focused on determining the Efficiency of Utilisation (η) of the system. t_i corresponds to the sum of the cycle times of each workstation, from 1 to m; c corresponds to the maximum cycle-time verified in the system; and m corresponds to the total number of workstations in the system.

This equation allows to evaluate how the system is behaving in terms of time utilisation identifying the workstations in the line where the manufacturing capacity is lower, denoting which areas should be improved and determining the total throughput pace of the system. Lower values for η indicate that the line is poorly balanced and therefore the objects in the system may be waiting longer times in queues, whereas when η is 100% then all operations are perfectly synchronized and no queue is expected to occur.

2.6. Simulation

"... in real life mistakes are likely to be irrevocable. Computer simulation, however, makes it economically practical to make mistakes on purpose. If you are astute, therefore, you can learn much more than they cost. Furthermore, if you are at all discreet, no one but you need ever know you made a mistake."

John H. Mcleod – Computer Scientist

As previously described, a simulation is a model, that aims to correctly represent the original system by creating a virtual environment in which the existent scenarios can be replicated with a high confidence, and in which new scenarios can be tested, being that this tool is used for the evaluation of the performance of a system (*vide* Section 2.6.). Operations systems, such as the one studied in this business case, are among the most capable of being modulated and studied through the use of simulation techniques.

2.6.1. Simulation

As described previously, an operating system is a configuration of resources combined for the provision of goods or services (Wild, 2002), being manufacturing plants examples of operating systems. Simulation allows a better understanding of how such a system is designed and its functionalities, identifying opportunities for improvements and threats to the system.

It is a modelling technique that allows the evaluation of an operating system prior to its implementation being so a managerial tool for the evaluation of changes in the manufacturing design. A simulation is described by Robinson (2004) as an imitation, in a computer environment, of a system as it progresses through time. These techniques allow a simplification of the reality, focusing on central aspects of it, and allowing a strong what-if analysis tool for managerial and operational decision making.

2.6.2. System evaluation models

Different models can be used to evaluate a system of operations. Pidd (2003) advocates that simulation models do not need to be as detailed as the reality itself, due to constraints related with data collection, data analysis, and computer power needed; or due to being unnecessary to evaluate with such detail some types of systems. Therefore, simulations should be as simple as possible.

Other models such as linear programming or heuristic methods, provide optimal and near optimum solutions to the problems, respectively, although these methods can only examine one scenario, identifying which features of that scenario should be improved. Simulation on the other hand allows the creation of a virtual environment, based on the inputs collected from the original system, that evaluates the performance of an operating system under a specific set of inputs. These inputs can be changed based on the observed results and can be tested comparing different results to different scenarios created. Simulation is so a very powerful "what-if analysis tool" in which the user adjusts the scenario, and the scenario predicts the result based on stochastic and statistical methods. Thus, simulation is "an experimenting approach to modelling" and should not be seen as a decision-making tool, but as a decision-supporting tool – supporting decision making instead of making decisions (Robinson, 2004).

Simulation is considered a best approach (Pidd, 1998) when studying operation systems when compared with other methods:

Experimentation with the real system: Instead of developing a simulation model, experiments could be done in the original system. Using such an approach reveals some reasons why simulation is preferable than direct experimentation. The experimentation with the real system leads to an increase in costs by using different resources, equipment and man power; is a time consuming process, whereas simulation is relatively fast process, and results can be obtained over a very long period of time; also, simulation models allow a better control of the experimental conditions since this system is not subjected to external factors, and stochastic variables can be analysed too.

Other modelling approaches: As it was detailed, simulation allows the modelling of variability and its effects, for example by introducing a stochastic parameter in an analysed variable, whereas other type of methods, can't without increasing drastically the complexity of the model. If the studied system is subjected to a high degree of variability other modelling approaches become obsolete when comparing with simulation. Also, simulation requires very little to no assumptions, although some are used to simplify the model; in other models such as the *Queuing Theory* some assumptions are required for the elaboration of the system, like distributions for arrivals and service times, which increase the complexity of the system. Also transparency is an important factor on evaluating the system "A manager faced with a set of mathematical equations or a large spreadsheet may struggle to understand (…) the results from the model" (Pidd, 1998), being the simulation a more appealing way to show the results.

2.6.3. Advantages of simulation

By adopting the use of simulation techniques on a managerial level it has been shown that it would (Robinson, 2004):

- *Fostering creativity* - With simulation techniques ideas can be tried free of risk, encouraging different perspectives and new problem tackling perspectives.

- *Knowledge creation and understanding* - By designing the simulation models there occurs a deep study and understanding of each of the constituents of the system.

- *Visualisation and Communication* - Allows the demonstration of the benefits of ideas and problem-solving methodologies to the managerial team. Visual simulations are powerful communication tools.

2.6.4. Modelling the progress of time

The most used simulation software, besides being built in an extremely intuitive way, also have an enormous power capacity and allow great variability, which prevents the user from having to resort to changes in the underlying code to be able to define a system in the virtual environment. Two methods (Robinson, 2004) to model how the virtual environment reacts to the passage of time are described, these being the most used methods in different simulation software:

- *The time slicing approach:* For this approach, a constant time interval is defined in which the system will check the scenario, reporting the situation in which it finds itself, and this time interval can be regulated to approach the specifics needed for the evaluation. In this way, all the scenarios obtained with a certain time interval will be detailed in the evaluation output and thus describing their behaviour over time. This model is quite inefficient, since during many of the time intervals there may not be any changes in the system, and as such would lead to a waste of computational power and all changes of great importance in the system may not be detailed since the time interval may not be defined according to the needs of the scenario to be studied.

- *The discrete*-event simulation. In this method is only represented the point in time at which the system changes, being represented the system as a series of points, marked in a temporal frame in which occurs a change in the system. This type of time modelling is widely used by commercial software being one of the best time modelling approaches available. This method is considerably better than the time-slicing approach, that pictures an image of the system at every fixed variation of time, being rather inefficient and generating high quantities of data that may not be used due to no change had occurred in during that time frame or missing some intermediate changes that occurred in the system in between the *slices times*.

2.6.5. Modelling the events

Inside the simulation environment there are classified two types of events:

- *Bounded (B) events:* These are events that cause a change in the system and that are programmed to occur after a certain amount of time, being these events bounded by time in a fixed or variable manner.

- *Conditional (C) events:* These are events that cause a change in the system and that are dependent to occur upon a certain set of conditions. The discrete-event simulation follows a three-phase model (Robinson, 2004) – A, B and C phases –. In A-phase, known as the simulation executive, there is determined the time in which will occur the next event, advancing the simulation time to the next event. In the B-phase, all *B events* of that clock-time are executed. In the C-phase, all *C-events* are attempted, and if the required conditions are met then these events are executed. After all the events for that simulation time are executed then the simulation returns to A-phase. This process is described in Figure 2.2 below:

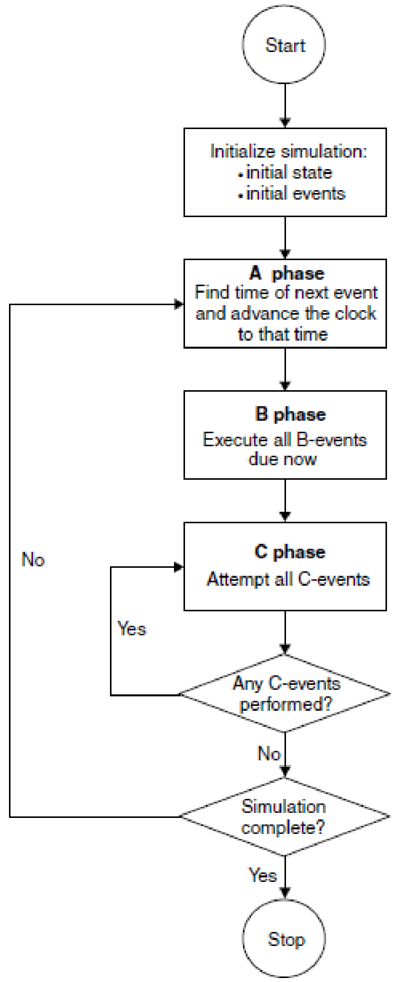

Figure 2.2. The three-phase simulation approach (Robinson, 2004).

2.6.6. Performance assessment: Empirical Findings

Previous research has been conducting on how simulation can be used to evaluate the performance of a manufacturing system, resulting in interesting findings that highlight some directions when applying theoretical knowledge into case studies.

Mean life-time - meaning the total time a product is in the system - *Throughput* - meaning the total number of objects that leave a manufacturing system - and *Throughput per hour* - meaning the total number of objects that leave a manufacturing system during the time period of one hour of production - are pointed out as variables to be considered when analysing manufacturing lines using simulation, as assessed by Jurczyk-Bunkowska (2019).

Mean Time Between Failures (MTBF) and *Mean Time to Repair* (MTTR) are metrics considered on the evaluation of a system performance by Pacheco (2014). These metrics correspond to the arithmetic mean of the times between any type of failure specific for a machine or workstation – for MTBF – and the arithmetic mean of the times of repair of a system – for MTTR.

Availability (Pacheco, 2014) is a parameter that evaluates the proportion of time that an equipment is in operation, performing the function to which was intended. The equation for this parameter is given by Equation 2.5 below:

$$\boldsymbol{A} = \frac{MTBF}{MTBF + MTTR} \tag{2.5}$$

In Equation 2.5. is specified the calculation of Availability (A), MTBF corresponding to Mean Time Between Failure and MTTR corresponding to Mean Time to Repair.

Other metrics described by Jurczyk-Bunkowska (2019) were used on the evaluation of manufacturing systems regarding to the utilization of simulation. These parameters are summarized in Table 2.3.

Table 2.3. *Parameters considered in the analysis of a manufacturing line recurring to computer simulations.*

Parameters	***Meaning***
Working time	Percentage of time that the workstation is working normally
Set-up time	Percentage of time that the workstation is stopped due to be occurring the set-up of a new batch production
Waiting time	Percentage of time that the workstation is waiting for an input to perform its operation
Stopped time	Percentage of time that the workstation is stopped due to a malfunction or breakdown in the workstation
Operation Duration	The average time it takes for an operation to be performed.

According to Li (2018), the mitigation of throughput bottlenecks allows the increase of the performance of the system since it is increased the capacity on the slowest operation of it. Normally the parameters in the manufacturing line that are adjusted to increase performance are the *machine repair time* and *cycle-time*. Since cycle-times are difficult to adjust in automated and *quasi-automated* manufacturing lines, focusing on the reduction of downtimes may lead to an increase in performance.

The concept of *Efficiency Utilisation* described in Section 2.5 and formulated by Equation 2.4. is described in the literature as a mean to evaluate the overall efficiency of the system, in terms of time use, identifying which workstations have the longer cycle-times, therefore determining which of these workstations can be bottlenecks of the system.

Besides verifying if the workstations are bottlenecks of the system there should also be analysed the queue size that precedes each workstation to confirm the assumption.

3. Conceptual Framework

A conceptual framework is a structure which the author believes can best explain the natural progression of the phenomenon to be studied (Adom, *et al.* 2018). It corresponds to the author's explanation of how the research problem should be explored, describing the relationship between the main concepts presented, showing how ideas and studies are related to each other (Adom, *et al.* 2018). Being the presented work a business project, the author does not intend to discover or characterize any gap in the already existing literature about this subject, but it intends to use the already published studies to propose a new operations framework to be used by the company allowing the development of the management team, providing them with new tools for analysing the company’s manufacturing operations.

3.1. Literature Review Summary

The integration of technologies in the business world, as well as the adoption of new techniques and functionalities is a vital characteristic of organisations to remain competitive and updated in the extremely volatile market environment.

Due to the environmental conditions, it is then necessary for companies to adopt lean strategies to increase their flexibility and efficiency by reducing all processes and activities that may be causing some type of waste and transforming these activities and processes into competitive advantages for the organisation (*vide* Section 2.1). Being that in the manufacturing sector, manufacturing excellence is required to constantly adapt and lead the market. Depending on the manufacturing system different requirements are needed to allow manufacturing excellence (*vide* Section 2.3).

Therefore, the systems of operations to be set up should be based on type of manufacturing process used and the final consumer needs and be sufficiently adaptable to be able to respond to possible sudden market variations. The design of these systems is a key process for defining the future performance of the operations system and consequently of the organisation. (*vide* Section 2.2 and Section 2.5).

In order to allow a correct collection and analysis of data regarding operation systems, the indications described by Barnes (1980) were followed, in which the popular methods for data collection and processing are described (*vide* Section 2.4.). Although many innovations are taking place in this field, the main methods for data collection remain quite similar to those initially described in Motion and Time Study (Barnes, 1980), and there have been significant changes in the way the technology is penetrating this area (*vide* Section 2.4.).

The correct evaluation of the performance of an operation system is a powerful tool that provides feedback to the management team on the quality of the analysed operations (Gu et al. 2010), being a strong tool to analyse it the simulation models (*vide* Section 2.6). The performance evaluation is linked to the definition of different metrics and parameters that allow the correct evaluation of the manufacturing system (*vide* Section 2.6). The evaluation of performance in a production system is bound to different parameters and metrics, Among the most common the Relative Efficiency and the Throughput per hour. The identification of Throughput Bottleneck is an essential step in the evaluation of production lines since it contributes greatly to the creation of waiting times (*vide* Section 2.6). Also, the Efficiency of Utilisation (Khlil, 2020), allows an indirect evaluation of the system according to size and quantity of queues that may arise.

By applying simulation techniques, it is possible to analyse the behaviour of an operations system before it is implemented in real life, creating a managerial tool to evaluate new system designs, as well as changes in the objects that go through those system. It also allows to characterize the system in much more detail since it allows to extend the time horizon of the experiment, allowing the test of conditions that normally would not occur, in a relatively fast way by testing a huge combination of different factors (*vide* Section 2.6).

3.2. Conceptual Framework

The main problem of this business project, and to which all Research Questions are related, is how to evaluate the performance of a manufacturing system, and how to do so with simulation techniques. As such, the concepts detailed in the previous chapter should be connected to allow answering all the Research Questions, enabling the reader to understand the theoretical connection of this project.

The market environment in the manufacturing sector is extremely competitive presenting a wide diversity of actors involved, and in which the demands of consumers, seeking a high degree of flexibility of products, leads to the need for organizations to be able to adapt quickly to changes in the market while maintaining the quality of their products and with high speed in their delivery (*vide* Section 2.1. and *Highly Competitive Market* on Figure 3.1.), this requires operation excellence (*vide* Section 2.3. and *Operation Excellence* on Figure 3.1.). It is also known that the success of organizations operating in this sector is related to the type of systems they use. For these organisations to succeed in the unstable environment, it is then necessary that these systems are able to withstand large variations in production capacity and also in the variability of their production (*vide System Design* on Figure 3.1.). Thus, there is the urge to constantly evaluate these systems so that they are in line with market needs (*vide System Evaluation* on Figure 3.1.). To carry out this evaluation it is first necessary to study these systems. To do so, the application of the Motion and Times Studies (*vide* Section 2.4. and *System Study* on Figure 3.1.) is required to correctly subdivide the operations of each system, analysing each one individually, and correctly determine the times that reflect their behaviour. With this type of studies a foundation is created for future studies in the same systems, and it is possible to collect important data regarding their behaviour that can be compared with other systems, or with the same system in different periods of time.

With the data collected and analysed using the methods described by Barnes (1980) it is possible to draw conclusions about the behaviour of the system. However, these data can be used to produce simulations (*vide Simulation Production* on Figure 3.1.). For that, based on the real systems, it is possible to create a replica in a virtual environment, which intends to mimic the real system, studying not only its characteristics but also possible changes (*vide* Section 2.6.). Based on the revised literature, some indicators were determined that can be used to evaluate the performance of the system (*vide* Section 2.5.2. and Section 2.6.6.).

Such tools, supported by existing and revised literature, allow the analysis of the production systems that are part of the scope of this project and as such infer the evaluation of its performance.

The process is detailed in further sections of this business project and the conceptual framework is presented on *Figure 3.1*.

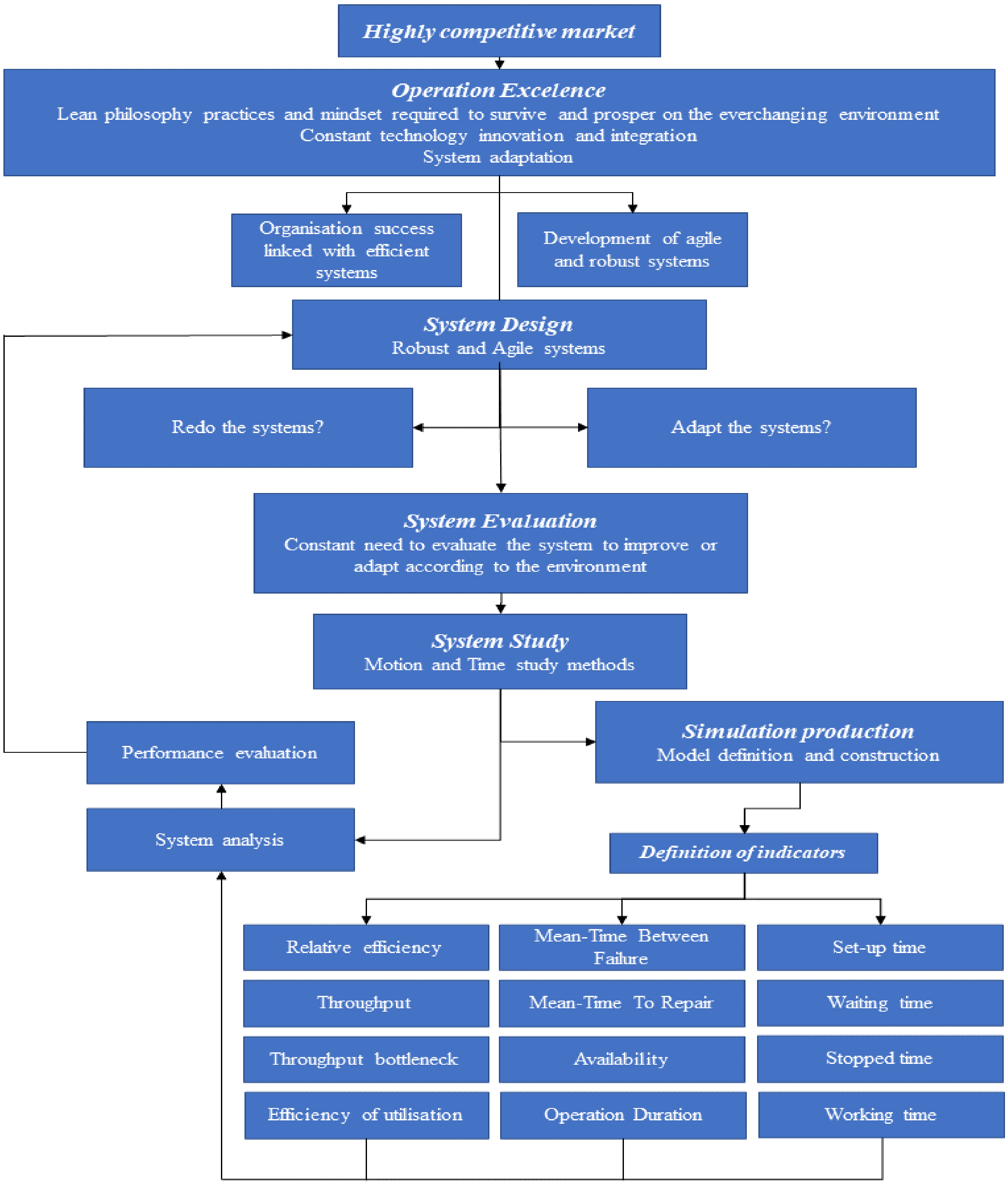

Figure 3.1. Conceptual Framework

4. Methodology

As previously mentioned, this business project aims to determine the efficiency of different assembly lines, characterizing them for a set of product mixes of utmost interest to the Company. It is expected with this project to enable the company with the knowledge and techniques needed to create a managerial tool that can be scaled to other segments of operations, in order to develop a virtual map of production and assembly lines of the Company. All the actions taken, methods and strategies used to collect the information that will be used to develop the project will be presented and explored in this Chapter.

4.1. Methodological General Issues

Robson (2011) states that a case study is a strategy for doing research involving an empirical investigation of a phenomenon within the real-life context using multiple sources of evidence. Yin (2003) distinguishes the cases according to their type, being these single or multiple cases. What distinguishes both types are precisely the number of cases under analysis. Yin (2003) argues that Case Studies should be used to find an answer to research questions (*vide* Section 1.5.) when these are in the form of a "How?" or "Why?" question. Also, when the research questions are formulated in the form of a "What" question, the development of an Exploratory Case Study can be carried out (Yin, 2003). The objective of a descriptive study is to portray an accurate profile of persons events or situations (Robson, 2011).

