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AN ASSESSMENT OF THE MIXED-MODEL ASSEMBLY LINE BALANCING AND SEQUENCING PROBLEM

Dissertação no âmbito do Mestrado em Engenharia e Gestão Industrial orientada pelos Professores Doutor Cristóvão Silva e Anthony Quenehen e apresentada ao Departamento de Engenharia Mecânica da Universidade de Coimbra

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Uma avaliação dos problemas de equilibragem e sequenciamento de uma linha de montagem de modelos mistos

Dissertação apresentada para a obtenção do grau de Mestre em Engenharia e Gestão Industrial

An assessment of the mixed-model assembly line balancing and sequencing problem

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C’est le temps que tu as perdu pour ta rose qui fait ta rose si importante.

Le Petit Prince

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Resumo

A manufatura evoluiu e com a sua evolução surgem novos desafios que se pretendem superar. A produção em massa foi substituída pela customização em massa, o que obrigou as empresas a reformular as linhas de montagem. O crescimento da procura por produtos customizados obrigaria a custos avultados na construção de uma linha para cada variante dos produtos. Assim, surgiram as linhas de montagem de modelos mistos, e o tradicional layout reto foi substituído pelo formato em U para obter maior flexibilidade. Com estas apareceram também novos problemas relacionados com a equilibragem das linhas e o seu sequenciamento. Este trabalho centra-se no sequenciamento destas novas linhas de montagem, mas para tal é necessário garantir que existe uma equilibragem teoricamente perfeita da linha. Para uma linha que monta cilindros pneumáticos e com uma possibilidade de gerar mais de 200 combinações distintas, a sua equilibragem e o seu sequenciamento são tarefas árduas e complexas. Através da simulação e da análise dos dados fornecidos pela simulação, espera-se obter as informações necessárias. As informações sobre as listas de combinações dos produtos que devem ser evitadas no sequenciamento são recolhidas para que não ocorram paragens não planeadas pela equilibragem. Ao serem eliminadas estas listas de maior percentagem de bloqueamento espera-se alcançar o sequenciamento ideal. Este método foi facilmente testado e verificado para uma linha perfeitamente equilibrada de três estações e dois produtos. Ao aumentar a complexidade de forma a aproximar-se da linha real, o número de sequências que causam o bloqueio da linha aumentam de forma exponencial. Minimizar o tempo bloqueado será cada vez mais crucial para a empresa, mas outras regras podem ser violadas. Definir claramente o peso da transgressão das regras estipuladas permitirá entender o impacto de desconsiderar as quantidades de produção para minimizar o tempo ocioso.

Palavras-chave: Linhas de montagem de modelos mistos, Problemas de equilibragem nas linhas de montagem, Simulação do sequenciamento.

Abstract

Manufacturing has evolved, and with its evolution, new challenges arise that are intended to be overcome. Mass production was replaced by mass customization, which forced companies to reformulate the assembly lines. The growth of demand for customized products meant high costs in the construction of a line for each product variant. Thus, the mixed-model assembly lines emerged, and the traditional straight layout was replaced for the U-shaped form to obtain greater flexibility. New problems related to the balance of the lines and their sequencing have arisen. This work focuses on the sequencing of these new assembly lines, but for this, it is necessary to ensure that there is a theoretically perfect balance of the line. For an assembly line that assembles pneumatic cylinders and with the possibility of generating more than 200 different combinations, its balance and sequencing are arduous and complex tasks. Through the simulation and analysis of the data provided by the simulation, it is expected to obtain necessary information. Information about lists of product combinations that should be avoided in the sequencing is collected so as not to occur unplanned stops in the balancing. When the lists of products with the highest blocking percentage are eliminated, the ideal sequencing is expected to be achieved. This method was easily tested and verified for a perfectly balanced line of three stations and two products. When increasing the complexity to approach to the real line, the number of lists that cause the line to block increases exponentially. To minimize the blocked time will be increasingly crucial for the company, but other rules can be broken. Clearly defining the weight of breaking the rules will allow understanding the impact of disregarding production quantities to minimize idle time.

Keywords Mixed-model Assembly lines, Assembly Line Balancing Problems, Sequencing Simulation.

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SYMBOLOGY AND ABBREVIATIONS

Symbology

$i = 1, \dots, p$ – product

$k = 1, \dots, m$ – workstation

$t(WS_k)_i$ – Task time in k and for i.

$C_S(WS_k)_i$ – Clock when i starts at the k

$C_F(WS_k)_i$ – Clock when i finishes the task at k

$C_S(S_{k,k+1})_i$ – Clock when i enter in the stock between k and k+1

$C_F(S_{k,k+1})_i$ – Clock when i leaves the task at the stock between k and k+1

$t(S_{k,k+1})_i$ – Time in stock between k and k+1 for i.