Considering the research questions defined previously (*vide* Section 1.5.), it is verified that the project to be developed can be integrated into an Explanatory or Exploratory Case Study (Yin, 2003), and a large amount of data is collected and analysed in order to explore the topic of this project, and these data are obtained through observation at the production site. In the context of the development of this business project only one production segment of only one organisation was studied, being a single case study type, as such, the generalisation of results may not be possible due to the small sample, so that the results obtained from this methodology can be generalised for theoretical propositions, but not for populations (Yin, 2003).

The conceptual framework presented previously (*vide* Section 3.2) will be operationalized through discrete-event simulation. This process will create a model that represents the system observed in the Company, and which is validated according to a set of pre-defined practices.

For this project, a mixed strategy was used, in which elements of Business Project and also Case Study were combined. The project was developed in a business context and is therefore a Business Project, however it was still necessary to develop academic research work and produce results based on existing literature on the subject. Thus, the project sponsor is considered a case study within the academic area of this project. The need to use this approach allows for the collection and processing of data within a corporate environment presenting the results according to the expected outlook for a profit oriented organisation, and also allows for the study of the systems through an academic perspective, characterising it as a project for learning and applying the theoretical and practical knowledge described in literature

By combining the elements of both types of study methodologies it is then possible to analyse the systems in greater detail, allowing the spectrum of research methodology and the operationalization of theoretical models to be broadened, allowing conclusions to be drawn from two different theoretical bases.

4.2. Data Collection

4.2.1. Data Collection – General remarks

As previously mentioned, before beginning the internship in the Company, a meeting was held with the Operations & Efficiency Department Leader and with other colleagues involved in the production process, in which it was determined how the project would be developed (*vide* Section 1.2.). In this and subsequent meetings the manufacturing conditions in the segment identified by the company as an hindrance in the system were presented, and how these could be studied having the company allowed the author to circulate freely through the production areas in order to carry out the collection of data regarding the operations that were performed there.

Due to the nature of the project, it was not necessary to perform any type of Qualitative Data collection such as interviews or questionnaires, being only collected Quantitative Data, that can be furthermore described as Primary, since it was collected directly from observations on site. Information regarding the functioning of the manufacturing site and its specificities has been detailed to the author and has been used for the definition of the methodology and operationalization of the operational model. The data used to answer the Research Questions were obtained through structured observation techniques (Saunders, 2009).

4.2.2. Data collection on site

4.2.2.1. Timing of collection

The data collection period is distinctly defined in time, and the author had full support of the production manager to clarify all doubts about the process and also about the production schedules that would be carried out for each of the products on each line.

4.2.2.2. System subdivision

A layout design of the production area was carried out to analyse the system more effectively (Barnes, 1980). The production lines and their respective operations have been subdivided into simpler and smaller operations. These sub-operations are considered to be indivisible and for each one a unique workstation is associated.

4.2.2.3. Types of data collected

In order to build the model of the system observed in the simulator it is necessary to obtain the data concerning the duration of the operations. The time each operation took to process an object was collected.

In the presented project stopping times were also considered, being analysed three different types of stop-times:

- *Set-up stop-times*: These times comprise the totality of production time that is not being leveraged due to the operation has not started.
- *Shortage of components stop-times*: These times comprise the totality of the times that the manufacturing lines was not operational due to shortage of components for each of the workstations.

- *Repair times*: These times comprise the totality of time that the system was not operational due to a break-down on one or more workstations.

4.2.2.4. Collection methods

The production in the factory was a batch production type, so different types of products were produced on the same manufacturing line in batches with different sizes, according to the stipulated planning. As such, during the data collection period the production manager gave the scheduling of the production planned to the author, who would collect the data for that same day of production considering the types of products and the manufacturing lines to be studied. The scheduling for each of the lines was determined on the day before the production and could be changed on the day. Thus, the data collection process could not be pre-planned, therefore factors such as production hours and the days of the week when these occurred cannot be considered.

During the initial meetings it was defined that the author could move freely around the manufacturing site. Also, all operators in the production segment to be analysed were informed about the project to be undertaken and they consented to the presence of the author for the purpose of the project,

Before starting the data collection process, the author was informed about the number of operators participating in each of the operations, and it was defined how the variation in the number of operators influenced the performance of each operation.

The times taken for each object to be processed by a workstation were collected based on the *Fly back method* (*vide* Section 2.4.), being these times only collected by indication of the production manager. Data were collected regarding the different stops (*vide* Section 4.2.2.3) that occurred during the production process, and the types of stops and their durations were recorded, following the guidelines established by Barnes (1980) (*vide* Section 2.4.), being times recorded based on the *Fly back method*.

Rating and Allowances have been defined according to the characteristics of the system and according to the information provided by the production manager about the production teams.

4.2.2.5. Number of samples collected

It was assumed a Confidence Level of 95% with a 10% Precision would be acceptable in view of the revised literature (Barnes, 1980) *(vide* Section 2.4.1.3.). In order to obtain this Confidence Level and Precision, the formula described by Barnes (1980) (*vide* Section 2.4.1.3.) was used to calculate the number of samples to be taken, taking into account the data obtained.

Initially 40 samples of operating times were taken from the total population, for each type of product and for each of the manufacturing lines studied, which made it possible to create a population diversity that would make it capable of being analysed statistically, and to surpass the number of samples necessary to reach the predefined Confidence Level and Precision. If necessary, a second data collection would be performed to exceed the number of samples to be obtained to make the study statistically significant.

4.2.2.6. Data types

All data collected were categorized as Descriptive Data, being collected by observational means. The observation methods will be classified as Personal Observation methods, since the data were collected from an actual functioning manufacturing line as it is functioning on normal circumstances. It will also be classified as Structured, Undisguised and Natural Observation, since it was analysed according to a set of predefined parameters and predefined metrics, being the observants in the workstations aware that they are being observed and in a normal functioning manufacturing line.

4.2.2.7. Final considerations

All operators, as well as the management team, allowed the data to be collected having a positive attitude towards the work to be done.

Following the methodologies described by Barnes (1980) (*vide* Section 2.4.) it is possible to guarantee the veracity of the data collected by positioning them in the distinct temporal environment. Moreover, by ensuring that an appropriate subdivision of the system takes place, it makes it possible to increase the reliability of the data obtained. Lastly by defining a Confidence

Level and Precision for the project, it is then possible to determine the number of samples required to ensure the statistical reliability of the project.

The collection of the different types of data described above also allows the construction of a representative model of reality within the simulation environment which covers the main aspects of the system studied, thus being a proper representation of it.

4.3. Data Treatment

From the data collected, it was determined which statistical distribution fits best to the existing sample for each of the manufacturing lines and for each of the products studied. To do so the *EasyFit* (Mathwave, n.d.) software was used to perform the analysis of these data, being recommended by experts as a tool to assign a statistical distribution to a set of observations. The data obtained by the system study were imported into the software, and a set of statistical distributions were returned that were more suitable for the imported sample.

The Anderson-Darling method, already included in the software (Razali, 2011), was used to determine the statistical distribution to be used. This method makes it possible to determine a statistical distribution for a given initial sample and checks whether a given sample is related to different statistical distributions, giving a degree of confidence between the sample and the distribution. It considers that if the sample data has a certain distribution, then its Cumulative Distribution Function can be assumed to be a uniform distribution. The user can then choose which statistical distribution best suits his population, considering the degree of confidence obtained through the software, and also the different statistical distributions existing in the simulator software. Compared with other methods to select distributions from samples it was verified that the Anderson-Darling method is the most effective (Razali, 2011).

By providing the degree of fit between each of the samples and each of the different distributions available, the software makes it possible to rank them. Thus, the statistical distributions found by the software have been adapted based on the statistical distributions available in the *SIMUL8* software.

These data are therefore inputs that will feed the simulator and thus characterize and determine the performance of the system.

4.4. *SIMUL8* model production

In order to analyse the system observed in the Company by using computer simulation tools, a virtual model of it was defined in the *SIMUL8* software. According to the data collected at the production site it was possible to define a layout of the production site as well as its workstations and associated operations. A set of statistical parameters for each of these workstations was defined, which allowed modelling the behaviour of the different operations.

4.4.1. Workstation definition

The workstations were defined within the virtual system as described according to the data collection methodology and according to Barnes (1980) (*vide* Section 2.4). The path of the objects within the simulator was defined according to what has been observed at the production site of the Company.

4.4.2. Stochastic modelling

For each of the workstations defined within the virtual environment, the statistical distributions resulting from the data processing undertaken through the *EasyFit* software were associated. For each of the workstations defined in the simulator, a statistical distribution was added, and the respective parameters.

4.4.3. Characteristics definition

A set of assumptions for the modelling of the system was defined which allowed it to become more similar to reality. The assumptions to be defined are described in Table 4.1 below.

Table 4.1. *Assumptions defined on the simulation software SIMUL8.*

Assumption	***Definition***
Defective Product	Number of defective products per minute of operation for which operations had to be repeated.
Set-up stop times	Time taken to set-up the manufacturing line on the beginning of the production process
Components' shortage stop-times	The frequency of a workstation stoppage due to lack of resources., and associated time until resources refill
Breakdowns stop-times	Frequency of breakdown of a workstation and associated repair time

4.4.4. Scenarios definition

A scenario has been created for each of the manufacturing lines studied with the respective products, considering the procedures presented previously. For each one of the defined scenarios 5000 trials were carried out with a duration of 7.5 hours, allowing to replicate one day of production. In this way it is possible to minimise the number of outliers associated with the stochastic and non-deterministic behaviour of the model, leading to the generation of a large amount of data about each of the scenarios. The ranges between which the results were obtained were also defined and it is possible to guarantee that 95% of the results are within a well-defined range of values.

4.5. Results Analysis

Through the runs, it was possible to collect a huge amount of data for each of the defined scenarios, which were then manipulated and analysed.

4.5.1. Results from *SIMUL8*

From the *SIMUL8* software a set of data was extracted which allowed to analyse the system in more detail allowing to infer conclusions about it. The parameters and respective definitions are detailed below in Table 4.2.

Table 4.2. *Parameters retrieved from SIMUL8.*

Parameter	***Definition***
Waiting Time	Total time the system is down, and waiting for inputs to process
Working Time	Total time the system is processing objects
Stopped Time	Total time the system is down due to a malfunction
Mean Life Time	Average time that the objects, in each run, were inside the system. The time was counted from the moment they enter the system until they are completely processed by the last workstation
Queue Size	Average number of objects in a queue
Queueing Time	Average time an object remains in a queue

4.5.2. Results manipulation

The data obtained directly from *SIMUL8* were subject to a manipulation that allowed them to be converted into the indicators used to evaluate the system.

1. The average value obtained for the 5000 trials was calculated, and for each of the previously defined parameters the average value was used for subsequent calculations.

2. The values of the indicators described in Table 4.3. below have been calculated.

Table 4.3. *Parameters calculated based on the data retrieved from SIMUL8.*

Parameter	***Definition***
Average Throughput *per* hour	Average number of objects leaving the system per hour of production.
Waiting Time (%)	Percentage of total operation time when the system is down and waiting for inputs.
Working Time (%)	Percentage of total operation time the system is processing objects.
Stopped Time (%)	Percentage of total operation time the system is down due to a malfunction.
Availability	Percentage of total operation time in which the system is operational (*vide equation 2.5. on Section 2.6.6.*)
Average Queue Size	Average number of objects in a queue over all runs.
Average Queuing Time	Average time an object remains in a queue throughout all runs.
Relative Efficiency	Ratio of outputs to inputs on the system (*vide Section 2.5.2.1.*)
Efficiency of utilisation	Determines how well balanced is the manufacturing line, by comparing the slowest operation with the amount of time an object is expected to stay in the system (*vide Section 2.5.2.3*)
Mean-life time	Average time that the objects, in each run, were inside the system. Time counted from the moment they enter the system until they are completely processed by the last workstation, throughout all the races
Operation Duration	The time that takes for an operation to be completed. It can be calculated by dividing the total number of products that are processed by the system by the time it is operational.

4.5.3. Results analysis

From the results obtained from the *SIMUL8* software, the indicators and parameters presented in Table 4.3. (*vide* Section 4.5.2.) were calculated. The different studied systems were compared with each other based on the values obtained for the different indicators. Thus, by analysing the variations in the system before and after the changes and comparing the different lines with each other based on the indicators described above (*vide* Table 4.3. on Section 4.5.2.) it was possible to draw conclusions about the use of each of the parameters, and how the behaviour of these systems is changed with the modification of certain characteristics that are described by the indicators presented.

4.5.4 Model validation

As defined by Yin (2003), the methodology is composed of a set of characteristics and logical links, and as such can be logically evaluated. Some concepts allow identifying the validation of the model obtained. To evaluate the validity of the model using a Case Study we must:

4.5.4.1. Construct validity

In order to determine whether the study carried out has *construct validity* it is necessary to determine which characteristics we intend to study and how these are related to the objectives of the study. Then it is necessary to check whether the metrics found to analyse these systems reflect the changes in these characteristics. For this we must use multiple sources of information (when possible) and establish relationships between the different concepts.

A theoretical foundation was defined with the conceptual framework, linking all concepts to be connected and of utmost importance for the project, being aligned with its objectives. The parameters used to characterise the system and to analyse the results are in accordance with the revised literature and thus are a reliable element for system analysis. These metrics also make it possible to analyse the system in all the dimensions necessary to answer the proposed research questions, and they are adequate and sufficient to obtain reliable conclusions from the project developed.

4.5.4.2. Internal validity

This type of validation concerns causality relationships between concepts and characteristics, in which the author tries to identify if *x* caused *y*. This point depends on how detailed the procedures are, and how rigorously they have been carried out. The results of the study will only be satisfactory if all other explanations can be ruled out for *y* to happen. To this end, the patterns identified should be mapped out, explaining them, and ruling out other possible explanations for the behaviour verified using logic models (Yin, 2003).

The internal validity of the data collected and treated is also achieved by a pre-defined Confidence Level and Precision, appropriate to the type of study to be developed. This allows to guarantee that the inputs on which the simulator is built are in accordance with the observed system and that they allow to represent it with a certain reliability. By respecting the Confidence Level and the Precision defined initially, and having the data adjusted to this, it is then possible to obtain data representative of the system. In this way it is possible to conclude that the model built in SIMUL8, when fed by data that respect the defined statistical standards, is then also a correct representation of the system.

Once the model in *SIMUL8* is defined according to the characteristics observed in the system, and being still shaped stochastically, it is then possible to obtain results that are directly related with the data collected and capable of mimicking the variability associated with production systems.

All metrics and indicators were explicitly defined and based on the existent literature, and also the data collection process followed the guidelines used by Barnes (1980) (*vide* Section 2.4). Therefore, was possible to consider that the obtained results represent the reality of the studied system, and the relationships between each characteristic of it was characterized by the different parameters used. Thus, was considered the causality relationship between the studied parameters, being possible to link all elements logically.

4.5.4.3. External validity

This type of validation concerns the generalisation of the results obtained, and whether they can be generalised beyond the detailed case study. Case studies are directly linked to *analytical generalisations* (Yin, 2003), in which the author tries to generalise a set of results for the general population. However, the repetition of processes in other systems needs to be performed in order to sustain their validity for other environments.

External validity was confirmed by comparing the results obtained with those presented in the literature and thus confirming that they are in accordance with the conceptual findings. For this reason, these practices and theoretical results can be extrapolated to other similar systems.

The results obtained from this study can be used for populations and systems similar to those described in this report so that the conclusions can be directly extrapolated and inferred on other systems.

4.5.4.4. Reliability

The concept of *reliability* is that the author carried out the same procedures for data collection, processing and analysis as described in the literature, so that by repeating the same steps in the same system the same conclusions could have been reached.

The reliability of the methods used and the results obtained was verified by following the methods of data collection and analysis described in the existing literature, describing all the processes obtained and critically analysing the results according to the existing metrics.

In this way and having detailed all the steps in the process of carrying out this study, it is also possible to replicate the results obtained through this investigation by following the same methodologies described.

5.1. Operationalization of the conceptual model

This chapter aims to illustrate how the conceptual model defined previously (*vide* Section 3.2.) has been operationalised, by applying the methodologies detailed in Chapter 4. To this end, a Case Study approach is followed, in which the analysed system of the project sponsor is studied as if it were an academic project (*vide* Section 4.1.)

5.1.1. Manufacturing lines resources

The studied system consists of 5 workstations, connected to each other by a conveyor belt, which allows the transport of objects between the workstations. Operations A, B and E require the presence of operators, while operations C and D are completely automated, requiring only human intervention to regulate the flow of objects and for of materials.

The number of workers distributed in each analysed Workstation is described in Table 5.1 These data are valid for both the analysed manufacturing lines, and the data collected was based on this number of workers.

Table 5.1. *Workers distribution alongside the different workstations of the analysed manufacturing lines.*

	Workstation				
	A	*B*	*C*	*D*	*E*
Number of Workers	2 to 3	8 to 9	-	-	2

For the assembly of the different types of product it is mandatory to ensure that the basic components of the products are placed near the manufacturing lines at the start of the production process. The processes that allow the replenishment of this are not contemplated in the scope of this master project. Although, there is the need to consider the time these processes take place between production operations, as these times take place during the operations time, and as so consume useful production times.

5.1.2. Manufacturing line characteristics and product mix

The analysed manufacturing system is divided into 2 similar subsystems divided equally into 5 workstations (*vide* Figure 5.1 on Section 5.1.5) during the data collection period was witnessed the replacement of the machinery that composes workstation C on the ULMA line, henceforth referred as *Line 2*, by a new equipment that allows the production of all the product types. The replacement of this equipment caused the manufacturing line to behave differently, and as so it was studied as a separated manufacturing line, that is henceforth defined as *Line 2 – New Machine*. Thus, during the data collection period were studied 3 different manufacturing lines, that can produce the product types described in Table 5.2., namely *Line 1* (*SMIPACK*), *Line 2* (*ULMA*) and *Line 2 – New Machine* (*ULMA*)

Table 5.2. *Product mix produced by each manufacturing line.*

	Line 1	***Line 2***	***Line 2 - New machine***
M	*x*	*x*	*x*
M2	*x*	*x*	*x*
XL	*x*	*x*	*x*
XL2	*x*		*x*
MiniKit	*x*	*x*	*x*

Table 5.2. describes the product types that are capable of being produced by each manufacturing line. The product types that each line can produce are marked with an “x”.

5.1.3. Manufacturing line processes

The different workstations that compose the manufacturing lines and that have the different operations associated to it are:

- Operation A - *Box Placement*: Operation that allows the folding and placement of the box on the conveyor belt. It is performed by 2 to 3 workers, being this operation fully executed by human labour. It is necessary to place the raw material at the beginning of the operation to allow the production process to start, being these materials replenished alongside the production process needs by other workers.

- Operation B - *Assembly Line*: Operation that fills the box previously folded with the contents. It is performed by 8 to 9 workers, and fully executed by human labour. The composition of the products varies from product to product, although there is maintained a general composition. Similarly, to operation A, the components to execute this operation are prepared and placed before the production process starts and are replenished alongside the production process needs. The output of this operation is a closed cardboard box with all the components inside it.
- Operation C - *Wrapping*: This operation allows the wrapping of the output of operation B in plastic, being a fully automated process that needs constant flow of a plastic sheets. The operation is subject to breakdowns due to errors on the wrapping of the input. The replenishment of the plastic sheets and repair of the machine is performed by a specialized worker nearby, being these details explained on Section 4.2.
- Operation D - *Sealing*: Operation that allows the plastic sheet placed around the cardboard box to be sealed onto the box as a protective measure. This operation is fully automated, and, also, subjected to breakdowns.
- Operation E - *Packaging*: Operation that allows the packaging of several units of outputs of Operation D into larger packages for ease of storage and transportation. This operation is performed jointly with human labour and machinery.

Workstation E is also responsible for the quality control of the products, being selected based on the quality of the wrapping and sealing activities. The objects that present some sort of defect are separated from the normal flow of the operation as soon as they left workstation D to be reinserted at workstation C redoing the wrapping and sealing process.

5.1.4. Defining inefficiencies

The times that are considered as inefficient are categorized in:

- *Replenishment of raw materials in the manufacturing line before the operation starts*: Corresponding to the times in which the line is stopped due to the replenishment of raw materials that compose the final product, and the packaging, before the operation starts.