Abbreviations

ENSAM – École Nationale Supérieure d'Arts et Métiers

Lispen – Laboratoire d’Ingénierie des Systèmes Physiques et Numériques

US – United States

GM – General Motors

AL – Assembly line

WS – Workstation

MMAL – Mixed-models assembly line

MuMAL - Multi-models assembly line

JIT – Just in time

ALBP – Assembly line balancing problem

SALBP – Simple assembly line balancing problem

GALBP – General assembly line balancing problem

UALBP – U-shaped assembly line balancing problem

MMALBP – Mixed-model assembly line balancing problem

MMP – Mixed-models Planning

OPR – Operational Ratio

WACT – Weighted average cycle time

SI – Smoothness index

BD – Balancing delay

1. INTRODUCTION

Manufacturing is the art of working. Manufacturing was present throughout humankind history; after all, “Man is a tool-using Animal”. Nevertheless, manufacturing, as we know it nowadays, has its origins in the 18th century, driven by the invention of the steam engine. The steam engine brought unprecedented power to almost any location as opposed to previous forms of obtaining power, like power mills, that necessitates being near a water supply. Therefore, the steam engine changed manufacturing dramatically, leading to the so-called Industrial Revolution. The steam engine and mechanization have allowed to produce large quantities of products in less time. Furthermore, the steam engine allowed the development of trains and railways facilitating the distribution of products to larger markets. The combination of these two advances were the foundations for mass production and the industry has we know it today.

By the end of the 19th century, the beginning of the 20th century, a leapfrog in industry was given with the advent of electrical energy and the emergence of the assembly line (AL). While there is no consensus about who is responsible for the invention of the assembly line. There is no doubt that it had its major contribution from Henry Ford with the development of the assembly line for his famous Model T. Ultimately, it can be said that assembly lines allowed for mass production of complex products.

With the assembly line for the Model T, Henry Ford was able to achieve unprecedented productivity improvements. The Model T front axle production time was reduced from 150 to 26,5 minutes. The transmission assembly was cut from 18 to 9 minutes and the engine from 594 to 226 minutes. But most impressive was the final assembly line, where the time needed for one car was reduced from 12,5 hours to 93 minutes, which represent an increase in productivity of 800%. At a given point, a Model T left the plant every 40 seconds (Roser, 2016). These numbers show the enormous impact of the assembly line manufacturing system on productivity. This impact on productivity had reflects on sales. In fact, in 1909, ford sold 17 000 vehicles, while in 1924, he sold 1,7 million of vehicles which represented two thirds market share in the US (Hoop & Spearman, 2008)

Nevertheless, the assembly line for Model T had a significant drawback: The lack of flexibility. In fact, the lack of flexibility of Henry Ford assembly line lead Model T to remain almost unchanged until 1925 and in 1923 the sale began to decrease. Costumers were not willing to keep buying an outdated car, forcing Ford to launch the Model A, the successor of Model T. Nevertheless, this change of models took 6 months to be achieved, resulting in high losses for Ford Motor Company.

Meanwhile, General Motors took another path in the automotive industry. The company decided to offer a wide range of models and frequent technical and cosmetic redesign. This strategy leads GM to take the place of Ford as the main auto manufacturer of the US. GM also used assembly lines, but they were more flexible, with less dedicated machines and more flexible operators. They were able to move from a model to a different one in 20 days, while Ford required six months to do so.

The previous text is a short summary of the history of the rise and fall of Ford Motor Company and the interested reader can find details of this history in (Roser, 2016). The important lesson from this history is that a given production system only will be successful if it responds to the costumers needs. Ford assembly line was a success at the beginning of the 20th century because costumers wanted cheap vehicles. But it was outperformed by the more flexible approach of GM by the end of the 1920's when costumer was interested in more customized products.

The needs of the market drive evolution in the industry. Throughout the years, several changes occur in assembly lines to improve, not only their efficiency but also their flexibility. First, the need for flexibility was solved by adjusting human resources based on demand variation. Later, it was necessary to improve the flexibility to cope with a broader product mix.

In the 1960's the Toyota Production System arose, bringing significant impacts to the assembly lines. Through the elimination of waste and the use of visual but effective tools to design and balance assembly lines, this kind of manufacturing system improved, even more, its efficiency. The Toyota Production System became one of the most popular methods to answer balancing and flexibility issues of assembly lines.

Nowadays, in addition to all these characteristics, the market wants what can be called mass customization, which leads to high variability in the assembly lines. The mass customization of goods or services allows to respond to the specific needs of each customer. However, costs expected from the customer are similar to non-customized products. To achieve those concepts, arose mixed or multi-model assembly lines.

This factor implied more decision variables, which makes it difficult to solve the assembly problems analytically. To facilitate the resolution, companies started to use more visual tools and different resolution techniques that allow reducing the complexity of the issues (Papakostas et al., 2014).

1.1. Objectives

This project aims to find the best solutions for a mixed-model assembly line, from balancing, and sequencing to obtain the highest operational ratio (OPR), efficiency, and better smoothness index. The solutions and strategies adopted seek to increase the productivity of the line, reducing idle time, and to discover the impact of removing, from the production sequence, a list of products that cause the blockage in the line. All objectives are interconnected, and the simul8 was an indispensable tool for the development of the simulation model. Only then, all the values were tested, and the hypotheses were easily analysed.

In this way, it is intended to achieve, as a secondary objective, an improvement of operational efficiency, through the better use of available resources, which allow the maximization of the company's profit. This problem arises with the evolution of the industry and the demand, it is also important offer mass customization, without increasing the final product price and to deliver it in a short time.