- *Replenishment of raw materials in the manufacturing line after the operation star*ts: Corresponding to the times in which the line is stopped due to the replenishment of raw materials that compose the final product, and the packaging, after the operation starts, such as shortage of any component in the manufacturing line.
- *Breakdown time*: Corresponding to the times that the line is stopped due to some breakdown in the line.
- *Repair time*: Corresponding to the times in which the line is stopped due to the reparation of a workstation, being this time distinct from the breakdown time since it involves a severe malfunction of the equipment.

5.1.5. Manufacturing system layout

At the beginning of the project the production scenario was the following, represented in Figure 5.1. Due to the focus of this business project only the operations segment that was studied is detailed, having been omitted the remaining systems upstream and downstream of it.

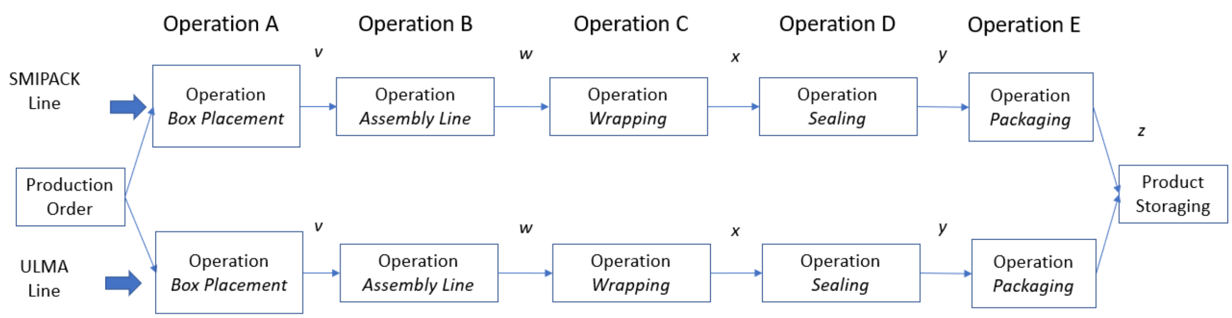

Figure 5.1. Layout of the final manufacturing lines.

As described in Figure 5.1., the system studied is composed of one starting point (Production Order), that can be directed to either of the manufacturing lines (SMIPACK Line and ULMA Line). Each line is composed by 5 workstations, that are presented in the figure being the abbreviations of each represented as Operation A, B, C, D and E. There is also detailed which of the presented queues between workstations that are represented with the abbreviations of v, w, x, y, and z. Both lines have the same endpoint, which is the storage of the output.

5.2. Operational model implementation with *SIMUL8*

To be able to analyse the Company's production systems, different virtual scenarios were created that allowed the replication of the observed systems. The main objective of simulating the production process on the final manufacturing line is to evaluate the system's efficiency, highlighting the workstations and associated operations that create a bottleneck points, and also evaluating the impact of adaptation of these manufacturing lines.

5.2.1. Model definition on *SIMUL8*

The manufacturing systems observed and studied in the Company through the methodology described in Chapter 4, allowed the creation of a virtual model of it so that it could be analysed in more detail, in which it was possible to model the stochastic behaviour normally associated with production systems.

The *SIMUL8* model is composed of 4 key entities:

- Work items: These are the objects that are processed by the system, which are the virtual representation of products.
- Activities: These are entities present in the simulation that allow the processing of work items, which are the virtual representation of the different workstations observed in the system. These activities have a set of characteristics associated to them, such as a statistical distribution that modulates their behaviour towards the work items, the existence of breakdowns, and repair times, which have been incorporated into the system in order to bring it closer to reality.
- Queues: These are entities that allow the management of the amount of work items that circulates within an activity.
- Time: Modulation is defined over a defined time period.

The simulation is governed by discrete-event simulation, and as such analyses the system with each change that has occurred (*vide* Section 2.6).

5.2.2. Definition of workstations

According to the observed system (*vide* Figure 5.1. on Section 5.1.5), a simulation model was designed in the virtual simulation environment that is represented in Figure 5.2. It was also considered an alternative path for the faulty objects after they were processed by workstation D, to implement the operational model in *SIMUL8*.

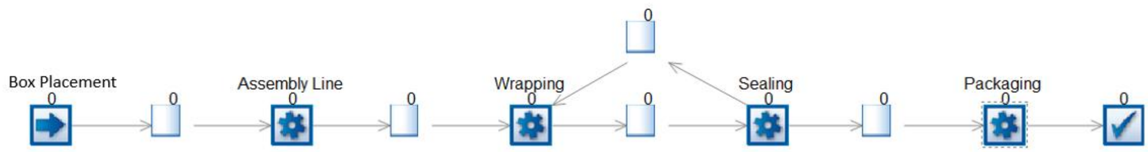

Figure 5.2. Layout of the final manufacturing line obtained through SIMUL8 software.

5.2.2.1. Activities

As defined above, the data obtained from the system observed in the Company were subjected to a statistical treatment that allowed the determination of the statistical distribution that most correctly allows its modelling *(vide* Section 4.3*)*, recurring to software *EasyFit*. The data generated through the software, to be used as *SIMUL8* inputs are displayed on Table A.1. in Appendix A.

These data correspond to the average processing time of a work item within the simulator, as well as the defined probability distribution, among other parameters to define the chosen distribution.

5.2.2.2. Characteristics definition

A set of characteristics has been defined to be able to detail the model more reliably, making it a more accurate representation of the systems observed.

5.2.2.2.1. Defective products

Workstation E (*vide* Section 5.1.3.) is responsible for the quality control. Therefore, before the object enters workstation E, if any defect is detected in the object, it is removed from circulation by an operator and placed in a queue before workstation C, this way the object will be processed again by workstations C and D, and will only be processed by workstation E if it meets the determined quality requirements.

For this process was also used the *fly back method* by which the time between occurrences was determined. It has been verified that no substantial difference from product type and manufacturing line was observed on the number of products that present some sort of defect *per* minute of operation. Hence it was considered that 0.785 products *per* minute of operation time that are removed from the system after operation *sealing* to be reinserted again at workstation C.

The information described previously is set out explicitly in Table B.1. (*vide* Appendix B.1.).

5.2.2.2.2. Set-up stop times

This time was defined as the average of the recorded set-up stop times. It was assumed that due to the fundamental nature of the process, it would not be necessary to collect the times for each of the types of products and manufacturing lines studied. Therefore, it was defined a set-up stop time of 11 minutes and 39 seconds.

The information described previously is set out explicitly in Table B.2. (*vide* Appendix B.2.).

5.2.2.2.3. Components' shortages stop-times

Only downtimes were checked due to the lack of components in Workstation C, leading to the interruption of the downstream production process. For this situation it was assumed that at every 11088 cycles there would be a shortage of materials on this workstation, based on the average consumption of the components for plasticization provided by foreman and assumed for all types of products. It was also defined that the time that take until these components were replenished was of 451 seconds (approximately 7 minutes and 30 seconds) (*vide* Table B.5. in Appendix B.4.).

Both assumptions were not deterministic, being modelled by an exponential distribution. This type of distribution allows the modelling of random behaviours, being used to model the time that passes between events (Kim, 2019) allowing the modelling of the phenomenon with a random behaviour.

It was assumed that there was no significant variation for each of the products studied, to simplify the system.

5.2.2.2.4. Breakdowns stop-times

During the data collection period, no breakdowns were recorded on any workstation except workstation C. There were no maintenance records within the documents made available by the Company, nor any information that could be provided about it. The cause of the malfunction on this workstation was due to an error in the operation, which led to the plastic being blocked inside the machine, leading to its stop. The repair process was immediately undertaken by a nearby operator, interrupting production downstream of the machine.

Therefore, it was defined an assumption for the average time between any failures at this workstation of 3240 seconds (approximately 54 minutes) based on the data collected (*vide* Table B.3. in Appendix B.3.). The repair time for such breakdowns was assumed as 293 seconds (4 minutes and 53 seconds) (*vide* Table B.4. in Appendix B.3.). Both assumptions were not fixed, being modelled by an exponential distribution.

5.3. Research quality control

5.3.1. Construct validity

For this project *construct validity* was achieved by mapping the different concepts used through a clear and explicit conceptual framework (*vide Session 3.2.*) that detailed how the project carried out has a theoretical foundation and is related to what the objectives defined for this one are. In this way, metrics and indicators were defined that are supported by the revised literature and that allow for the correct evaluation of the expected changes in the system, characterising them unequivocally. During the data collection process different sources of information were used, complementing the data collected in the production system with the information provided by the Operations & Efficiency department.

5.3.2. Internal validity

Since the procedures described by Barnes (1980) were followed (*vide* Section 2.4.), and all the indications of the Company in the collection and analysis of the data. The possible existing biases were minimised by taking a significant number of samples (40) for the chosen Confidence Level and Precision; in addition, a statistical representation of the samples collected has been defined, this being a correct representation of the different systems; as well as the runs within the *SIMUL8* software 5000 times to allow a correct analysis of possible statistical interferences. The logical consistency of the results obtained was guaranteed by verifying that 95% of the results obtained were within a range of well-defined values, thus making it possible to guarantee that the results analysed are representative of the model. Considering the logical consistency of the simulator, guaranteed by the manufacturer, it is then assured that the results obtained from it are in accordance with the data entered, being also representative of reality.

Furthermore, the indicators and parameters used for the evaluation of the system are well grounded by the existing literature, the method leading to the determination of these parameters being clearly defined and thus being analysed only one change at a time. All the results obtained were analysed and a logical explanation for variations in them was defined and presented previously. In this way, the author can state that the model used has internal validity and therefore it is possible to define causality and inference relationships about the results obtained and their causes.

5.3.3. External validity

For this master's project, the underlying theoretical basis is already well supported by the reviewed literature, and a relationship between the theoretical concepts presented has been reviewed, but it is not possible to define a mathematical relationship between them. Thus, the results obtained may be extrapolated to other systems, regarding the causal relationship between the concepts, however it is not possible to predict that a change of *x*% in a characteristic of the system may lead to a variation of *y*% in its productivity since each system has its characteristics and specificities, making its analysis quite complex and subject to interpretation errors.

By analysing the literature presented previously (*vide* Section 2.2.) it can be stated that the mitigation of throughput bottlenecks in a manufacturing system leads to an increase in production capacity, and consequently in the efficiency increase of the system itself. This relationship has been confirmed with this study and is further detailed in the following sections.

Furthermore, the data collected and analysed, and the results obtained for this system relate to a well-defined time period, in which the equipment was in very specific conditions, so any extrapolation to another system would be subject to major changes due to fundamentally different systems. However, it is possible to extrapolate the theoretical conclusion confirmed with this study from one manufacturing system to another.

5.3.4. Reliability

The procedures for data collection were carried out as described in the literature, following the Barnes (1980) procedures (*vide* Section 2.4.). However, the information regarding the use of *SIMUL8* software for the analysis of this type of data and consequent generation of results was carried out through a procedure developed by the author, allowing for the results necessary for the creation of the indicators and parameters used by other authors to assess the performance of the system. All the steps were documented and made explicit throughout this master's project, thus being possible for any member of the scientific community to reproduce these same steps in order to obtain the same results, if the same initial system was involved.

5.4. Data Collection and Treatment

5.4.1. Data collection

All the data were collected between June 3rd and August 2nd of 2019, and during this period the production manager monitored the system to clarify all doubts about the process and also about the production schedules that would be carried out for each of the products on each line.

At the beginning of the data collection process the foreman brought together all the workers in this segment of operations with the author, and explained to them the purpose of the work to be carried out by the author, and its importance for the Company. During this meeting, the operators' consent was requested so that their actions could be analysed for the purpose of data collection for the development of this master's project. Whenever human operators were involved in the operations, they were informed about it and the time study would only be carried out with their proper authorisation.

Before starting the data collection process, for each workstation the number of operators participating in the operations was verified and it was confirmed by the production team that the increase or decrease in the number of operators in each workstation has no effect on the duration of an operation, being only a management action of the existing human assets allowing in this way the operators to run several operations. This condition has therefore been assumed for the system.

Based on the instructions received by the production manager it was assumed that the rate of performance of the operators was normal and average, of 100, therefore no factor had to be applied to the measured times to match the performance rate of the operator.

Since the collection of the observation data did not always take place at the same time, being subject to the different batches to be produced, and being subject to the author's need for the data, it was not possible to carry out a fixed collection at a certain time of the day. It was assumed that Fatigue and Personal allowance are non-existent because the workers are not taking more production time than is already foreseen by the 8-hour work schedule, which already includes a total of 30 minutes of breaks to be used freely by operators for rest and personal needs.

However, it was possible to consider the delay allowance in the data collection process, by collecting the of data regarding stops in the production system and in each of the workstations (*vide* Section 2.4.). These data were not considered on the determination of the of the operations standard time, although it was considered within the simulator by assuming different factors and parameters that are used on the determination of the normal duration of operations and also what the actual production capacity of each of the manufacturing lines is (*vide* Section 2.4.).

For each manufacturing line and product type there were collected 40 samples of operation times, by using the *Fly back method*. These observations are not detailed in this document due to the volume of data collected but are available on request to the author for consulting by a fellow researcher.

The data collected with regard to the stop times (*vide* Section 4.2.2.3.) were also collected based on the *Fly back method*.

5.4.2. Confidence Level and Precision

It was considered a Confidence Level of 95% with a Precision of 10% according to the practices defined by Barnes (1980) (*vide* Section 2.4).

5.4.3. Definition of the number of samples

The data were analysed according to the methodology described in Section 4.2.2.5. and it was determined that the collection of the 40 samples was sufficient to ensure that the samples collected met the statistical targets set and described above (*vide* Section 5.4.2.).

The data demonstrating the calculation of the number of samples required to obtain the necessary Confidence Level and Precision are not presented in this document due to their extent, however are available on request to the author for consulting by a fellow researcher.

5.4.4. *EasyFit* application

Based on the methodology described in Section 4.3., the statistical distribution that best suited to the samples collected was determined by the *EasyFit* software. For this purpose, the data on the observations made were imported into the software and a set of statistical distributions were returned. From the different statistical distributions obtained, a confidence ranking was determined based on the Anderson-Darling method. The output of this analysis and treatment, which was used to build the model in the *SIMUL8* software, is described in the Table A.1. (*vide* Appendix A).

5.5. Results

This business project, which began with a meeting within the Operations & Efficiency department of the Company, proved to be quite challenging in terms of the construction of the models and their analysis due to the complexity and the enormous amount of data generated. A complete analysis of the results was carried out.

5.5.1. Results presentation

5.5.1.1. Results manipulation

Based on the results obtained by the *SIMUL8* software, they were manipulated so that they could be transformed into the previously determined standard indicators (*vide* Section 4.5.2.). The calculation method for each of these indicators is described in Table 6 (*vide* Section 4.5.2.) and has been detailed for each of the products and manufacturing lines.

5.5.1.2. Results Presentation

For each type of product, and for each manufacturing line, the indicators previously detailed have been described (*vide* Section 4.5.2.).

A presentation of the results was made for the initial scenario, in which Line 1 and Line 2 were involved, and the values of the indicators were detailed and presented in a comparative manner. Subsequently, the homologous results were presented after the change in the production system, detailing the line that had been changed - Line 2 - New machine.

The results obtained and the corresponding graphical representations are detailed in Appendix C.

5.5.2. System analysis

5.5.2.1. General analysis

This Section aims to summarize the information presented on the previous Section (*vide* Section 5.5.1.) allowing the comparison between the lines and evaluating the adaptation of *Line 2* into *Line 2 – New machine* through the previously presented metrics.

Table 5.3. *Summary of the data related with throughput per hour presented on the previous Sections.*

	Line 1	***Line 2***	***Subtotal***	***Line 2 - New machine***	***Subtotal***	***% Variation***
Product M	*1249.5*	*1072.3*	*2321.9*	*1173.2*	*2422.7*	*4.3%*
Product M2	*951.4*	*807.4*	*1758.7*	*994.4*	*1945.8*	*10.6%*
Product MiniKit	*1280.4*	*1044.3*	*2324.7*	*1266.1*	*2546.6*	*9.5%*
Product XL	*697.2*	*738.6*	*1435.8*	*729.5*	*1426.7*	*-0.6%*
Product XL2	*711.5*	*-*	*711.5*	*325.3*	*1036.8*	*45.7%*

The %Variation calculation in Table 5.3. concerns the variation between the number of objects produced per hour by Line 2 - New machine in comparison with Line 2, being calculated as

Throughput per hour of the initial system (Line 1 and Line 2) to be divided by Throughput per hour of the final system (Line 1 and Line 2 - New machine) - 1. The value is presented in percentage units.

According to the results described in Table 5.3. the change in the production system from *Line 2* to *Line 2 - New machine* resulted in a general increase in the production capacity of the system as a whole. With the exception of product type XL - for which there was a reduction of 0.6% - for all products studied there was an increase in the *throughput per hour* and allowed the production capacity of product XL2 to be significantly increased, since it was not produced before in both manufacturing lines.

Table 5.4. *Summary of the data related with relative efficiency presented on the previous Sections.*

	Line 1	***Line 2***	***Line 2 - New machine***	***% Variation***
Product M	*99.1%*	*85.1%*	*93.1%*	*9.4%*
Product M2	*64.1%*	*54.4%*	*87.3%*	*60.6%*
Product MiniKit	*84.1%*	*92.3%*	*74.5%*	*-19.3%*
Product XL	*83.7%*	*88.5%*	*73.6%*	*-16.9%*
Product XL2	*83.3%*	-	*74.7%*	-

The *%Variation* calculation in Table 5.4. concerns the variation between the *Relative efficiency* by *Line 2 - New machine* in comparison with *Line 2*, being calculated as *relative efficiency* of the initial system (Line 2) to be divided by the *relative efficiency* of the final system (Line 2 - New machine) - 1. The value is presented in percentage units.

The comparative analysis of the results obtained for *relative efficiency*, described in Table 5.4., reveals that the change in the system led to an increase in resource efficiency usage for M and M2 products, but led to a decrease for XL and XL2 products. Since XL2 was not produced on Line 2 then no comparison was made before and after the system change.

Table 5.5. *Summary of the data related with efficiency of utilisation presented on the previous Sections.*

	Line 1	***Line 2***	***Line 2 - New machine***	***% Variation***
Product M	*80.8%*	*94.3%*	*94%*	*-0.3%*
Product M2	*78.2%*	*80.4%*	*85.4%*	*6.2%*
Product MiniKit	*80.7%*	*89.3%*	*72%*	*-19.8%*
Product XL	*85.9%*	*88.4%*	*80%*	*-9.7%*
Product XL2	*94.5%*	-	*73%*	-

The *%Variation* calculation in Table 5.5. concerns the variation between the *efficiency of utilisation* by *Line 2 - New machine* in comparison with *Line 2*, being calculated as *efficiency of utilisation* of the initial system (Line 2) to be divided by the *efficiency of utilisation* of the final system (Line 2 - New machine) - 1. The value is presented in percentage units.

According to the results described in Table 5.5. the change in the manufacturing system led to a change in the efficiency of use of the system. There was only an increase in this indicator for M2 product and a decrease for all other products. Since XL2 was not produced on Line 2 then no comparison was made before and after the system change.

Table 5.6. *Summary of the data related with throughput bottleneck and operation duration presented on the previous Sections.*

	Line 1		***Line 2***		***Line 2 - New machine***		
	Workstation	***Operation Duration***	***Workstation***	***Operation Duration***	***Workstation***	***Operation Duration***	***% Variation***
Product M	*C*	*2.1*	*C*	*3.0*	*C*	*2.6*	*-11.7%*
Product M2	*B*	*3.0*	*B*	*3.3*	*E*	*3.5*	*6.1%*
Product MiniKit	*E*	*2.8*	*C*	*2.6*	*E*	*2.8*	*7.7%*
Product XL	*E*	*5.0*	*B*	*4.7*	*B*	*4.7*	*1.5%*
Product XL2	*C*	*4.5*	-	-	*C*	*10.0*	-

The *%Variation* calculation, in Table 5.6 concerns the variation between the *operation duration* by *Line 2 - New machine* in comparison with *Line 2*, being calculated as *operation duration* of the initial system (Line 2) to be divided by the *operation duration* of the final system (Line 2 - New machine) - 1. The value is presented in percentage units.

In Table 5.6. is verified the behaviour of the throughput bottlenecks of the different systems studied, detailing the workstation in which they are located, and the operation duration associated to the operations of these workstations. It is verified that with the change of the system from *Line 2* to *Line 2 - New machine*, there occurred a change of the *bottlenecks throughput* to downstream workstations for the M2 and MiniKit products, while for the other products the *bottlenecks* were kept in the same workstation. It was also found that, apart of the M product, there was an increase in the operation duration associated with the bottleneck workstation. Since XL2 was not produced on Line 2 then no comparison was made before and after the system change.