1.2. Structure

This dissertation is divided into seven essential stages, distributed in the following order:

1. The Introduction presents a picture of the project's theme, objectives and adopted structure.
2. The Theorical framework consists in bibliographic research that focuses on the evolution of assembly lines, their problems until today, the flexibility, and the production sequencing, as well as the chosen simulation tool.
3. The Methodology describes the thinking adopted for the resolution. It is possible to visualize through a scheme for the development of the project and the increase of complexity.
4. The Description of the case study presents the product and presents the production process.

5. The Methodological Approach exposes the initial steps developed for the validation of the simulation models, as well as the indicators to compare the different results.
6. Resolution and Discussion, the results of all analyses performed are presented and commented, in this section.
7. In the Conclusion the results are presented, and a proposal is made for future work on questions that have not yet been answered.

2. THEORICAL FRAMEWORK

This work aims to discuss a significant problem that exists in the context of industrial manufacturing - the difficulties associated to the management of mixed model assembly lines.

It is important to note that, although there is an extensive literature on the problems of the assembly line, the type of solutions and their application in the industry, these are mainly aimed at simplified versions in which mass production is considered. The solutions that have been published have some obstacles. The obstacles are related to their implementation due to their complexity and the challenges of understanding.

From the need to understand the industrial environment and the solutions found so far, it is essential to explore, in a first phase, crucial aspects for understanding the assembly lines and all the factors that may be related to them. These include the types of products that can be produced on the line, the way of assigning tasks to workstations (WS) to guarantee a balanced line, and not least how to respond to the flexibility required by the market. It will also be critical to review the forms of sequencing as well as the tool that was used to simulate the solutions developed.

2.1. Assembly Line

The evolution of manufacturing has gone through several phases in human history. And it was interconnected as an increase in the ability to create tools to achieve a more enjoyable lifestyle. Primitives formed a pure society that lived off the natural resources it found around them. For the collection of goods, they produced their hand tools. It can be said that they started the assembling.

The following phase of manufacture was the development of skilled artisan workers. From change in the way of life to an increase in consumerism, led to a rise in available capital. This drove the emergence of the manufacturing system, at the end of the 18th century. At the end of the 19th century, it represented the beginning of mass production. The mass production was a consequence of the economic and technological development of society. Commerce was faced with the need to offer a wide variety of products and react fast to market trends (Rekiek & Delchambre, 2006).

Given the above, assembly work is not recent, since ancient people knew how to create useful products composed of various elements. However, the product complexity has developed exponentially. The product is any item that is designed, manufactured, and delivered to generate profit for the generator, meeting the expectations of customer interest. Most products consist of several elements. The association of different components forms a final production unit. The assembly, therefore, can be described as the component aggregation operation, manually or automatically. In the assembly process, the unfinished product circulating on the assembly line is called a workpiece (Törenli, 2009).

In today's industry, the assembly can occur in a line or in a bench, what differs in these two methods is the type of layout. A line assembly follows a product layout since the workpieces move in a sequence adapted to the development of the product. On the other hand, when assembling on a bench, the workpiece is fixed, and the necessary resources move around it, presenting the same characteristics as a fixed-position layout.

The automobile industry is an example of the result of the combination of technologies developed over time. Henry Ford is considered the inventor of the assembly line, which revolutionized the way of producing cars, and their price. Employees assembled cars one by one piece, instead of one car at a time. This principle allowed workers only to need to perform one task instead of being responsible for a series of tasks (Rekiek & Delchambre, 2006).

The assembly line is a flow-oriented production system, in which the units that carry out the operations are called workstations. At each station, the activities are performed repeatedly. A workstation can, at best, contain, at a time, a single product to assemble and a worker to perform one or more operations. Operations may be subject to precedence constraints.

The total amount of work required to assemble a workpiece is divided into a set of tasks. The time of a task may vary depending on the worker or equipment. The total workload required to assemble a workpiece is measured by the sum of the task times (Kriengkorakot & Pianthong, 2007a)

The jobs are launched consecutively on the line and moved from station to station. The workpieces are carried by a conveyor that joins the workstations. The transition through the workstations occurs as they are transported successively along the assembly line (Becker & Scholl, 2006). The finished product at the last station leaves the line.

2.1.1. Assembly Line Models

Since Henry Ford, production systems have been built around a *takt time*. The *takt time* represents the production rate desired by the company to respond to market requirements. In this way, the number of product units to be assembled in each period follows an appropriate production plan. The line can be a single-model assembly line, multi-model assembly line, or mixed-model assembly line.

The single-model assembly line is used to produce a single product. If a deterministic time for tasks is considered, the workload is expected to remain constant over time. This model is the most advantageous when the demand is stable, and the delivery needs to be as fast as possible. Either when the product has unusual characteristics, and the cost of quality is high, or the assembly of the product requires massive resources.

The multi-model assembly line is practised in the case of products from the same family that show significant variations. The creation of a single-model line for each product typology requires costs that the company can, eventually, not support. This type of model has advantages for products with a stable demand, and the setup time for the product change is short. In this kind of system products enter the line in batches, thus, the associated problems occur in terms of scheduling and batch sizing.

The mixed-model assembly line is used for a differentiated set of products, but whose primary functions are similar. These types of products are usually modular-based products. A typical example is a family of cars, where the car base model can have several variants. These lines are advantageous when the products are quite similar, which leads to the same resources for assembling all the products. The setup time is zero or very short, and one line for each product is not executable.

2.1.2. Assembly Line Configurations

The layout is the physical organization of the elements of a system, considering the physical restrictions, resource requirements and the expected result of the system. The physical configuration of an assembly line can affect its efficiency as well as costs. A large part of the total manufacturing costs is related to the transfer of materials. The performance of a line can be improved by reducing distances between workstations or approaching the necessary resources. A critical point in deciding the layout is the preliminary analysis of the product (Becker & Scholl, 2006).

The straight assembly line was initially designed for mass production. Mass customization has become challenging for this organizational form. The reorganization of the system was developed to maintain the advantages of traditional assembly lines while being able to produce customized products at low cost (Otto & Li, 2020).

New arrangements for assembly lines were developed like the U-shape, C-shape, circular, parallel, and two-sided, for example. Each assembly line type was proposed to answer to new market characteristics based on the type of product produced.

Because of the introduction of the just in time production principle, the U-shaped line brought various advantages over the traditional configuration. The U-shape line allows having fewer workers than workstations due to the proximity between them.

When the longest task time exceeds the specified cycle time, comes up the parallel stations. A standard solution is to create stations with parallel or serial stations, where two or more workers perform the same task. This concept reduces the average task time duration.

It is common to duplicate the entire assembly line when demand is high enough to justify it. Parallel lines have the advantage of shortening the response time but may require resources. These systems are coordinated separately.

For complex products, the assembly system is most often broken down into subsystems. These subsystems are called work centres that are more accessible to manage than the entire system.

2.2. Flexibility

According to the literature, flexibility is a complex, multidimensional and challenging concept. The concern with flexibility is not new, and it is believed that it has been around for more than 80 years. However, over the years, flexibility has gained higher weight in the strategic dimension for companies. Hart, in 1940, recognizes that flexibility would be the fundamental means to face the uncertainties of the future.

By the 1950s, the traditional thinking that the machine was designed for the product, changed. The operation replaced the product. The machine started to be designed in terms of the functions that it will perform. In 1987, Jaikumar said that flexible management was poorly understood in manufacturing systems in the United States, with few exceptions. Mainly, compared to the Japanese, who had higher levels of flexibility. A new way of work replaced a conventional way, but it got worse results. Technology itself was not the problem, as what would make the difference would be more effective resource management.

A system's flexibility is the ability to adapt to the environments it confronts. A flexible system can control the reaction to uncertain environments through an increase in variety, speed, and quantity.

Manufacturing flexibility means being able to adapt resources to produce different products efficiently and with the necessary quality. Flexibility is a property of the elements of the manufacturing system that are interconnected to provide the adaptation of resources to different production tasks, (Sethi & Sethi, 1990).

The manufacturing flexibility can provide organisations with the ability to change levels of production rapidly, to develop new products more quickly and more frequently, and to respond more quickly to competitive threats (Oke, 2005). Manufacturing flexibility is the broad universe, and it is crucial to think about everything. The adaptability is associated with the machine, the material handling system, the operation, the process, the product, the routing, production volume, among others. The essential flexibilities can be considered the flexibility of the product, production, and market.

Product flexibility is the facility with which new components can be added or replaced in the existing ones. In other words, product flexibility is the ease with which the elements that are being used for production can be changed quickly and without extra costs. The flexibility of the product is dependent on the flexibility of the process as changing the components can imply changes in assembly time and costs.

The flexibility of production allows the manufacture of products with considerable variations without a significant capital investment. Production flexibility defines within the product set, represented by the product's flexibility, its form of processing without changing the system configuration.

Market flexibility is the expertise with which the manufacturing system can respond to the changing market circumstances. This concept highlights the importance of market orientation, mostly since market changes occurs at high speed. When considering the market, the flexibility of response is related to the flexibility of the product, and the flexibility of production, it is a long-term response flexibility.

2.2.1. Product Flexibility

The increased demand for products with greater variety and shorter life cycles forces companies to develop flexible manufacturing systems. To meet this need, companies have implemented assembly lines for mixed models (MMAL) and multi models (MuMAL). The creation of a variety of products on the assembly lines helps to absorb volume fluctuations. Both offer product flexibility, which creates the ability to handle changes in the product mix, (Mönch et al., 2020).

Modularity is a powerful strategy that has proved useful in a large number of fields dealing with complex systems and is used for different functional purposes, for example, product design, production and use. Modular product design is a product design activity made up of modules. Based on a cross view of all the different product families and the main general modules existing in them, a general assembly sequence is developed (Asadi et al., 2019).

Considering the previous concept, the mixed-model assembly lines have modular products as their final product. An MMAL consists of creation of distinct product units on the same line without the constitution of production batches. These products have numerous variations with a small complexity. The Multi-model allows the assembly of products with entirely different characteristics in the same production line. In the production of multi models' batches of the desired size are created to be able to meet the market.