Table 5.7. *Summary of the data related with mean life times presented on the previous Sections.*

	Line 1	***Line 2***	***Line 2 - New machine***	***% Variation***
Product M	*199.0s*	*1840.4s*	*976.1s*	*-47.0%*
Product M2	*899.6s*	*1158.4s*	*395.5s*	*-65.9%*
Product MiniKit	*406.1s*	*257.8s*	*672.8s*	*161.0%*
Product XL	*416.2s*	*343.0s*	*721.0s*	*110.2%*
Product XL2	*2440.8s*	-	*3692.6s*	-

The *%Variation* calculation in Table 5.7. concerns the variation between the *mean life times* by *Line 2 - New machine* in comparison with *Line 2*, being calculated as *mean life times* of the initial system (Line 2) to be divided by the *mean life times* of the final system (Line 2 - New machine) - 1. The value is presented in percentage units.

By analysing Table 5.7. it is possible to see that for M and M2 products, the average time that an object is in the system has decreased with the system adaptation. However, a sharp increase has been noted for MiniKit and XL2 products. Since the XL2 product was not produced in Line 2 then no comparison was made before and after the system change.

Table 5.8. *Summary of the data related with average queue size and average queuing time presented on the previous Sections.*

		Line 1	***Line 2***	***Line 2 - New machine***	***% Variation***
Product M	***Average queue size***	*14.3*	*142.7*	*73.9*	*-48.2%*
	Average queueing time	*36.5*	*365.8*	*191.5*	*-47.7%*
Product M2	***Average queue size***	*63.5*	*92.0*	*53.2*	*-42.1%*
	Average queueing time	*168.2*	*264.7*	*174.6*	*-34.0%*
Product MiniKit	***Average queue size***	*24.9*	*15.7*	*67.0*	*327.4%*
	Average queueing time	*58.8*	*49.3*	*159.8*	*224.1%*
Product XL	***Average queue size***	*62.7*	*14.0*	*35.6*	*153.9%*
	Average queueing time	*141.3*	*66.7*	*49.2*	*-26.2%*
Product XL2	***Average queue size***	*114.5*	-	*89.0*	-
	Average queueing time	*495.0*	-	*733.4*	-

The *%Variation* calculation in Table 5.8. concerns the variation between the *average queue size* or *average queuing time* by *Line 2 - New machine* in comparison with *Line 2*, being calculated as *average queue size* or *average queuing time* of the initial system (Line 2) to be divided by the *average queue size* or *average queuing time* of the final system (Line 2 - New machine) - 1. The value is presented in percentage units.

Based on the results displayed on Table 5.8., it was verified for product M and M2 a decrease both in the *average queue size* and the *average queueing time*. For Product MiniKit was denoted an increase both the *average queue size* and the *average queueing time* values, and for Product XL it was observed an increase on the *average queue size* and a decrease on the *average queuing time*.

6. Results Discussion

6.1. Expected Results

The manufacturing lines segment studied had its production as a *batch production* type (*vide* Section 2.2) because of the small production batches required and because of the high variety of products to be produced. As previously described, one of the biggest challenges for any organisation is the identification of the features of its systems that need to be improved (Tsou and Huang, 2010). According to existing literature on these types of manufacturing systems the mitigation of throughput bottlenecks allows the increase of the performance of the system since it is increased the capacity on the slowest operation of it (Li, 2009). In systems that are already fixed and in which there will be no change in their layout, there is a need to reduce the repair time of machines and equipment - thus leading to an increase in the time in which the system is operational - or reducing the cycle time - this parameter being difficult to adjust in most cases (Li, 2009). The identification of throughput bottlenecks and their modification will thus increase the efficiency of the production lines, according to the relative efficiency metric, by increasing the time the system is operational and thus increasing its production capacity.

6.2. Obtained Results

6.2.1. Production capacity

Based on the data summarised in the previous tables, it is verified that the total production *per* hour increases in all product types, apart from product type XL, in which is denoted a small decrease in the overall production capacity. Therefore, the change in the production line led to gains in production capacity, which were generally verified.

The reasons for the apparent decrease in the production capacity of the system when XL2 product is produced can be explained by the change in throughput bottlenecks. It was verified that when the bottleneck remained on the same workstation, and decreased it *operation duration*, was observed an overall increase in the productivity capacity, being also observed the same pattern when the bottleneck is postponed to later operations, even when there is an increase on the *operation duration*. When the bottleneck remains on the same operation, and increases its *operation duration*, then is verified a decrease of the productivity capacity of the line, as is represented by the product type XL.

6.2.2. Relative efficiency

An increase in the relative efficiency is verified for product M and M2, meaning that the adaptation of the manufacturing line allowed a better use of the resources that served as inputs on the system, and so transforming a higher quantity of inputs into outputs, however such increase was not verified for the MiniKit and XL products. This increase may be justified by the time the objects stayed in the system, characterized by the mean life time, in which it was observed that for the product MiniKit and XL2 there was a sharp increase in the time they stayed in the system to be processed. Such data is further confirmed by the average queue size and average queueing time parameters in which an increase for these products is also demonstrated. Thus, it can be seen that for these products the change in the manufacturing line has proved to be a hindrance to production in which there is still room for improvement by controlling the queues and the entry of products.

6.2.3. Efficiency of utilisation

Furthermore, based on the *efficiency of utilisation* there was only denoted an increase to product type M2, that means that the manufacturing line, when adapted, is not perfectly balanced, and so there is room for improvement on these systems by adjusting, when possible, the *operation durations* of the different workstations.

6.2.4. Final remarks

Overall there was an increase in production capacity, as there was also a decrease in the associated operation durations, so the systems were able to process the different products faster, although leading to an increase in the average queue size and average queueing time, and therefore increasing the amount of work-in-progress within the system.

6.3. Results conclusions

As was verified in the results obtained, when there was a decrease in the *operation duration* associated with an operation that was also *throughput bottleneck* of the system, there was an increase in the production capacity of the system, so the results obtained are in accordance with the revised literature. Furthermore, the indicators used allowed the analysis at different levels of the various manufacturing systems, and it was not necessary to define new indicators in order to perform a correct system analysis.

From the results obtained it was possible to verify that the use of metric *efficiency of utilisation*, which is not widely used in the literature as a method to evaluate the performance of manufacturing lines, made it possible to analyse and predict the behaviour of manufacturing lines, determining whether they were prone to the appearance of queues or not, and as such to verify how well balanced the systems were. In this way, and together with the use of the indicators average queue size and average queueing time, it is possible to identify which *throughput bottlenecks* exist in the system. By comparing these data with the *operation duration* indicator values, it is verified how it is possible to model the system to make it better balanced, thus decreasing the size of the existing queues, and consequently the time that each object is retained in them, leading to an increase in productive capacity, reflected by the increase in *relative efficiency*.

A new conceptual framework for this study would thus be suggested, detailing the importance of evaluating the system by using efficiency of utilisation as a key parameter for performance evaluation, and for comparing the system with its theoretical maximum production capacity.

Regarding the adaptation of the manufacturing line, it was verified that there was an overall increase of the production capacity, although in most cases there was verified a decrease of the *efficiency of utilisation*. Apart from product M2 there was a decrease of this metric in all workstations, meaning that improvements can be done on the adaptation of *operation durations* of the line to better utilise the production times leading to an increase of the productivity capacity and *relative efficiency* and also decrease the average number of products in queues. By analysing the systems, is observed that changes on the *operation durations* can be managed in operations that have human labour involved.

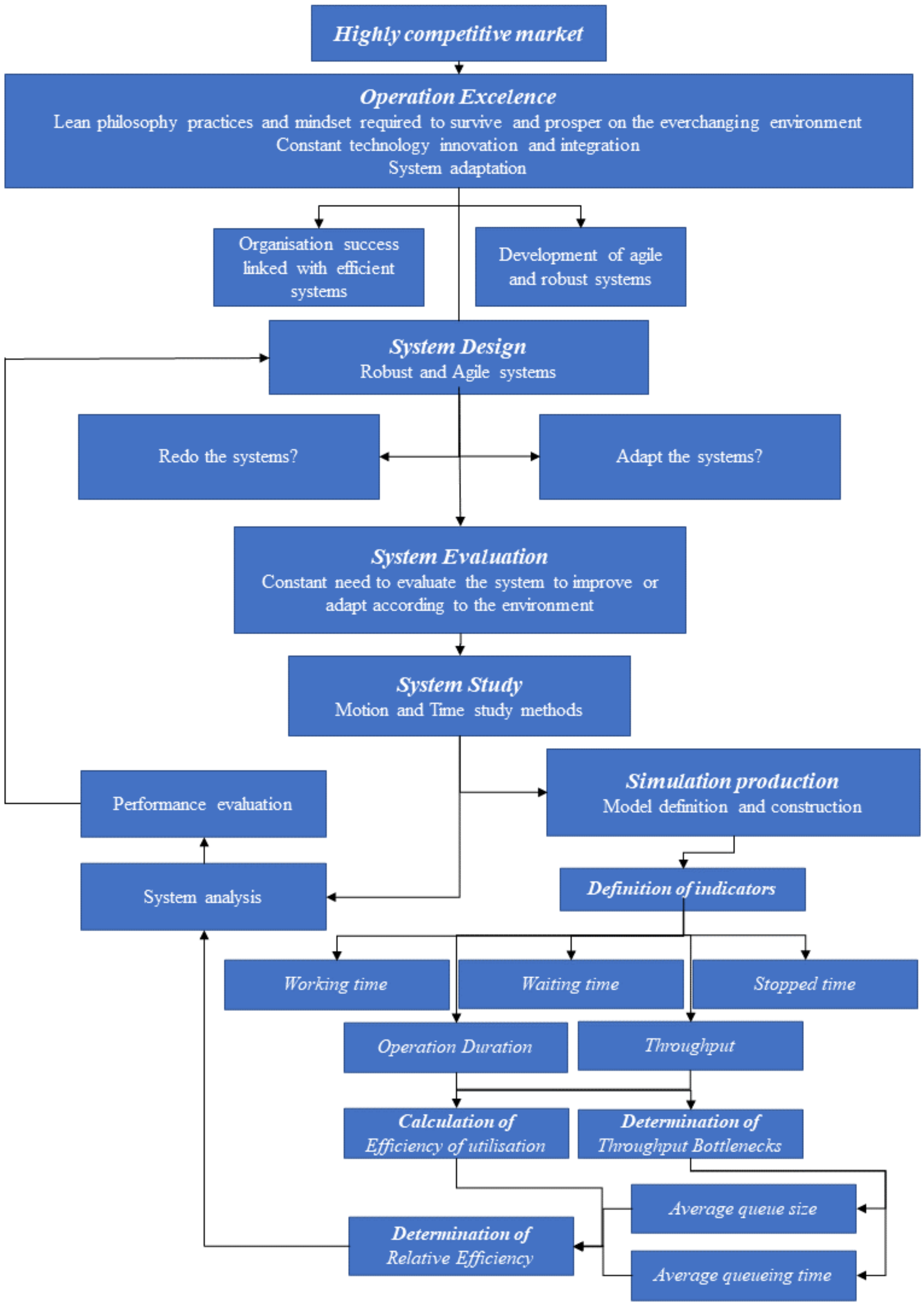

Figure 6.1. Conceptual framework considering the use of Efficiency of Utilisation as a key parameter for performance evaluation.

For product type M and M2, would be impossible to increase the *efficiency of utilisation* without vary the equipment used on operation *Sealing*, since is the one with a higher *operation duration* of the system operation. A similar scenario is verified for product type XL2, being the operation *Wrapping* the one with a higher *operation duration*.

For product type MiniKit, by decreasing the *operation duration* of operation *Assembly Line* and *Packaging* to 2.12 seconds, would be reached the *efficiency of utilisation* of 86.33%, being the maximum obtained without changing any equipment. On product type XL, by decreasing the *operation duration* of operation *Assembly Line* to 3.78s, matching the value of operation *Sealing*, would cause an increase of the *efficiency of utilisation* to 94.86%. The summary of changes, and the variation on the total production capacity is described in Table 6.1. below.

Table 6.1. *Summary of the adaptation of the operation durations of different workstations on Line 2 – New machine.*

	Original Scenario	***Target Changes***	***Initial Production***	***Target production***	***% Variation***
Product M	*94.07%*	*94.07%*	*1173.17*	*1173.17*	*0.0%*
Product M2	*85.38%*	*85.38%*	*994.40*	*994.40*	*0.0%*
Product MiniKit	*71.57%*	*86.33%*	*1266.14*	*1698.11*	*34.1%*
Product XL	*79.83%*	*94.86%*	*729.45*	*952.38*	*30.6%*
Product XL2	*73.04%*	*73.04%*	*325.34*	*325.34*	*0.0%*

7. Conclusions

The project presented and developed began with a meeting between the author and the head of the Operations & Efficiency department of the Company. In this meeting it was explained to the author that a segment of the production lines was being considered as a general bottleneck of the system, and as such it would be necessary to make changes to it in order to increase the production capacity and overall efficiency of the system. The Company had the desire to access the efficiency of their manufacturing lines, allowing it to know its resources better and to determine, or confirm, the best metrics for analysing them.

To this end, it was defined that this segment of operations would be studied using simulation techniques to create and analyse large quantities of data arising from the definition of the manufacturing conditions and the statistical distributions associated with the production process of each workstation.

Not only were the existing production lines characterised, but the effect of the adaptation of the production lines was also studied, thus making it possible to compare the results obtained and to draw conclusions about the reasons that led to this variation.

7.1. Satisfaction of the Research Questions

All the work done was in accordance with the research questions set out earlier (*vide Section 1.5.*) and allows us to satisfy the initial curiosity that led to the creation of this project.

1. *How to measure the efficiency of manufacturing systems recurring to simulation techniques?*

In order to evaluate the efficiency of the manufacturing systems, a rigorous collection of data in the study system should be carried out, detailing the time period and the conditions under which the collection took place. The techniques described by Barnes (1980) should be used for this purpose, and more current methods and equipment than those described by this author may be used. A statistical analysis of the collected observations should be performed, thus allowing the determination of their stochastic behaviour. All relevant information for the system analysis should be detailed in supporting documents in order to allow the future confirmation of the procedures used as well as to evaluate the evolution of the systems over time. All important features of the system should be discussed with the foreman, and be defined in the virtual environment, creating a reliable replica of the system in the computational environment. In this way the results obtained through the simulator will be approximate replicas of the verified system and can be analysed and thus determine the efficiency of the system through one or more metrics

2. *Which indicators, or set of indicators, can be used to determine the overall efficiency of a production system?*

According to the revised bibliography set out on the Literature Review chapter (*vide* Chapter 2), and according to the data collected, the analysis of *operation durations, relative efficiency*, *efficiency of utilisation*, as well as the analysis of the size and average time that an object remains in the queues allows to characterise the production systems in great detail.

By analysing the *operation duration* is possible to determine the real times of the operations in the constructed model, taking into account all the characteristics that were defined for it based on the data collected from the observed systems. These results serve as basis and input for the other indicators and parameters studied, being therefore an essential element in the evaluation of the systems. By using these parameters is possible to calculate the *throughput* parameters that serves as basis for the calculation of the *relative efficiency* and the *efficiency of utilisation*.

The *relative efficiency* parameter (*vide* Section 2.5.2.1) is of enormous importance in the literature since it allows the comparison between the quantity of outputs and inputs in each time period. Thanks to this parameter it is possible to verify how inputs and outputs are related in the different systems, comparing them in a percentage way and thus establishing a basis for comparison between the different systems studied.

Lastly, the use of the parameter *efficiency of utilisation* (*vide* Section 2.5.2.3) allows the evaluation of a manufacturing system in terms of time use, and thus determine how the system is correctly balanced or not. In this way it is possible to determine which workstations and corresponding *operation durations* are not optimised. As presented in Section 6.3. it is possible to analyse the systems based on this indicator, determining the maximum theoretical capacity of the system and checking which workstations are below the system capacity threshold. Thus, new measures can be taken and implemented to increase the performance of manufacturing lines by serving this indicator as an excellent managerial tool.

3. *What parameter, or set of parameters, is responsible for the most significant variation in the behaviour of the manufacturing line?*

According to the results obtained, it was found that by decreasing the operation duration of the operations that are throughput bottlenecks of the system, an increase in production capacity occurs and these results are according to the revised literature (Li, 2018). Thus, the change in cycle time associated with an operation is of great importance in determining the performance of manufacturing systems. It was also verified that if there is a movement of the bottleneck to a later point in the manufacturing process, even if there is an increase in the operation duration, it leads to an increase in production capacity, being also the ability to identify the bottlenecks, not only by the operation durations, but also by the average queue size and average queueing time of vital importance to change the performance of manufacturing systems.

4. *How can the organisation use and implement simulation techniques on other operation systems?*

The organization will be able to implement simulation techniques, and systems analysis through simulation by applying the methodologies described in this business project to other operations systems. In this way, the indications described by Barnes (1980) (*vide* Section 2.4.), to the different systems to be studied, subdividing them and studying each one of the operations according to the techniques of study of methods and times, will be possible to define the characteristics of each one of the systems, defining the times of operations and particularities of the system. Using statistical inference software, it will also be possible to determine which statistical distributions best suit the different sets of observations obtained. The data obtained can then be inserted into a simulation software, where the different production conditions should be defined and characterised. The results obtained from the simulator should be analysed according to the needs of the system under study.

7.2. Objectives

The purpose of this project was to analyse the different production lines through the use of simulation techniques. In this way, a study methodology was developed that allowed to relate the different concepts described in the literature on the subject, as well as the determination of the practices to be used to evaluate the production systems studied.

As presented in Chapter 1 (*vide* Section 1.4.) the goals of the project were as follows:

1. *To identify the baseline level of production for each of product types and manufacturing lines, in the initial conditions as well as the relevant indicators values.*

As outlined in Table 5.3. (*vide* Section 5.5.2.1.) it was possible to identify the basal production levels for each of the manufacturing lines studied, using the indicator *throughput per hour*, in the initial manufacturing conditions. A set of other different indicators has been tested for this manufacturing systems and the results obtained are presented in Section 5.5.2.1.

2. *To perform a comparative analysis between the performance of the manufacturing lines before and after the updating of the equipment that composed the operation segment.*

A comparison was made between Line 2 and Line 2 - New machine which allowed conclusions to be drawn about how the changes in this line led to the variation in the production capacity of the system. These results are detailed in Section 5.5.2.1. where there were compared the values of the different indicators for the different manufacturing systems.

3. *To determine the main issues concerning the assembly line.*

It has been determined that the existence of throughput bottlenecks in the system leads to a decrease in production capacity, and consequently to a decrease in the efficiency of the system, being these observations supported by the existent literature (Li, 2009). These throughput bottlenecks were confirmed both by using the average queue size and average queueing time indicators (*vide* Table 4.3. in Section 4.5.2.) and by analysing the operation duration (*vide* Table 4.3. in Section 4.5.2.) on the different scenarios, being these results described in more detail in Appendix C.

4. *To transmit the main processes and techniques used in the evaluation of production lines, allowing the managerial team to have new tools for decision making.*

A document with the methods performed as well as the results and conclusions obtained from this study were delivered to the project sponsor to be used as a managerial tool for decision making for the Company.

During the whole project, the author had the support of the Company for his doubts and questions, having also obtained the support and sympathy of the operators in the workplace. It was also possible to generate results of interest to the Company, enabling it to train the study and analysis techniques of its systems.

Thus, it was concluded that the project goals were met, since it was possible to extensively characterise the studied systems, and the results obtained were generated according to the evaluation standards of the systems described in the literature, and the data that served as inputs for these systems were also collected according to the good practices described in the literature.

Therefore, it can be concluded that the objectives of this project have been achieved, fully satisfying its purpose of assessing the efficiency of the different manufacturing lines. Moreover, the research questions were answered in a clear and concise manner, allowing the reader to understand the answers as well as the theoretical support for them.

7.3. Limitations

Simulation modelling models are a representation of reality that are bounded to a specific period, in specific conditions, therefore these results can neither be directly extrapolated to other systems nor to other time periods. The model built is dependent on the type of distributions used, these distributions being dependent on the data collected. Thus, the distributions used are related to a limited time period in specific manufacturing conditions. A detailed study on the impact of the use of other statistical distributions should be undertaken to determine existing biases by using this set of parameters.

Moreover, different operators in the workstations would make the system behave differently, so the model created is also conditioned by the human assets used during the data collection process.

Due to the SARS-CoV pandemic during the year 2020 there has been a strong change in the production lines of the sponsor of this project, and for this reason it was not possible to compare the created simulation model with the observed system in different periods.