Currently, customer-centric manufacturing systems adopt mixed assembly lines. These models allow the assembly of different work content without long setup times. When inserting several models on the same line, companies face two associated problems: the line balancing and the sequencing problem. They are closely related to the issue of distributing the total workload across the stations in the most uniform and compact way possible, considering a set of precedence restrictions, (Otto & Li, 2020)

2.2.2. Production Flexibility - U-shaped Assembly lines

The balancing of the MMAL becomes hard with a traditional line configuration. In that way, the U-shaped line was an excellent key to bring betters solutions for a proper balancing of the flexible assembly line.

In addition to flexibility, it is essential to take into account the agility and reconfigurability of the assembly lines. The development of new products and the establishment of the necessary capacity to respond to new markets are linked to the system's agility. Reconfigurability is the ability to adjust the production and functionality of resources to different circumstances through structural rearrangement or changes in system configuration, (Asadi et al., 2019).

One of the notable developments resulting from the implementation of just in time (JIT) production was the replacement of traditional straight lines with U-shaped production lines which brings several advantages. The main benefits of the U line compared to a straight line include:

- greater operator flexibility
- greater volume flexibility
- the number of workstations never exceeds what is necessary for a straight line, and may even be less
- greater flexibility in moving workpieces
- Compact size allows reduced movement of operators and stock
- Greater visibility and communication between the team
- Ease of reworking a product with quality problems, since the end of the line is parallel to the beginning, (Sethi & Sethi, 1990).

The most significant gain in using U-shaped lines is in terms of productivity. Productivity can be improved by about 40% when there is an adequate balance of resources on the assembly line, (Cheng et al., 2000)

2.2.3. Production Flexibility - *Seru* Assembly lines

The word *seru* means cell in Japanese. *Seru* is following two guidelines *kanketsu* and *majime*. At *kanketsu*, the cells can perform all the required tasks and have the necessary tools to produce a product or a module. *Majime* means that all the resources are located compactly, (Liu et al., 2014). In that way, the space between workers, parts, workers, and parts are reduced as much as possible, (Sun et al., 2019).

The *seru* production was usually applied in assembly, testing, and packing. This production system can be split into three different types divisional *seru*, rotating *seru*, and *yatai*. Design of *seru* depends on the selection of processing and transfer rules, production balancing and planning, (Liu et al., 2014).

In a divisional *seru*, each operator is responsible for one operation, and have an area to work. An operator travels back and forth at his workstation. The divisional *seru* is efficient for low-skilled workers in cross-training, complex products with several components and to products requiring precision operations.

In rotating *seru*, the operator performs one by one order per time. The operators perform all the assembly tasks for the product. This type of *seru* has a high performance in environments with a large variety in production volumes and with an intermediate level of complexity.

Yatai is the *seru* production with one worker in one workstation. It is the best solution for high precision products, small volumes, and frequent variation in the output. The *Yatai* should only be implemented after the evolution of the two other types of *seru* in the organisation. Thus, becoming the main objective of the organisation, (Liu et al., 2014).

2.3. Balancing Problems

One of the purposes of the assembly line is to produce high quality and low-cost products. However, its installation is a decision that requires significant capital investments. Thus, this system must be designed and balanced to perform in a suitably way, (Asadi et al., 2019). In addition to restoring a new system, a functioning system must be rebalanced periodically or after modifications in the production process.

There are numerous problems in the assembly line, wherein one of the most relevant, and studied, is the issue in the assembly line balancing (ALBP), (Becker & Scholl, 2006). ALBP was first introduced by Salveson (1955).

The task process time is a fundamental parameter in ALB. Simple tasks can have a small variation in process time, while complex and unreliable tasks can have highly variable execution times. Ghosh and Gagnom, in 1989, considered that the type of time admitted should be included in the ALBP classification.

In the case of human workers, some factors have a significant influence across AL. Operators sometimes take longer to operate than after they become familiar with it. The dynamic time associated with the human factor may have associated systematic reductions possible due to the learning effects or successive improvements in the production process, (Rekiek & Delchambre, 2006).

In this way, they consider that ALBP can be classified as deterministic or stochastic. For the deterministic version of the problems, the task times have a fixed time, and the variability is not relevant. The category of stochastic problems introduces the concept of task time variability. This consideration makes ALBP more realistic for manual assembly lines. In manual assembly, workers' operating times are rarely constant. With the introduction of stochastic task times, it is essential for a resolution as close as possible to the reality of AL.

The balancing problems have the objective of optimizing a proper goal where the purpose will depend on the association of tasks with jobs, as well as respect for precedence. (Kriengkorakot & Pianthong, 2007a), described the ALBP, through which problem-solving offers the assignment of assembly tasks to workstations to optimize performance measures while executing technological, operational, and organizational constraints on the assembly line.

Currently, companies have as main objective to maximize the use of the line. Line utilization is measured by line efficiency as the productive fraction of the total line operating time. This productive efficiency depends directly on the cycle time and the number of stations, (Kriengkorakot & Pianthong, 2007b).

ALBP has been studied for several decades, and since it is a significant problem in the literature, several classifications have been added. As it is a complex problem, the designations differ from a simplified version of the problems to a generalized version. This classification considers several different restrictions and objectives.

2.3.1. The simple assembly line balancing problems (SALBP)

This type of problem considers a few requirements that the line needs to obey to transform the complex subject in a simple issue. In SALBP, only the central part is deemed to be relevant about the number of stations, the tasks assigned and their cycle time. The assumptions to the SALBP can be split in the premises of the production line and the jobs. The assembly line produces a single model, and the *takt time* is fixed and known. The assembly task has a known processing time, and it does not depend on the workstation. Also, a job can be performed in any workstation, but it cannot be divided by various workstations.

- Type 1 (SALBP-1) has as main objective to minimize the number of stations for a given fixed cycle time.
- Type 2 (SALBP-2) aims to minimize the cycle time for a certain number of fixed stations.
- Type 3, 4 and 5 has the same main objective the maximization of the workload smoothness index,

$$Smootheness\ Index = \sqrt{\sum_{k=1}^{m} (S_{max} - S_k)^2} \quad (2.1)$$

$, where\ S_{max} = Cycle\ Time, and\ S_k = Workstation\ time\ for\ the\ WS\ k.$

The SALBP-3 consider the maximization of the workload smoothness index and the workload ratio. SALBP-4 contemplate the maximization of the workload smoothness index and more one different objective like balancing delay, for example. The SALBP-5 only obtain a maximization of the workload smoothness index.

- Type E (SALBP-E) is the version of the most general problem, intended to maximize the efficiency of the line. Thus, minimize cycle time and the number of stations.
- Type F (SALBP-F) is a viability problem that does guarantee the existence of balance for a line, given a combination of cycle times.

2.3.2. The general assembly line problems (GALBP)

In the literature, all kinds of problems that remove some assumptions from SALBP are called generalized assembly line balancing problems (GALBP). This class of problems becomes very extensive. This type of problems contemplates the more relevant issues in practice since it encompasses problems with different configuration lines and mixed products.

Figure 1 is the schematic representation of the ALBP classification suggested by (Becker & Scholl, 2006).

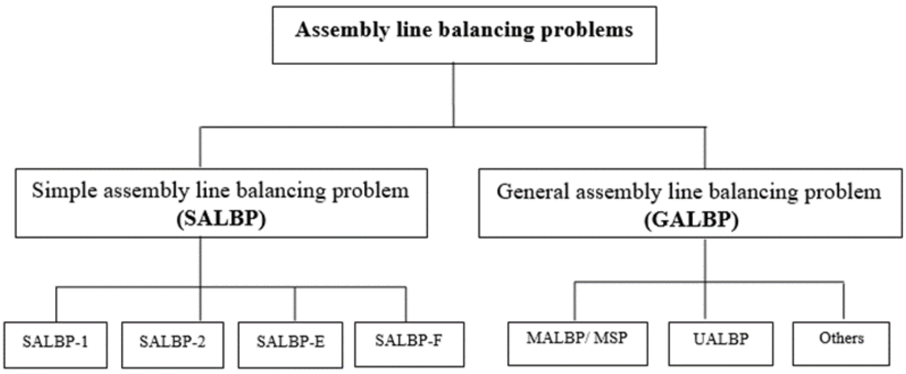


Figure 1 - ALBP classification, **(Becker & Scholl, 2006)**

In GALBP class, the most studied problems have been the U-shaped Assembly line balancing problems (UABLP) and the mixed-model Assembly line balancing problems (MMALBP).

The balancing problem of the mixed-model assembly line (MMALBP), intends to assign tasks to stations considering the different task times for different models. So, the objective is to find the number of stations and a cycle time. As well as a line balance for which your capacity or cost target is optimized, (Scholl et al., 1998). In opposite to the single-model case, the cycle time is no longer the maximum time available in each station to perform the tasks on a workpiece, but the average time defined based on the desired production rate.

The problem is more complicated than in the case of a single model because the task times of the different models must be smoothed for each workstation, characterized by horizontal balance, (Merengo et al., 1999). In the absence of typical cycle time, that is, all stations operate at a single speed, workpieces may have to wait before entering the next station, and stations may be idle when they need to wait for the next piece of work. This idle time is partially solved through balancing and sequencing. The better this horizontal balancing works, the better solutions will be possible in the problem of sequencing mixed models.

The U line balancing problem (UALBP) considers the case of U-shaped assembly lines, and a single product, where the stations are arranged inside the U. Consequently, workers can work on both sides of the U. That is, it allows for a smaller number of workers for the same amount of stations. Therefore, the worker who performs the first task at the first workstation can also perform the finishing job at the last workstation. Accordingly, precedence constraints are modified compared to a traditional configuration line.

The general problems contain practical problems that include processing alternatives and allocation restrictions. It is believed that there is no feasible method for resolving it, since most of studies have no or very limited industrial case applications and, it only, offer numerical experiments to validate their proposed approaches, (Mönch et al., 2020). Conventional resolution methods, such as enumerative methods, evolutionary, heuristic approaches, are time-consuming for more complex problems. Through the read literature, it can be concluded, the GALBP is not so investigated, which means that the resolutions for it are few. Due to its complexity, the methodologies require a vast knowledge of the companies.