7.4. Recommendations to the project sponsor

For a deeper analysis of the manufacturing lines with a global operations perspective, it would be recommended to extend this study to all other operations of the organisation. Such study would allow the determination of the real operation times on each operation segment, determining the rate to which products with defect are produced, the failure rate and reparation time of the equipment used and the set-up times of each individual operation.

With such a study would also be possible to better characterize the different manufacturing lines of the organisation, in a easily mutable virtual environment identifying the theoretical system throughput and so determining the efficiency of it when compared with other similar operations; calculating the efficiency of the utilisation, highlighting parts of the operation that are not perfectly balanced with the overall system and so undermining its efficiency; identifying the through point bottlenecks of the different manufacturing systems, allowing the determination of which components of the system may need to be deeply affected to improve its efficiency and productivity capacity of it; and also the evaluation of the total time an object stays on the system.

With such tools would be possible to test and verify how the manufacturing lines would behave when adapted. For an initial scenario could be used the provided parameters of the new equipment to be tested or the calculated parameters of a new operation, and verify, with that information, how would the system behave. Also, the production and characterization of different scenarios could be done, according with the needs and desires of the organisation.

Although the quantification of the monetary gains of the utilisation of such systems is not in the scope of this master project, the increase in the productivity capacity, linked with a better use of the production times, may result in the system becoming more efficient by decreasing the amount of *waste*, based on the lean manufacturing philosophy.

In order to allow a constant analysis of the different systems of operations it would be recommended to carry out this type of studies more recurrently. It would also be recommended to implement a stricter maintenance plan to the workstations that have machinery and other type of equipment to minimize the risk of line stoppages due to failure of these equipment. Would also be recommend to at least one member of the manufacturing team to be vigilant about the supplies needed for the different operations, since there is verified that some workstations present idle stop times due to shortage of materials, and so undermining the manufacturing process by reducing the amount of working time.

Based on the data collected and the results obtained, further studies should present the same or a similar methodology of data collection, defining the allowances for times of operations and also defining the ratings in greater detail, situations which should be discussed further with the Production Manager. Furthermore, it is not necessary to use all the indicators described in this study, and the author of future studies should focus on defining the indicators presented in Figure 6.1, focusing on the use of *efficiency of utilisation* as a key indicator for performance evaluation and definition of production capacity.

7.5. Innovation contribution to the work

The work carried out has enabled the company to develop new techniques for analysing its production systems, and defining methodologies to be used for applying these techniques to other systems, and determining the parameters and indicators to be used when evaluating an operations system. These techniques are of highest interest to the organisation because they allow the analysis of its operations in an intuitive way, easily representable and at a reduced cost.

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A. Statistical distributions obtained through the use of EasyFit software

Table A.1. describes the statistical distributions obtained using the *EasyFit* software. In this table the column *Product and Line* identifies the type of product being evaluated, the Manufacturing line and Workstation. The product type is identified by the first letter (M, M2, MiniKit, XL and XL2), the line being analysed by the second parameter (L1 – Line 1, L2 – Line 2, and L2N – Line 2 New machine), and the last parameter identifies the workstation (A, B, C, D and E). The column *Distribution* identifies the statistical distribution of the observed sample, and the column *Parameters* identifies the parameters that characterize the featured distribution.

Table A.1. Definition of the parameters used for each distribution.

Product and Line	***Distribution***	***Parameters***
M_L1_A	Pearson 5	α=19.114 β=46.676
M_L1_B	Lognormal	σ=0.19041 μ=0.67139
M_L1_C	Erlang	μ=47 β=0.04027
M_L1_C	Gamma	α=47.29 0.04027
M_L1_D	Pearson 5	α=49.207 β=98.421
M_L1_E	Gamma	α=52.913 β=0.03722
M_L2_A	Pearson 5	α=19.114 β=46.676
M_L2_B	Pearson 5	α=34.11 β=83.104
M_L2_C	Gamma	α=37.936 β=0.07112
M_L2_D	Pearson 5	α =16.066 β=39.708
M_L2_E	Normal	σ=1.7642 μ=3.0636
M_L2N_A	Pearson 5	α=19.121 β=46.696
M_L2N_B	Pearson 6	α_1=213.83 α_2=39.991 β=0.45532
M_L2N_C	Pearson 6	α_1=657.42 α_2=15.761 β=0.05355
M_L2_D	Pearson 5	α=16.066 b=39.708
M_L2_E	Normal	σ=1.7642 μ=3.0636

M2_L1_A	Normal	σ=0.31092 μ=2.4042
M2_L1_B	Gamma	α=16.859 β=0.17473
M2_L1_C	Weibull	α=6.0402 β=2.8589
M2_L1_D	Weibull	α=6.1918 β=3.076
M2_L1_E	Pearson 5	α=13.086 β=45.123
M2_L2_A	Pearson 5	α=59.248 β=177.73
M2_L2_B	Pearson 6	α_1=356.01 α_2=20.346 β=0.17796
M2_L2_C	Pearson 6	α_1=213.15 α_2=28.181 β=0.44245
M2_L2_D	Pearson 5	α=19.434 β=69.38
M2_L2_E	Pearson 5	α=11.99 β=47.055
M2_L2N_A	Pearson 6	α_1=307.1 α_2=13.423 β=0.12682
M2_L2N_B	Pearson 6	α_1=356.01 α_2=20.346 β=0.17796
M2_L2N_C	Normal	σ=0.39513 μ=3.0623
M2_L2N_D	Pearson 5	α=28.466 β=94.881
M2_L2N_E	Pearson 5	α=17.946 β=61.191
MiniKit_L1_A	Pearson 5	α=10.251 β=21.697
MiniKit _L1_B	Pearson 6	α_1=397.17 α_2=10.95 β=0.05066
MiniKit _L1_C	Pearson 6	α1=219.02 α2=24.576 b=0.2111
MiniKit _L1_D	Pearson 5	α=11.791 b=22.25
MiniKit _L1_E	Pearson 6	α_1=147.07 α_2=9.1374 b=0.15292
MiniKit _L2_A	Pearson 6	α_1=148.46 a α_2=6.3895 b=0.11456
MiniKit _L2_B	Pearson 6	α_1=267.35 α_2=19.821 b=0.17153
MiniKit _L2_C	Pearson 5	α=24.64 β=61.218
MiniKit _L2_D	Pearson 6	α_1=436.69 α_2=10.13 β=0.06168
MiniKit _L2_E	Pearson 6	α_1=147.07 α_2=9.1374 β=0.15292

MiniKit _L2N_A	Uniform	α =1.5387 β =2.6615
MiniKit _L2N_B	Pearson 5	α=33.681 β=73.621
MiniKit _L2N_C	LogNormal	σ=0.12187 μ =0.67096
MiniKit _L2N_D	Pearson 5	α=41.363 β=84.85
MiniKit _L2N_E	Pearson 6	α_1=147.07 α_2=9.1374 β=0.15292
XL_L1_A	Pearson 5	α=10.986 β=42.785
XL_L1_B	Pearson 6	α_1=246.12 α_2=7.6382 β=0.12471
XL_L1_C	Pearson 5	α=20.93 β=70.945
XL_L1_D	Pearson 6	α_1=248.83 α_2=8.2857 β=0.11197
XL_L1_E	Pearson 5	α=8.6694 β=37.928
XL_L2_A	Pearson 6	α_1=388.31 α_2=10.929 β=0.10939
XL_L2_B	Pearson 6	α_1=246.12 α_2=7.6382 β=0.12471
XL_L2_C	Weibull	α=4.5142 β=4.1099
XL_L2_D	Pearson 5	α=10.684 β=39.936
XL_L2_E	Pearson 5	α =24.615 β=86.484
XL_L2N_A	Pearson 5	α=23.563 β=81.245
XL_L2N_B	Pearson 5	α=7.6714 β=31.31
XL_L2N_C	Pearson 6	α_1=200.00 α_2=8.00 β=0.12471
XL_L2N_D	Pearson 5	α=21.101 β=75.356
XL_L2N_E	Weibull	α=6.5128 β=3.3502
XL2_L1_A	Pearson 5	α=23.998 β=96.874
XL2_L1_B	Pearson 5	α=11.5 β=45
XL2_L1_C	Pearson 5	α=39.778 β=175.17

XL2_L1_D	Pearson 5	α=34.695 β=159.22
XL2_L1_E	Gamma	α=8.9131 β=0.51364
XL2_L2N_A	Weibull	α =2.7285 β=9.2791
XL2_L2N_B	Weibull	α =2.5899 β =9.04
XL2_L2N_C	Erlang	μ=10 β=0.54979
XL2_L2N_D	Weibull	α=2.6525 β=6.3579
XL2_L2N_E	Gamma	α=8.9131 β=0.51364

B. *SIMUL8* model characteristics definition

B.1. Defective products

Table B.1. *Data collected on the site regarding the number of seconds that passed until defective product was verified, in seconds.*

	Line 1					**Line 2**					**Line 2 - New machine**				
Product Type	**MK**	**M**	**XL**	**M2**	**XL2**	**MK**	**M**	**XL**	**M2**	**XL2**	**MK**	**M**	**XL**	**M2**	**XL2**
Observation 1	48	42	48	36	126	60	42	36	42	12	54	42	54	48	42
Observation 2	54	48	54	48	48	6	54	42	54	48	48	42	48	48	66
Observation 3	48	48	48	42	42	42	42	54	48	54	48	54	48	54	54
Observation 4	42	48	48	48	36	48	42	48	48	42	42	54	48	48	48
Observation 5	42	48	48	30	48	42	54	54	60	54	48	42	48	54	24
Observation 6	54	48	48	54	54	54	54	36	54	48	54	48	42	54	48
Observation 7	48	36	36	48	42	42	48	30	53	48	48	60	42	54	36
Observation 8	42	48	48	48	42	42	48	52	54	54	42	48	48	42	42
Observation 9	48	42	54	42	42	42	48	54	42	36	42	48	48	42	42
Observation 10	42	48	48	50	54	48	54	54	42	36	42	48	54	48	42
Observation 11	54	48	48	36	42	42	60	48	54	48	42	48	48	54	36
Observation 12	54	36	48	54	42	54	54	48	36	42	42	48	42	42	54
Observation 13	54	48	48	60	36	48	48	48	54	54	42	60	42	42	42
Observation 14	48	54	50	54	54	48	42	54	42	54	48	48	48	48	42
Observation 15	48	60	60	48	42	48	42	48	36	48	48	54	54	48	42
Observation 16	48	36	54	48	42	54	36	48	42	42	48	48	36	42	42
Observation 17	54	48	42	54	42	48	42	42	42	54	54	54	54	54	48
Observation 18	44	48	42	48	54	48	54	48	48	54	42	42	48	48	42
Observation 19	42	48	42	42	48	42	42	54	42	48	42	48	42	48	48
Observation 20	48	47	48	35	54	54	36	42	42	42	54	42	54	48	54
Average	***47.1***														

B.2. System set-up times

Table B.2. *Observed set-up times in the system, in seconds.*

Observation number	*Set-up time (s)*
Observation 1	***404***
Observation 2	***1173***
Observation 3	***600***
Observation 4	***620***
Observation 5	***753***
Observation 6	***621***
Observation 7	***946***
Observation 8	***575***
Observation 9	***1168***
Observation 10	***670***
Observation 11	***544***
Observation 12	***704***
Observation 13	***823***
Observation 14	***614***
Observation 15	***945***
Observation 16	***621***
Observation 17	***915***
Observation 18	***504***
Observation 19	***160***
Observation 20	***623***
Average Set-up time	***699.22***

B.3. System breakdowns

Table B.3. *Average time between breakdown in seconds.*

Observation number	*Number of breakdowns observed per hour of production*
Observation 1	***1***
Observation 2	***2***
Observation 3	***4***
Observation 4	***0***
Observation 5	***0***
Observation 6	***0***
Observation 7	***5***
Observation 8	***0***
Observation 9	***0***
Observation 10	***0***
Observation 11	***1***
Observation 12	***0***
Observation 13	***0***
Observation 14	***0***
Observation 15	***0***
Observation 16	***2***
Observation 17	***0***
Observation 18	***1***
Observation 19	***2***
Observation 20	***0***

Average number of breakdowns per hour	***0.9***
Average time between breakdowns	***3240 seconds***

Table B.4. *Average repair time on breakdowns for workstation C, based on the data collected on the site, in seconds.*

Observation number	*Time of reparation of a breakdown (s)*
Observation 1	10
Observation 2	60
Observation 3	1100
Observation 4	90
Observation 5	205
Observation 6	282
Observation 7	306
Observation 8	271
Observation 9	282
Observation 10	275
Observation 11	345
Observation 12	285
Observation 13	284
Observation 14	219
Observation 15	329
Observation 16	288
Observation 17	349
Observation 18	299
Observation 19	351
Observation 20	239
Average time	***293***

B.4. Components' shortage stop-times

Table B.5. *Time, in seconds, that the system awaits the replenishment of materials, in seconds.*

Observation number	*Time the system is waiting for supplies to be supplied (s)*
Observation 1	460
Observation 2	174
Observation 3	900
Observation 4	511
Observation 5	210
Observation 6	432
Observation 7	449
Observation 8	449
Observation 9	451
Observation 10	442
Observation 11	444
Observation 12	458
Observation 13	450
Observation 14	460
Observation 15	426
Observation 16	456
Observation 17	463
Observation 18	414
Observation 19	435
Observation 20	545
Average time	***451***

C. Detailed Results

C.1. Initial manufacturing system

This Section aims to characterize the previously described parameters on the studied manufacturing lines (*vide* Table 4.3. in Section 4.5.2.), comparing these metrics between the different manufacturing lines. Based on the previously presented conditions and data it was created an initial scenario that reflects the initial situation of the analysed manufacturing lines, characterizing only *Line 1* and *Line 2*.

C.1.1. Product M

This product can be produced both in *Line 1* and *Line 2*. The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the systems, both to *Line 1* and *Line 2*.

Table C.1. *Performance of Line 1 when producing the product M.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1260.4*	*1249.6*	*1266.3*	*1264.3*	*1249.5*
Operation Duration (s)	*2.9*	*2.1*	*2.1*	*2.3*	*2.2*
Relative Efficiency (%)	*99.14*				
Efficiency of utilisation (%)	*71.18*				
Mean-life time (s)	*199.0*				

Table C.2. *Performance of Line 2 when producing the product M.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1260.3*	*1260.3*	*1085.0*	*1085.0*	*1072.3*
Operation Duration (s)	*2.9*	*2.8*	*3.0*	*2.9*	*2.6*
Relative Efficiency (%)	*85.09*				
Efficiency of utilisation (%)	*94.31*				
Mean-life time (s)	*1840.4*				

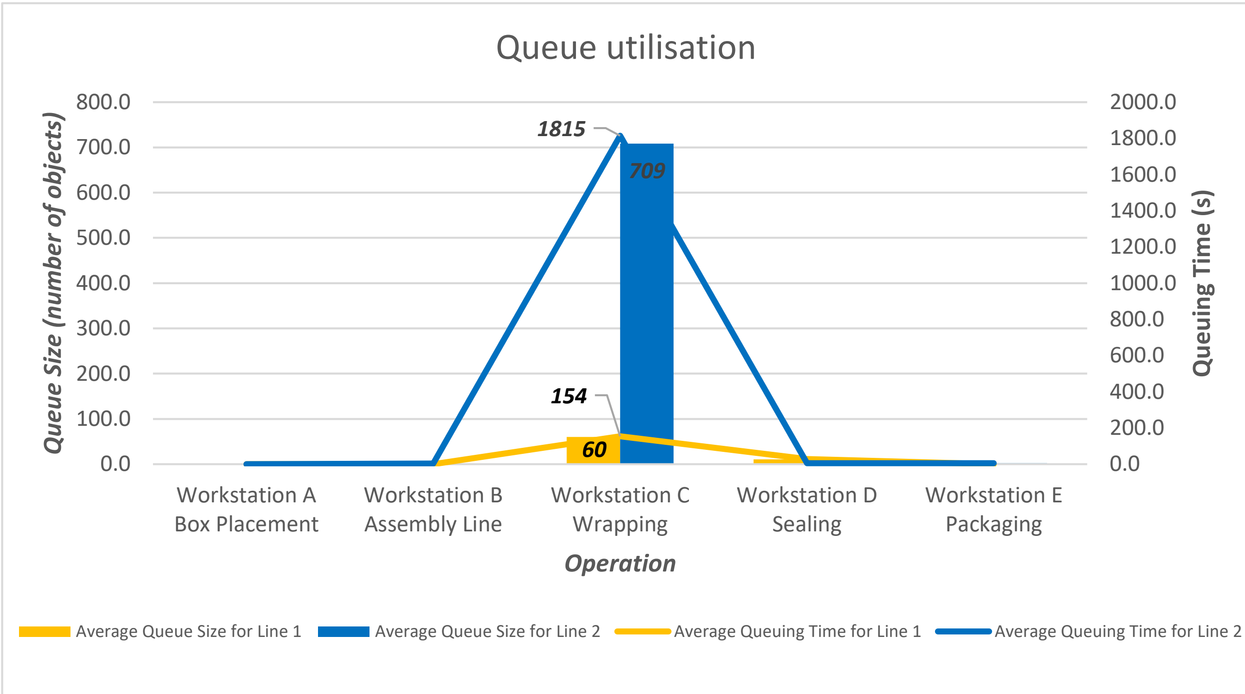
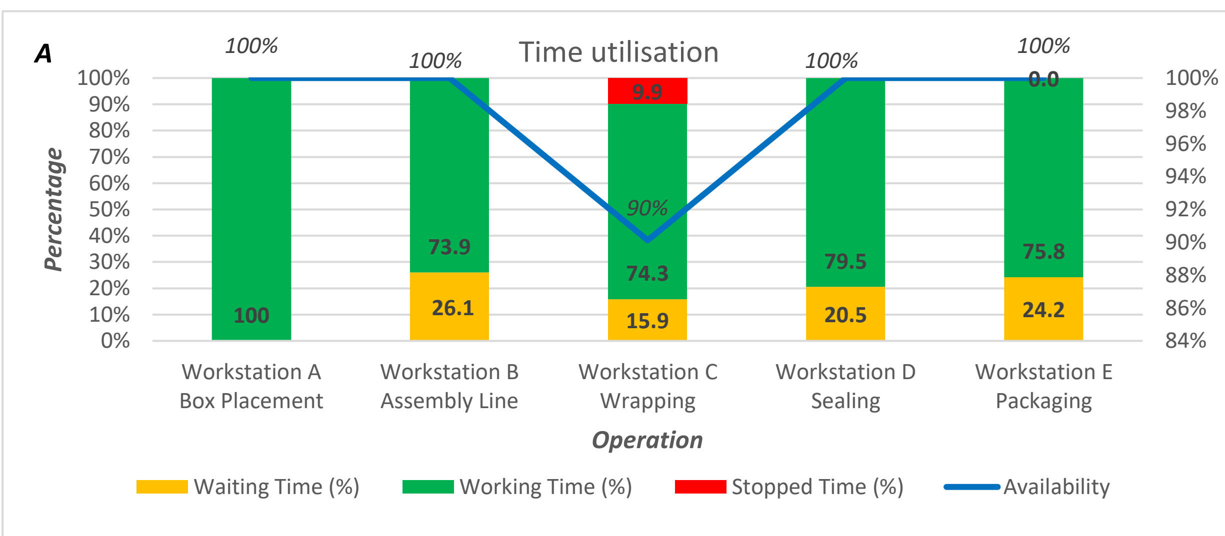


Figure C.1. Characterisation of the Line 1 and Line 2 on the queue utilisation, both in queue size and queueing time for each workstation.



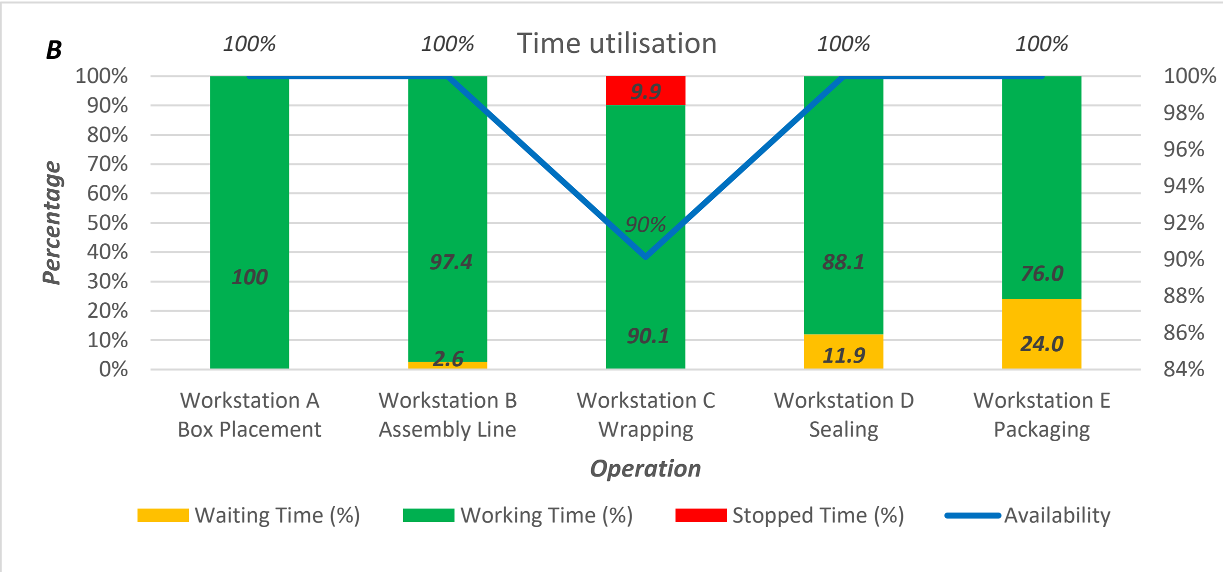


Figure C.2. Characterisation of Line 1 (A) and Line 2 (B) in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.1.2. Product M2

This product can be produced both in *Line 1* and *Line 2*. The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the systems, both to *Line 1* and *Line 2*

Table C.3. *Performance of Line 1 when producing the product M2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1484.9*	*1211.9*	*1163.3*	*1147.1*	*951.4*
Operation Duration (s)	*2.4*	*3.0*	*2.7*	*2.9*	*3.8*
Relative Efficiency (%)	*64.07*				
Efficiency of utilisation (%)	*78.19*				
Mean-life time (s)	*899.6*				

Table C.4. *Performance of Line 2 when producing the product M2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1484.9*	*1090.2*	*947.5*	*905.2*	*807.4*
Operation Duration (s)	*2.4*	*3.3*	*3.5*	*3.8*	*4.3*
Relative Efficiency (%)	*54.37*				
Efficiency of utilisation (%)	*80.37*				
Mean-life time (s)	*1158.4*				

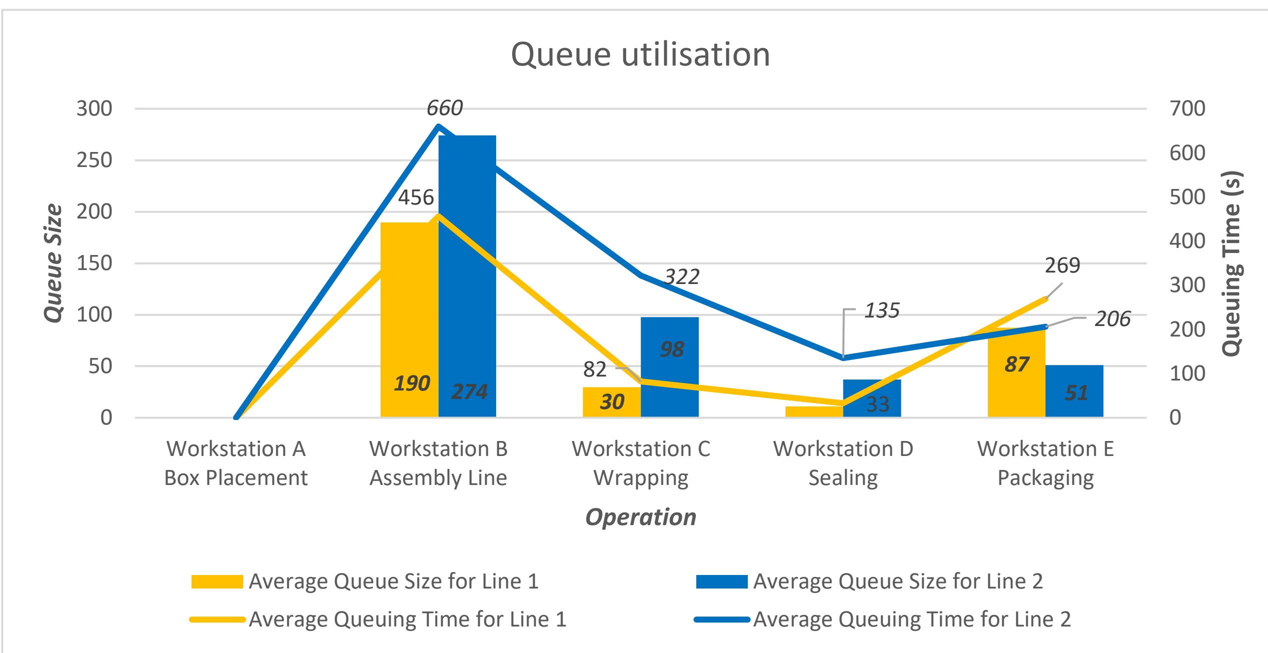
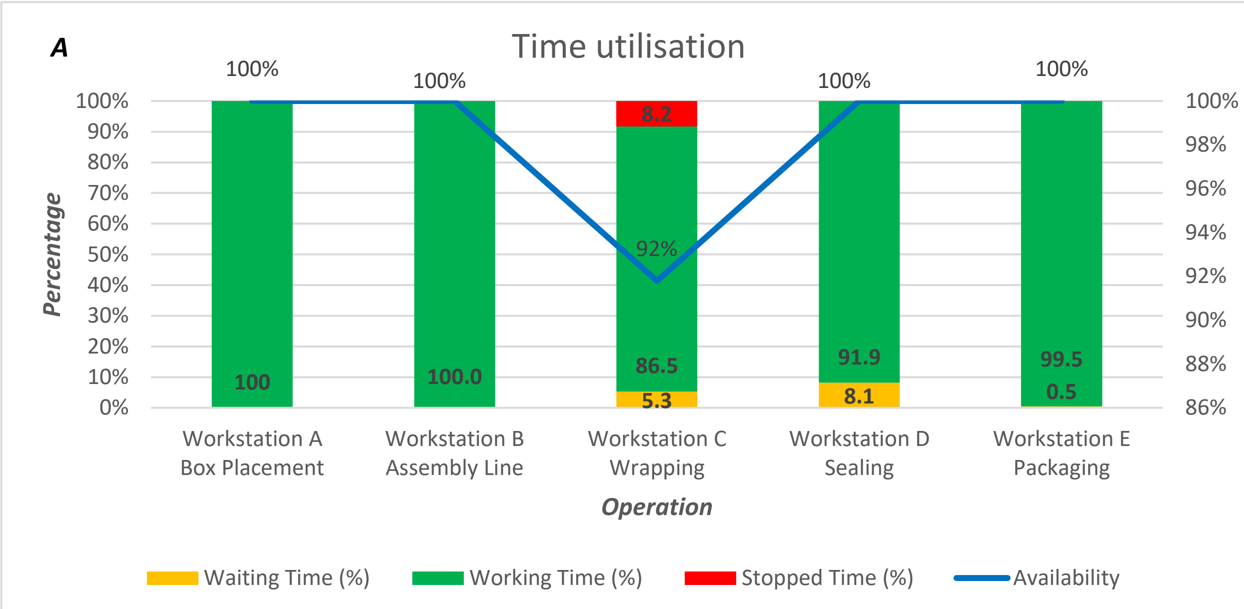


Figure C.3. Characterisation of Line 1 and Line 2 on the queue utilisation, both in queue size and queueing time for each workstation



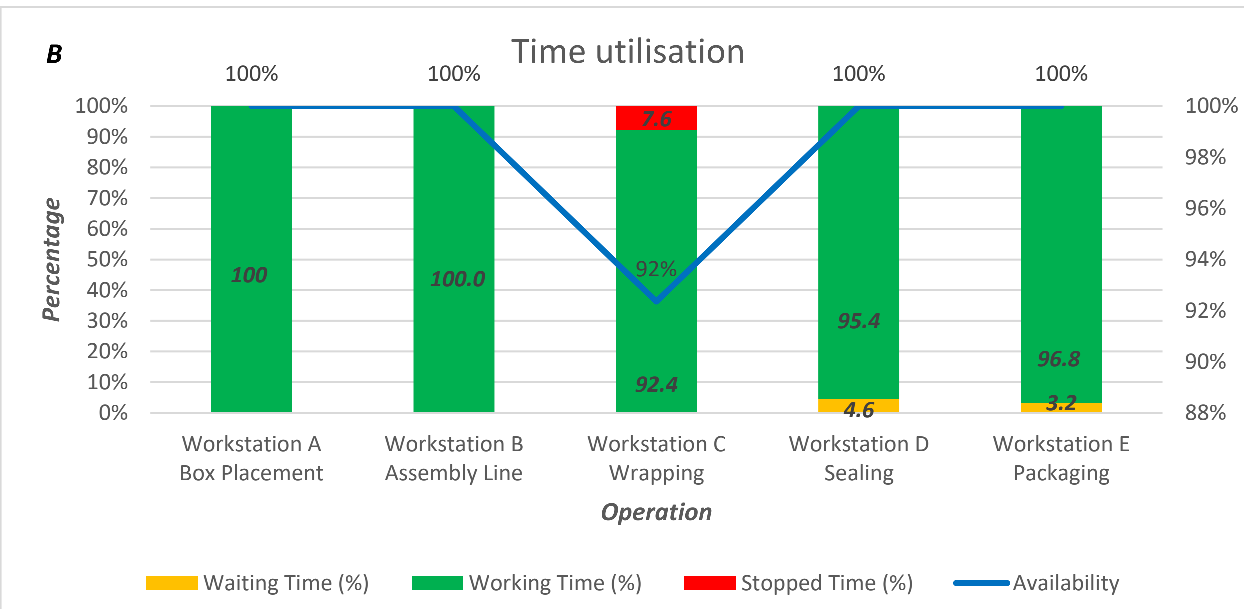


Figure C.4. Characterisation of Line 1 (A) and Line 2 (B) in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.1.3. Product MiniKit

This product can be produced both in *Line 1* and *Line 2*. The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the systems, both to *Line 1* and *Line 2*.

Table C.5. *Performance of Line 1 when producing the product MiniKit.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1522.1*	*1522.1*	*1477.4*	*1470.8*	*1280.4*
Operation Duration (s)	*2.4*	*2.0*	*2.0*	*2.1*	*2.8*
Relative Efficiency (%)	*84.12*				
Efficiency of utilisation (%)	*80.71*				
Mean-life time (s)	*406.1*				

Table C.6. *Performance of Line 2 when producing the product MK.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1131.5*	*1131.5*	*1108.0*	*1056.8*	*1044.3*
Operation Duration (s)	*3.2*	*2.5*	*2.6*	*3.2*	*2.8*
Relative Efficiency (%)	*92.29*				
Efficiency of utilisation (%)	*89.25*				
Mean-life time (s)	*257.8*				

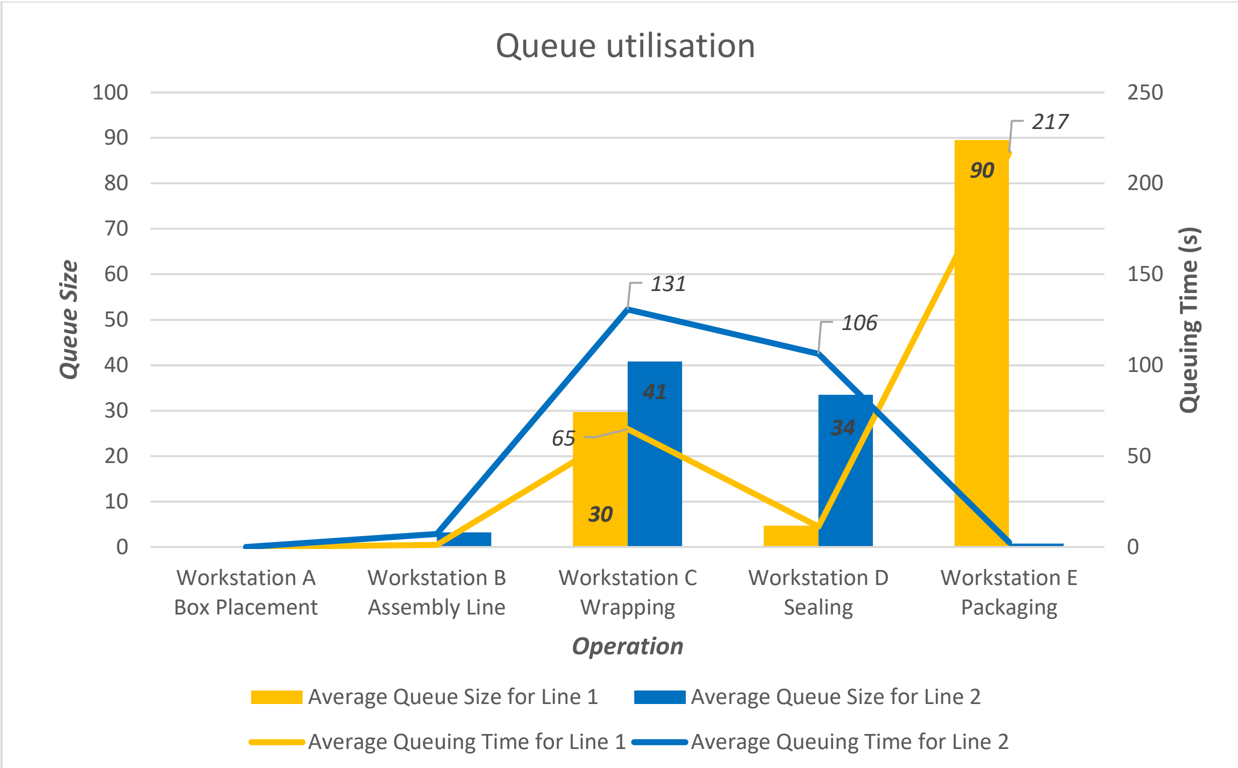
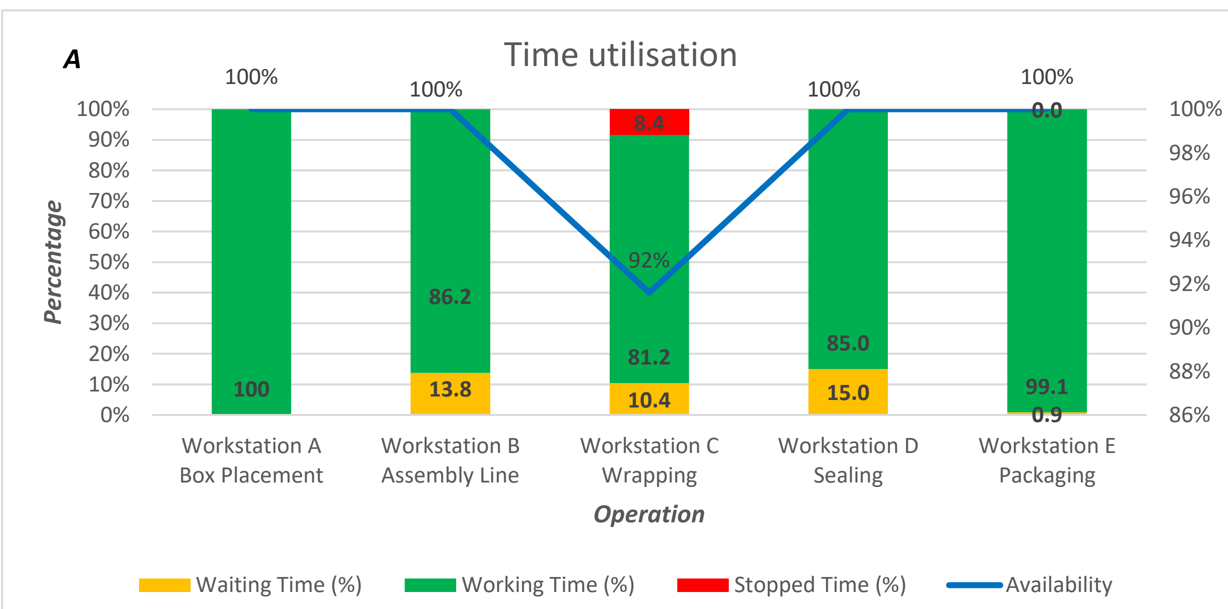


Figure C.5. Characterisation of the Line 1 and Line 2 on the queue utilisation, both in queue size and queueing time for each workstation.



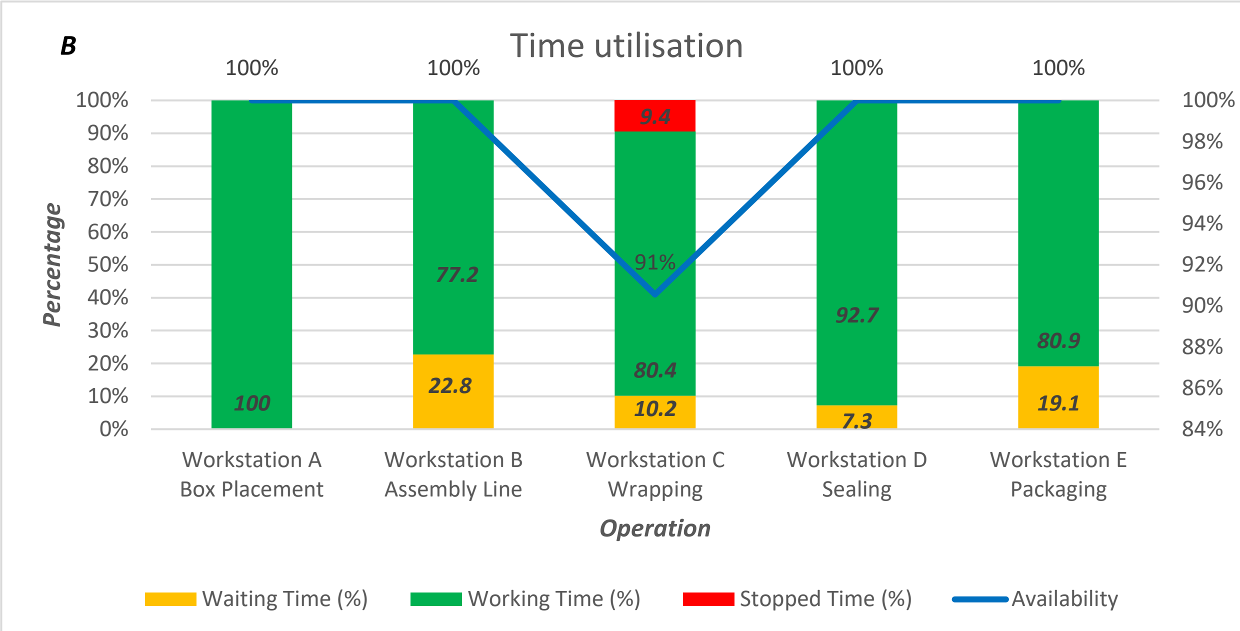


Figure C.6. Characterisation of Line 1 (A) and Line 2 (B) in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.1.4. Product XL

This product can be produced both in *Line 1* and *Line 2*. The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the systems, both to *Line 1* and *Line 2*.