2.4. Sequencing

If several models are assembled on the same line, the ALBP is connected to a sequencing problem that must decide the assembly order of the model units. The sequence is essential concerning the efficiency of a line, as task times can differ considerably between products. It is crucial to consider that a mixed model line produces the units of different models in an arbitrarily mixed sequence, (Bukchin & Tzur, 2000).

The planning of mixed models (MMP) has received increasing attention over the past decade. MMAL is more susceptible to inefficiencies, such as work overload, line stoppage, and offline repair. The sequencing of mixed models aims to find a placement of all model units to be produced so that inefficiencies are minimized. In other words, its main objective is a smooth balance of various products sequenced on the same assembly line, (Kreiter & Pferschy, 2020).

Recent publications focus on short-term re-sequencing decisions, (Taube & Minner, 2018), and constraints such as machine lead time, (Abdul Nazar & Madhusudanan Pillai, 2018).

2.4.1. *Heijunka*

The lean production method that preserves the production from variability in the sequence of tasks to be processed is *Heijunka*. It means smoothing in Japanese. The purpose of the *Heijunka* is to avoid irregularities on the production schedule that can eliminate waste, such as starved or blocked time, (Grimaud et al., 2014).

This lean method, when balancing the production, reduces variation in the production process, as well as the bullwhip effect, and minimises lead time. Minimising these factors allows greater use of production capacity, (Korytkowski et al., 2013).

The smoothing can be done, considering the production volume or the product type. In the case of levelling by a type of product, it permits to prepare the production based on the average demand for each product in the catalogue, (Bohnen et al., 2011). Therefore, fluctuations in customer orders are not transferred directly to the manufacturing system, allowing for smoother production and better utilisation of production capacity, (Korytkowski et al., 2013).

Heijunka distributes the tasks that take the longest time in the entire production schedule, to provide greater average use, assuming that the cycle time is kept constant over time. The smoothing of production becomes a cyclical plan of a levelling pattern, (Grimaud et al., 2014). This creates regularity on output, simplicity, and coordination. The pattern is determined and kept constant for a defined period, (Rewers et al., 2017). Whenever significant changes occurred in the product mix or consumer request, the levelling pattern needed to be adapted.

A *Heijunka* box is a scheduling tool used to view work items that need to be performed, (Grimaud et al., 2014). A typical *Heijunka* box has horizontal lines for each member of a product family, and vertical columns that symbolise equal time intervals. Control is done using the conventional *Kanban* method. Each *Kanban* is placed in the slots created in proportion to the number of items to be produced.

It is a system that enables to view the orders for each product, and according to demand, a production sequence is established to achieve an optimal flow.

2.5. Simulation

The desire for knowledge of the future motivates the human being to use techniques such as simulation to try to predict and understand the world around him.

Before the 17th century, the search for predictive power was limited to deductive methods of philosophers such as Platão and Aristoteles. In 1620, Francis Bacon recognized the limitations of speculative philosophy as a methodology for predicting the future. According to him, reason alone has no ability to predict, and it achieves it only with the help of observation. Deductive and inductive logic must go together in search of the knowledge. Francis Bacon is considered the creator of operational research, which consequently originated the simulation, (Naylor, 1971).

The impossibility of testing techniques and hypotheses for resolution directly in the real system motivated the human being to methods such as simulation. Simulation is a word that has recently appeared in scientific documentation to describe the ancient art of model building.

Simulation is a method used to study the performance of a system through the formulation of a mathematical model, which must reproduce, in the most accurate way, the characteristics of the original system, (ECKER & KUPFERSCHMID, 1988). Several factors affected the performance of the system, such as the manipulation of the model and the analysis of the results.

Simulating is building models of real systems, experimenting with them, and learning from them. The models are a description of the systems. They are built according to the problem to be solved following an organized structure. The simulation language intends to represent any specific case, through the insertion of specific values for the parameters. Simulation languages have the benefit of reducing the time required to implement a model.

Simulation has become a study approach increasingly used in the most varied areas of knowledge. The increasing complexity of the problems and the more availability of computational resources were two significant drivers of the development of the simulation. Simulation has the following characteristics:

- More realistic models through greater freedom in the construction of the simulation model. Compared to linear programming, the simulation does not require framing a problem in a given standard model to obtain a solution.
- Evolutionary modelling process: start with a relatively simple model and increase its complexity little by little, identifying more clearly the peculiarities of the problem.
- The "what if" analysis; the goal is to clarify the possible consequences of a set of decisions.
- Application in problems of which we do not have in-depth knowledge, many real-life problems refer to situations in which we only have partial knowledge about the variables or relations. Simulation is one of the few tools for studying this type of problem.
- Ease of understanding concerning a set of mathematical equations.
- Quick solutions when the variables change quickly and commit resources for the execution of tests.
- It can be applied to the most varied problems and contexts.
- Once a valid simulation model has been developed, new policies, operating procedures, physical arrangements, or methods can be explored without disturbing the real system.
- The simulation provides a better understanding of the interactions between the variables of complex systems. Thus, allowing the diagnosis of problems, the development of perception, and a systemic view of the overall performance of the problem.

- Preventive preparation of changes and investment analysis, since the transformation of a system, can incur high costs, the simulation is a low-cost investment that allows an analysis of consequences.