Table C.7. *Performance of Line 1 when producing the product XL.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*833.3*	*771.7*	*757.6*	*753.7*	*697.2*
Operation Duration (s)	*4.3*	*4.7*	*3.6*	*3.9*	*5.0*
Relative Efficiency (%)	*83.67*				
Efficiency of utilisation (%)	*85.90*				
Mean-life time (s)	*416.2*				

Table C.8. *Performance of Line 2 when producing the product XL.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*834.6*	*772.3*	*755.3*	*747.5*	*738.6*
Operation Duration (s)	*4.3*	*4.7*	*3.8*	*4.2*	*3.7*
Relative Efficiency (%)	*88.5*				
Efficiency of utilisation (%)	*88.42*				
Mean-life time (s)	*343.0*				

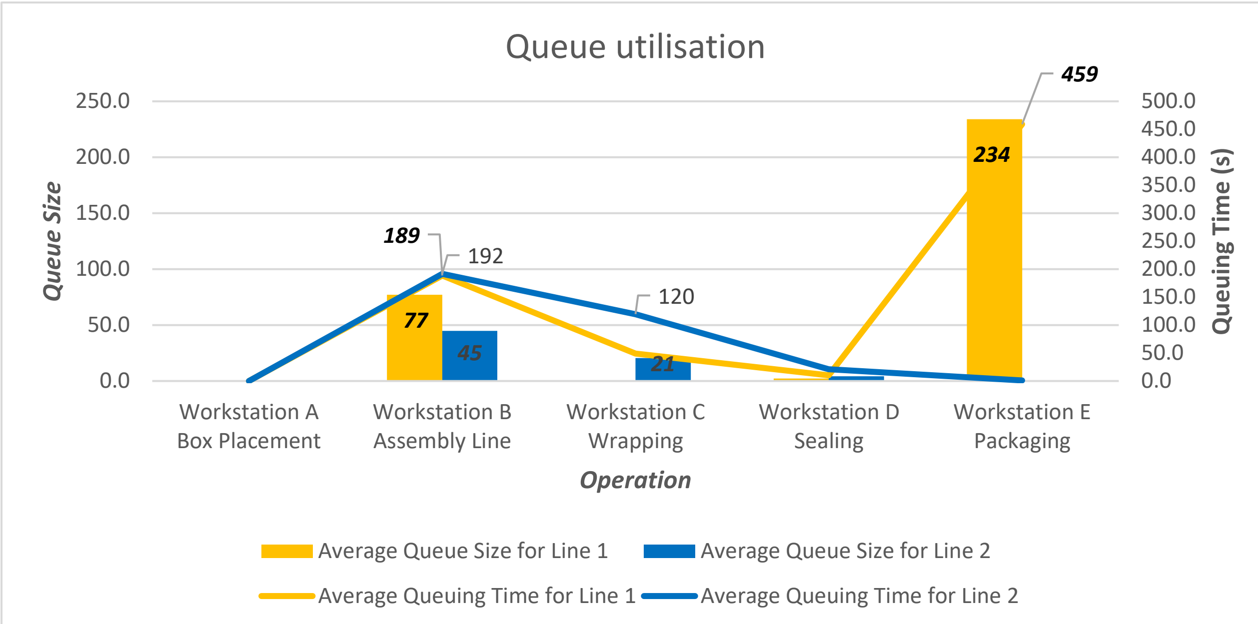
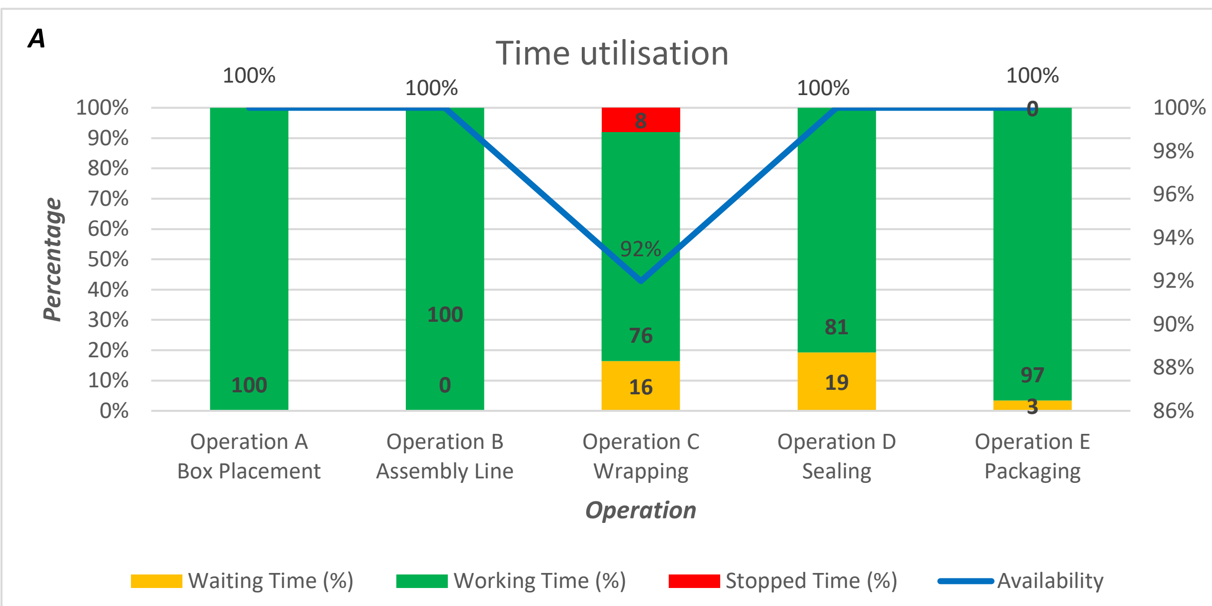


Figure C.7. Characterisation of the Line 1 and Line 2 on the queue utilisation, both in queue size and queueing time for each workstation



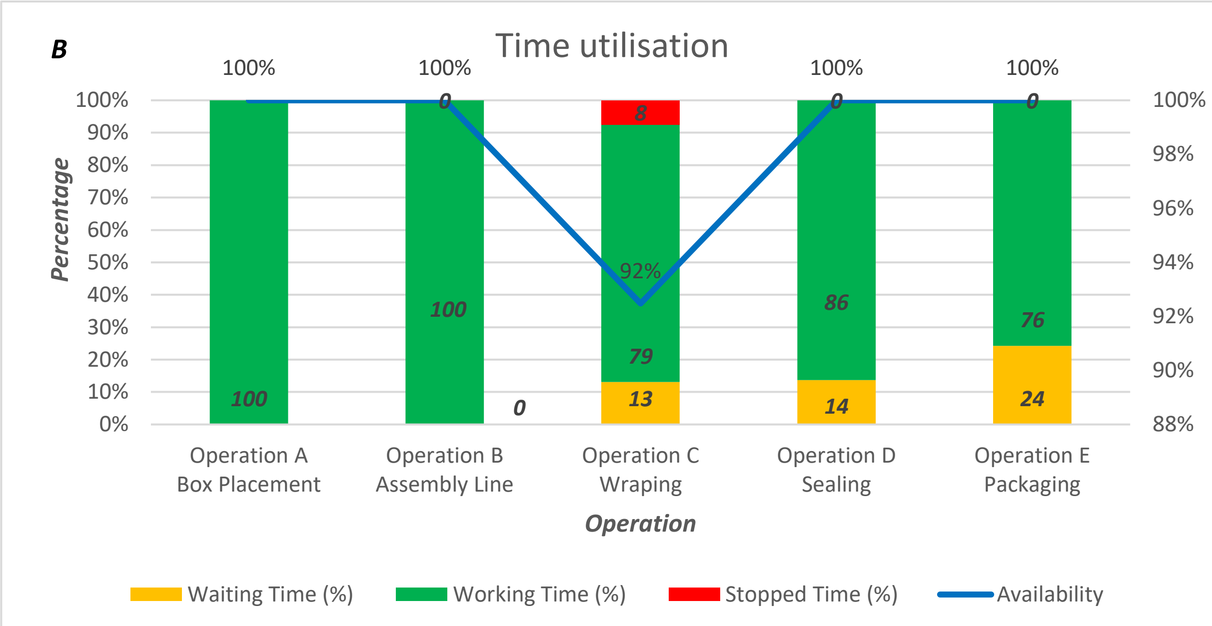


Figure C.8. Characterisation of Line 1 (A) and Line 2 (B) in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.1.5. Product XL2

This product can be produced only in *Line 1*. The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.9. *Performance of Line 1 when producing the product XL2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*853.8*	*838.9*	*725.8*	*719.9*	*711.5*
Operation Duration (s)	*4.2*	*4.3*	*4.5*	*4.7*	*4.6*
Relative Efficiency (%)	*83.33*				
Efficiency of utilisation (%)	*94.46*				
Mean-life time (s)	*2440.8*				

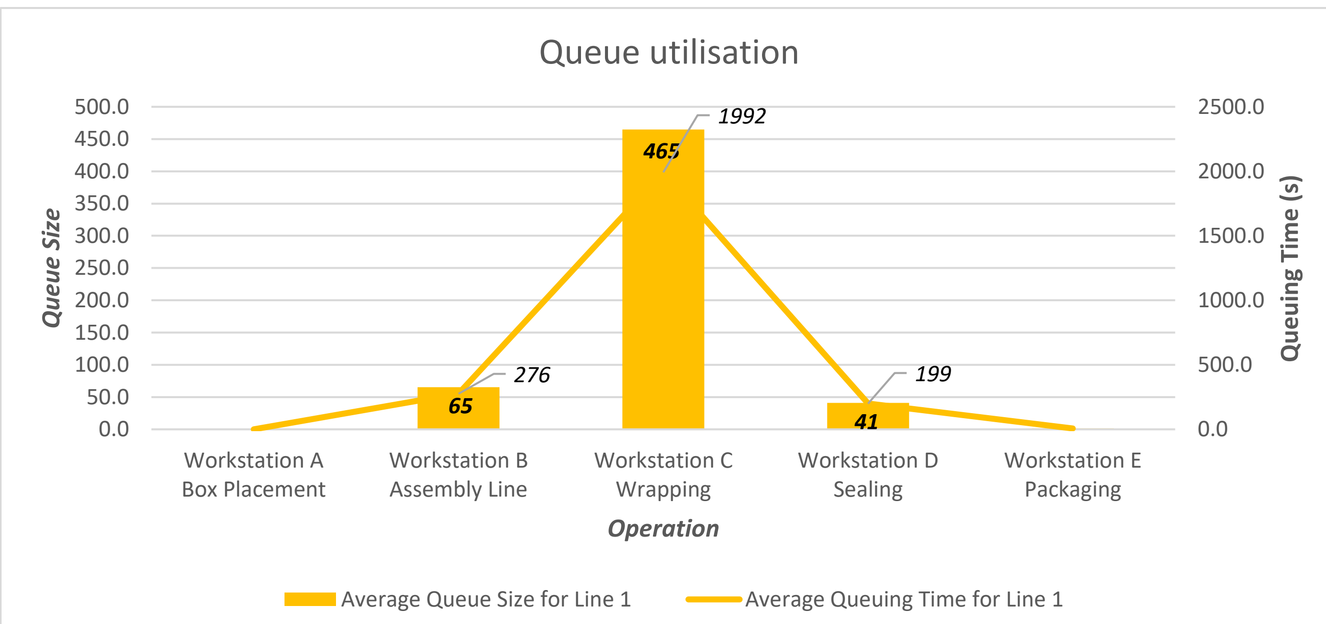


Figure C.9. Characterisation of Line 1 on the queue utilisation, both in queue size and queueing time for each workstation

Figure C.10. detail the time utilisation on this system, allowing to evaluate it in a wider set of parameters.

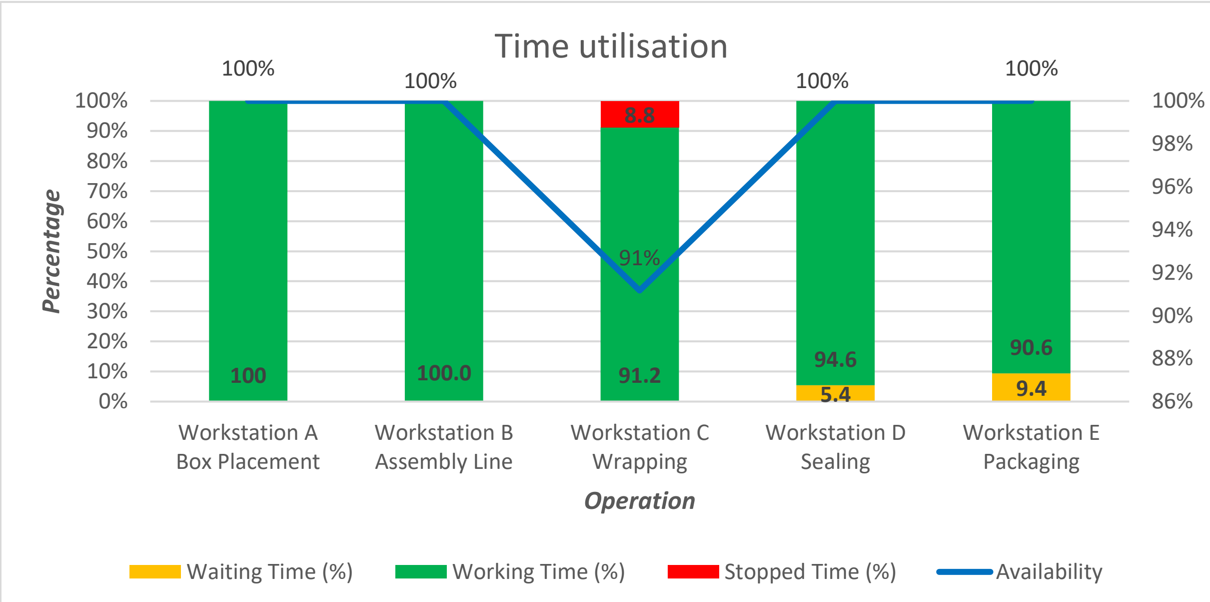


Figure C.10. Characterisation of Line 1 in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.2. Line adaptation

With the modification of some equipment that composed Line 2, a structural change occurred, and it had to be analysed as a new production line. This new line is capable of processing all product types.

C.2.1. Product M

The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.10. *Performance of Line 2 – New machine when producing the product XL2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1260.2*	*1260.2*	*1214.8*	*1187.0*	*1173.2*
Operation Duration (s)	*2.9*	*2.8*	*2.6*	*2.9*	*2.6*
Relative Efficiency (%)	*93.09*				
Efficiency of utilisation (%)	*94.07*				
Mean-life time (s)	*976.1*				

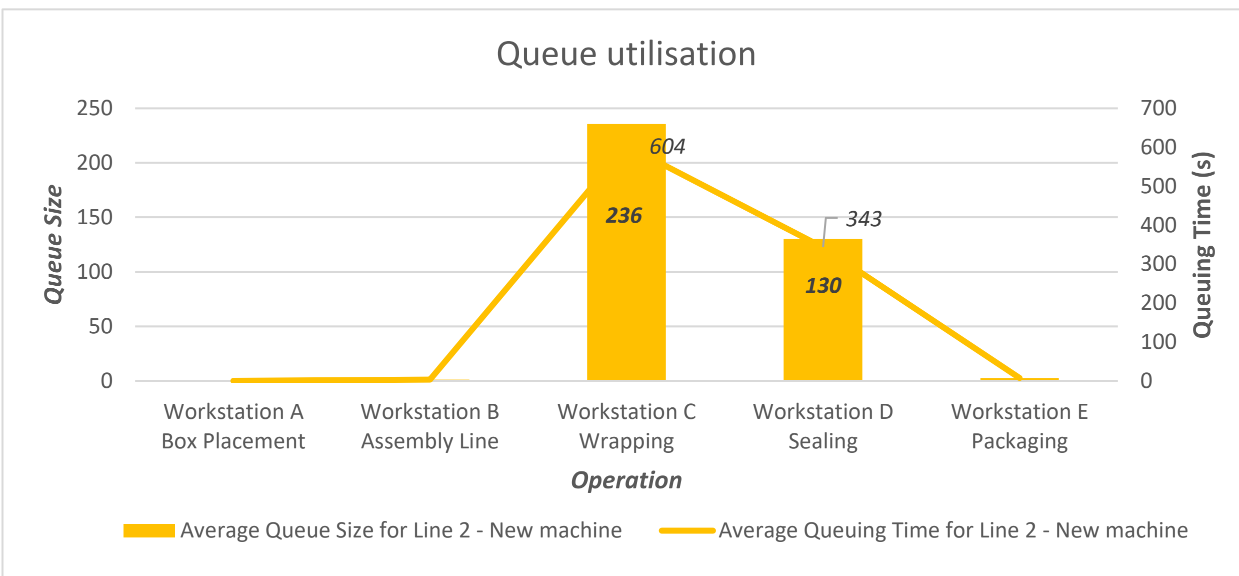


Figure C.11. Characterisation of Line 2 - New machine on the queue utilisation, both in queue size and queueing time for each workstation.

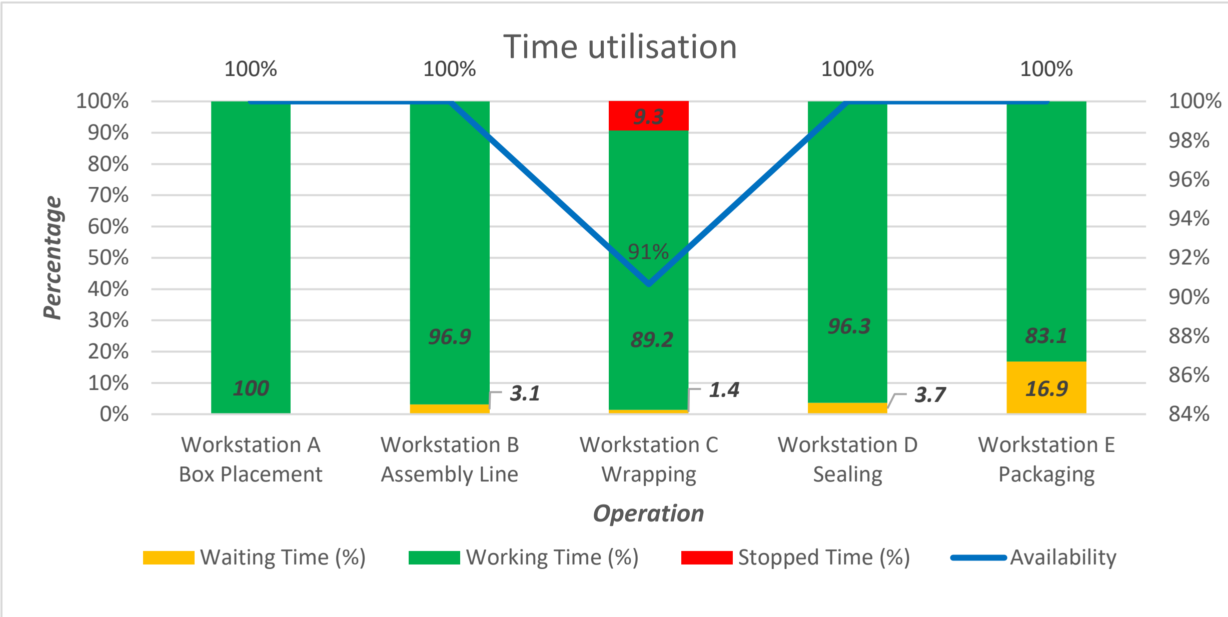


Figure C.12. Characterisation of Line 2 – New machine in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.2.2. Product M2

The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.11. *Performance of Line 2 – New machine when producing the product M2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1139.0*	*1090.0*	*1087.6*	*994.4*	*994.4*
Operation Duration (s)	*3.2*	*3.3*	*1.4*	*3.5*	*3.5*
Relative Efficiency (%)	*87.31*				
Efficiency of utilisation (%)	*85.38*				
Mean-life time (s)	*395.5*				

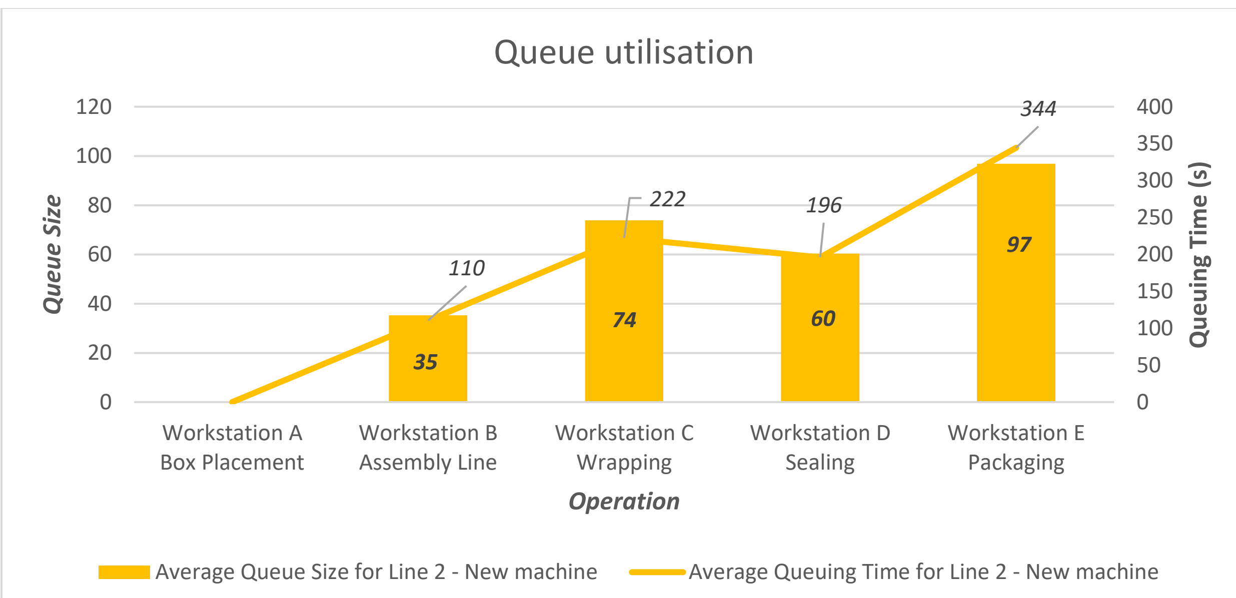


Figure C.13. Characterisation of Line 2 – New machine on the queue utilisation, both in queue size and queueing time for each workstation.

Figure C.14 details the time utilisation on this system, allowing to evaluate it in a wider set of parameters.

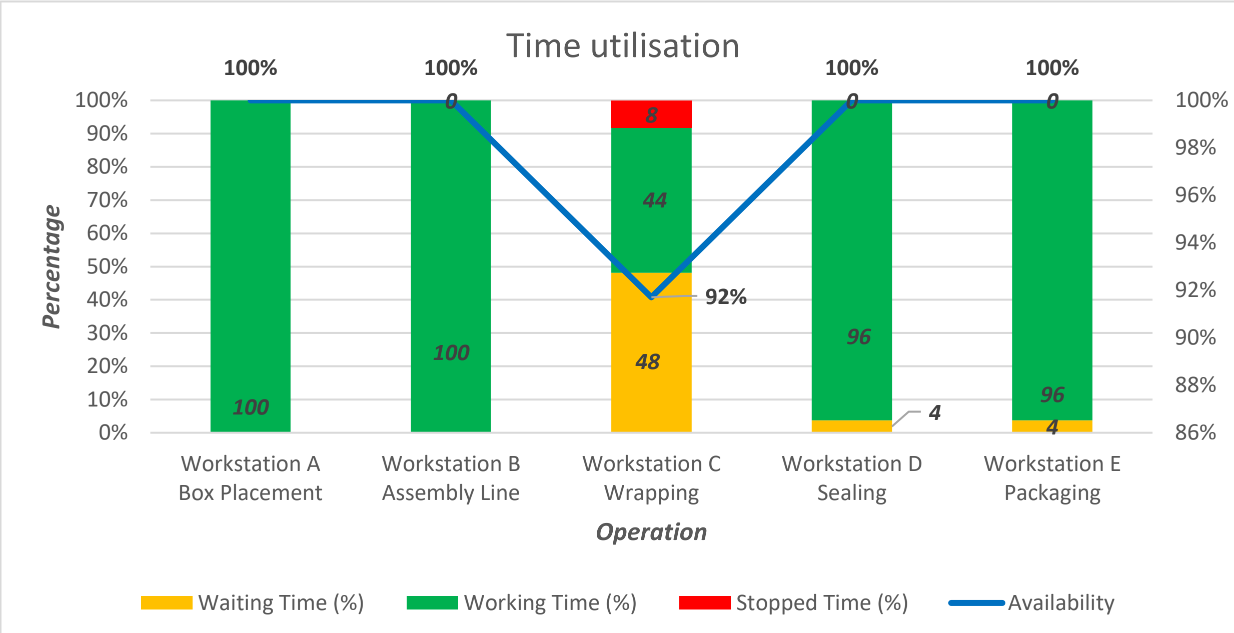


Figure C.14. Characterisation of Line 2 – New machine in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.2.3. Product MiniKit

The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.12. *Performance of Line 2 – New machine when producing the product M2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*1699.9*	*1584.8*	*1592.9*	*1509.0*	*1266.1*
Operation Duration (s)	*2.1*	*2.3*	*0.7*	*2.1*	*2.8*
Relative Efficiency (%)	*74.48*				
Efficiency of utilisation (%)	*71.57*				
Mean-life time (s)	*672.8*				

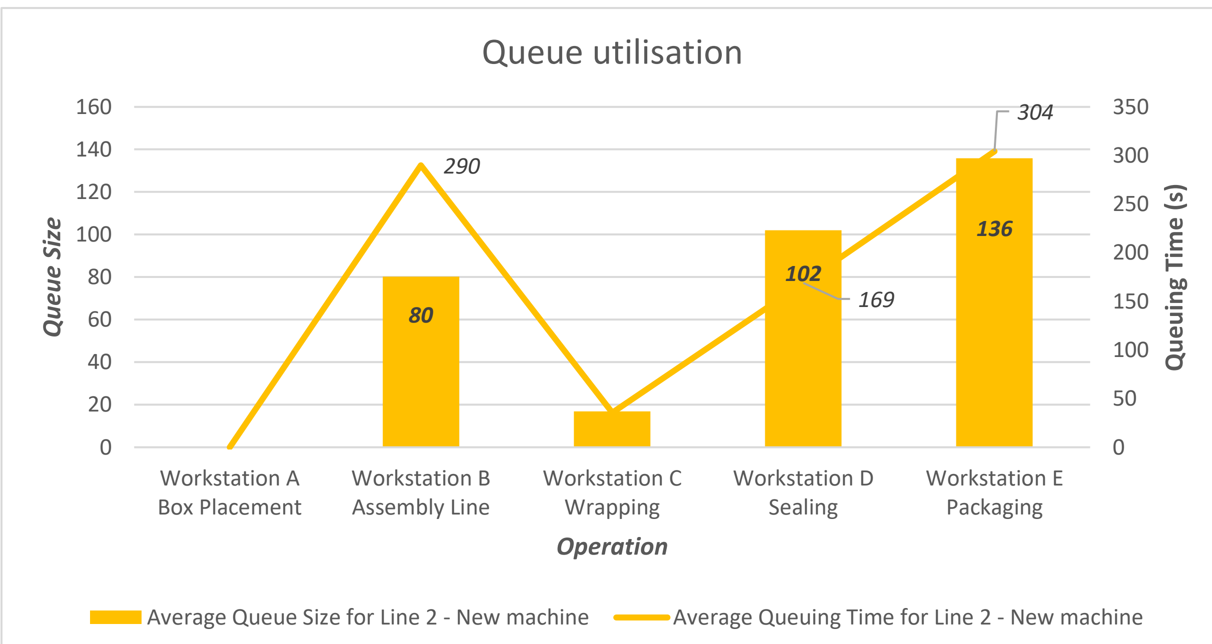


Figure C.15. Characterisation of Line 2 – New machine on the queue utilisation, both in queue size and queueing time for each workstation.

Figure C.16. details the time utilisation on this system, allowing to evaluate it in a wider set of parameters.

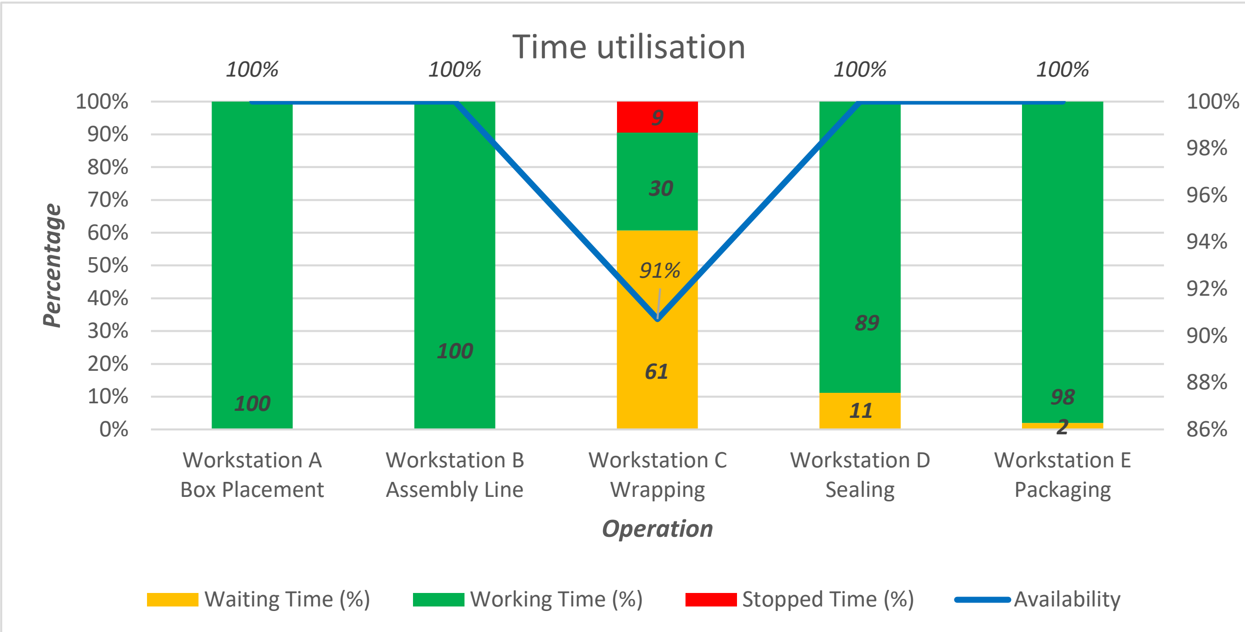


Figure C.16. Characterisation of Line 2 – New machine in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.2.4. Product XL

The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.13. *Performance of Line 2 – New machine when producing the product M2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*991.5*	*760.9*	*742.0*	*738.1*	*729.5*
Operation Duration (s)	*3.6*	*4.7*	*3.6*	*3.8*	*3.1*
Relative Efficiency (%)	*73.5*				
Efficiency of utilisation (%)	*79.83*				
Mean-life time (s)	*721.0*				

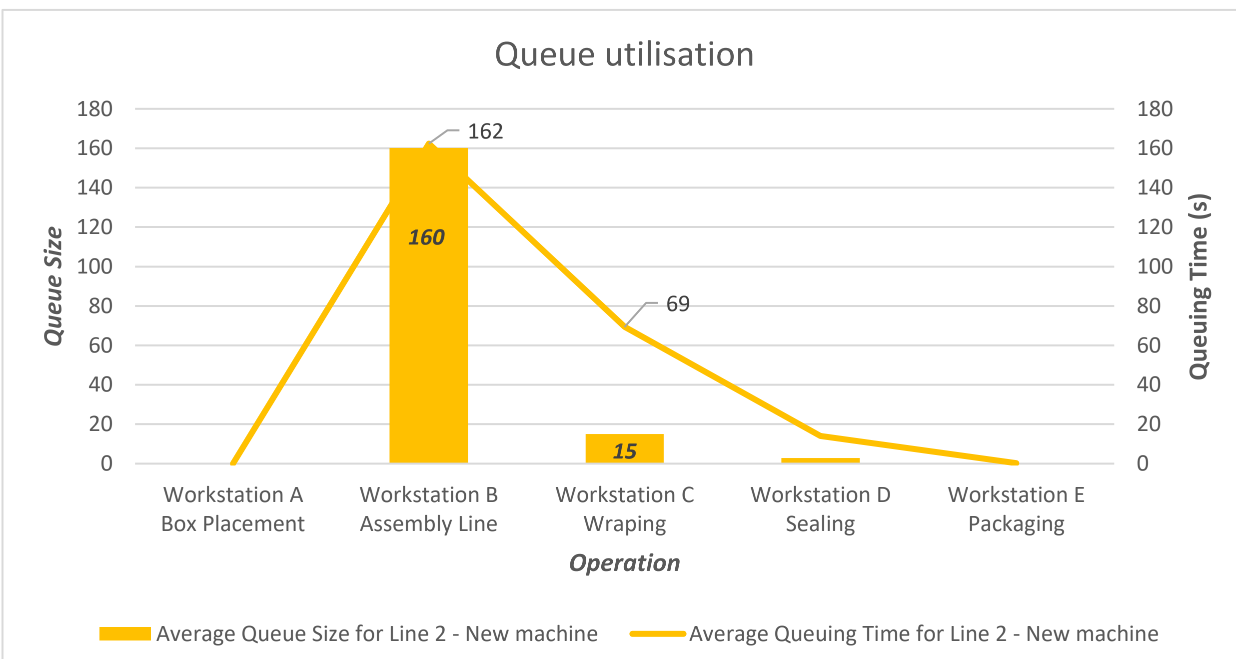


Figure C.17. Characterisation of Line 2 – New machine on the queue utilisation, both in queue size and queueing time for each workstation.

Figure C.18. details the time utilisation on this system, allowing to evaluate it in a wider set of parameters.

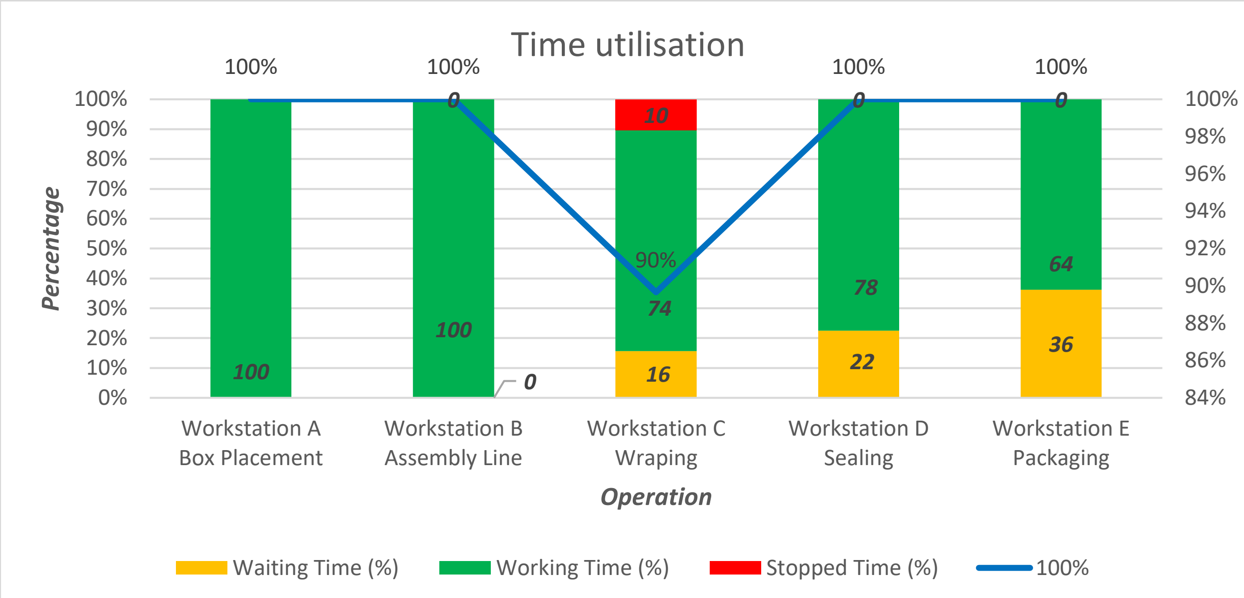


Figure C.18. Characterisation of Line 2 – New machine in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.

C.2.5. Product XL2

The following tables and figures express the performance of the manufacturing lines, on the amount of output produced, the time utilisation of the system and the identification of bottlenecks on the system.

Table C.14. *Performance of Line 2 – New machine when producing the product Xl2.*

	Workstation A Box Placement	***Workstation B Assembly Line***	***Workstation C Wrapping***	***Workstation D Sealing***	***Workstation E Packaging***
Average Throughput per hour (number of objects)	*435.7*	*435.4*	*329.2*	*329.2*	*325.3*
Operation Duration (s)	*8.3*	*8.0*	*10.0*	*5.7*	*4.6*
Relative Efficiency (%)	*74.67*				
Efficiency of utilisation (%)	*73.04*				
Mean-life time (s)	*3692.6*				

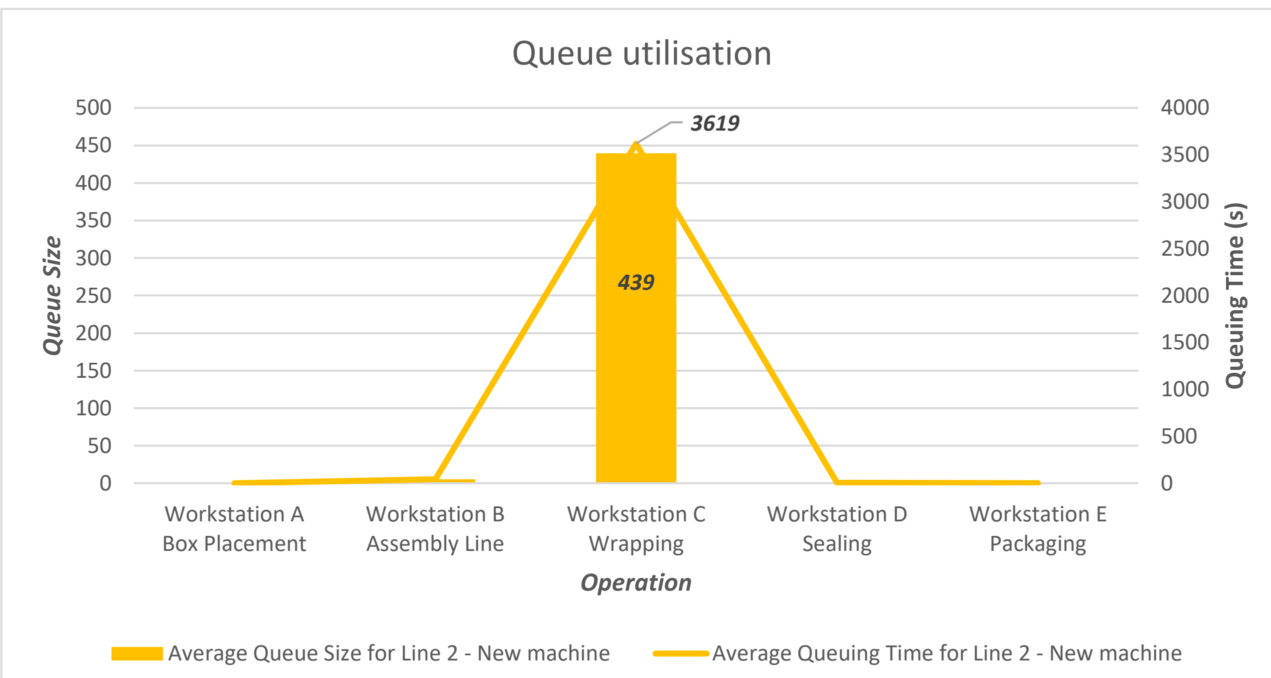


Figure C.19. Characterisation of Line 2 – New machine on the queue utilisation, both in queue size and queueing time for each workstation.

Figure C.20 details the time utilisation on this system, allowing to evaluate it in a wider set of parameters.

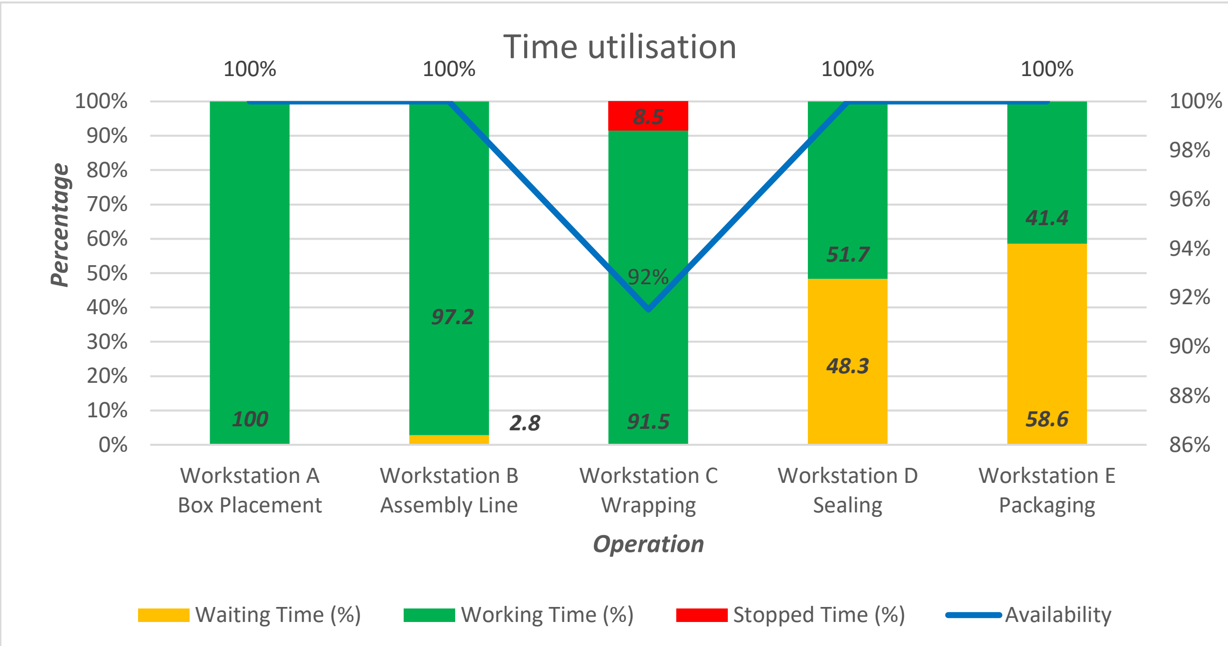


Figure C.20. Characterisation of Line 2 – New machine in terms of time utilisation detailing the percentage of Working, Waiting and Stopped Time, and the Availability.