Simulation as another tool has disadvantages:

- Model building is not accessible and requires training. The technique is learned and perfected over time and through experience.
- The results of the simulation can be difficult to interpret, as the outputs of the simulation are usually random variables to implement in real life.
- Model development and simulation analysis can be costly in terms of financial resources and time.
- Low precision of the results makes the simulation inaccurate. It is usually a consequence of using the sample, and of a poorly formulated model.

2.5.1. Simulation of an assembly line

The simulation is applied to facilitate precession, and to evaluate the performance. Examining alterations into the line costs money, people, and time are required to do the test and estimate each change. Currently, the complexity of an assembly line is high. This complexity can vary depending on in terms of product, resources, and the allocation of resources to workstations.

A significant disadvantage arises with the increase in the number of products to be produced in an assembly line, the complexity rises. In this point, the simulation is more profitable than the analytical methods. Nevertheless, the simulation must be designed so that the degree of complexity gradually increases. Only in this way, the probability of errors occurring is less than in the other methods.

A simulation model of an assembly line requires developing a model with the same characteristics of the shop floor. These characteristics may already exist or to be the features that are expected to be built in the factory. This technique becomes the most advantageous to be able to test and to compare all the modifications.

The simulation is beneficial when it is possible to utilize optimization tools to find a better solution for the case study developed with simulation. This alliance does not require any knowledge of the analytical methods and the performance time is smaller with the simulation.

The formulation of the problem from which it is intended to be optimized must be made as close to reality as possible. Likewise, the simulation must also be carefully formulated. Bearing the above, the data obtained from the simulation should allow understanding the principal conclusions for the real problem. Otherwise, the simulation will not be advantageous and will not help to draw any outcomes.

2.5.2. Simul8

Simul8 was the simulation software chosen for this work. This software allows to build any model from just five principal building objects: Arrival, Queue, Activities, Resources and Exit. It is a simple to understand and visual software which creates intuitive learning. Although its dialogue boxes avoid the need to program long lines of code, the software also has an internal language: Visual Logic.

A simulation wizard, based on an artificial intelligence technique, automatically informs you of the problems that may arise from a given model. This is especially interesting for beginners in simulation, who need more help when building a model.

Simul8 has the Simul8 Viewer version that allows running simulation models on computers without Simul8 installed. This version can be obtained free. Simul8 Viewer even enables the user to change input data and generate new output data.

Simul8 has the possibility to associate simulation with other specific functionalities, programs, and software. Simul8 incorporates specific functionalities or packages such as Optquest (optimization), Stat: Fit (input data analysis), Transport (modelling of transport systems, such as AGV and forklift trucks), Virtual Reality (virtual reality module), and Process (continuous simulation). Simul8 allows the exchange of information with several other software, such as Word, Excel, AutoCAD, and databases in SQL standard, for example. The import and export tools allow the conversion of models to/from Automod, and Witness simulation software. It is also possible to import and simulate models from software to create process flowcharts, such as Visio, Flowcharter, Igrafx, Mega, and Salamander. Simul8 also incorporates a library and icon editor that reads graphic files in the BMP, JPEG, and GIF standard.

3. METHODOLOGY

The initial diagnosis of the assembly line was carried out in partnership with a group of students. The students had already performed data collection on the variables involved in the production times. In addition to the task times, to understand the problem, it was essential to understand the product, the process, and the assembly line.

After an initial diagnosis, the work methodology can be characterized by a four-step cycle, Figure 2. The steps can be described by the development of the simulation, collection of the simulation results, and the respective analysis and evaluation. These steps allowed us to verify if the changes have the better performance in each model developed. Otherwise, a new cycle was performed.

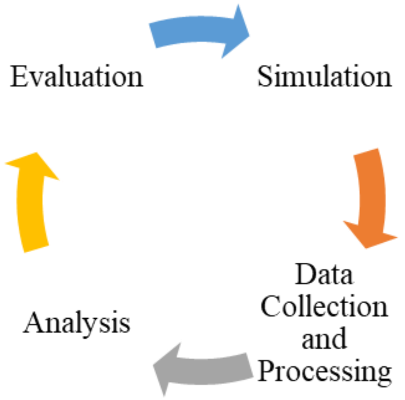


Figure 2 - Cycle with the analysis steps of each simulation model developed

The simulation performs the actions of the evaluation made previously and return the data for processing. The implementation of corrections in the simulation allows the reflection of their positive and negative impacts.

After implementing the improvement actions, it is necessary to collect and process the simulation data. The simulation does not return the results to perform the direct analysis. Results are measured by performance indicators considered adequate to estimate the impact of changes made to the system. The processing of the data serves to place them in the format necessary for the analysis.

The analysis of the data obtained for each cycle supports extracting conclusions and detecting possible problems. The detection of failures is only possible through the review of finished products and the analyses already performed.

The final cycle phase is the evaluation of the analysis results. This phase serves to define the changes to be performed in the next simulation, considering the continuous improvement of the model.

The work sequence defined for the execution of the data collection can be analysed through Figure 3. It is also possible to obtain information regarding decision-making that may be necessary during the analysis of the data. These are used to identify a simulation with invalid data. The occurrence of non-valid data requires the reformulation of the simulation and subsequent repetition of the data collection and analysis steps.

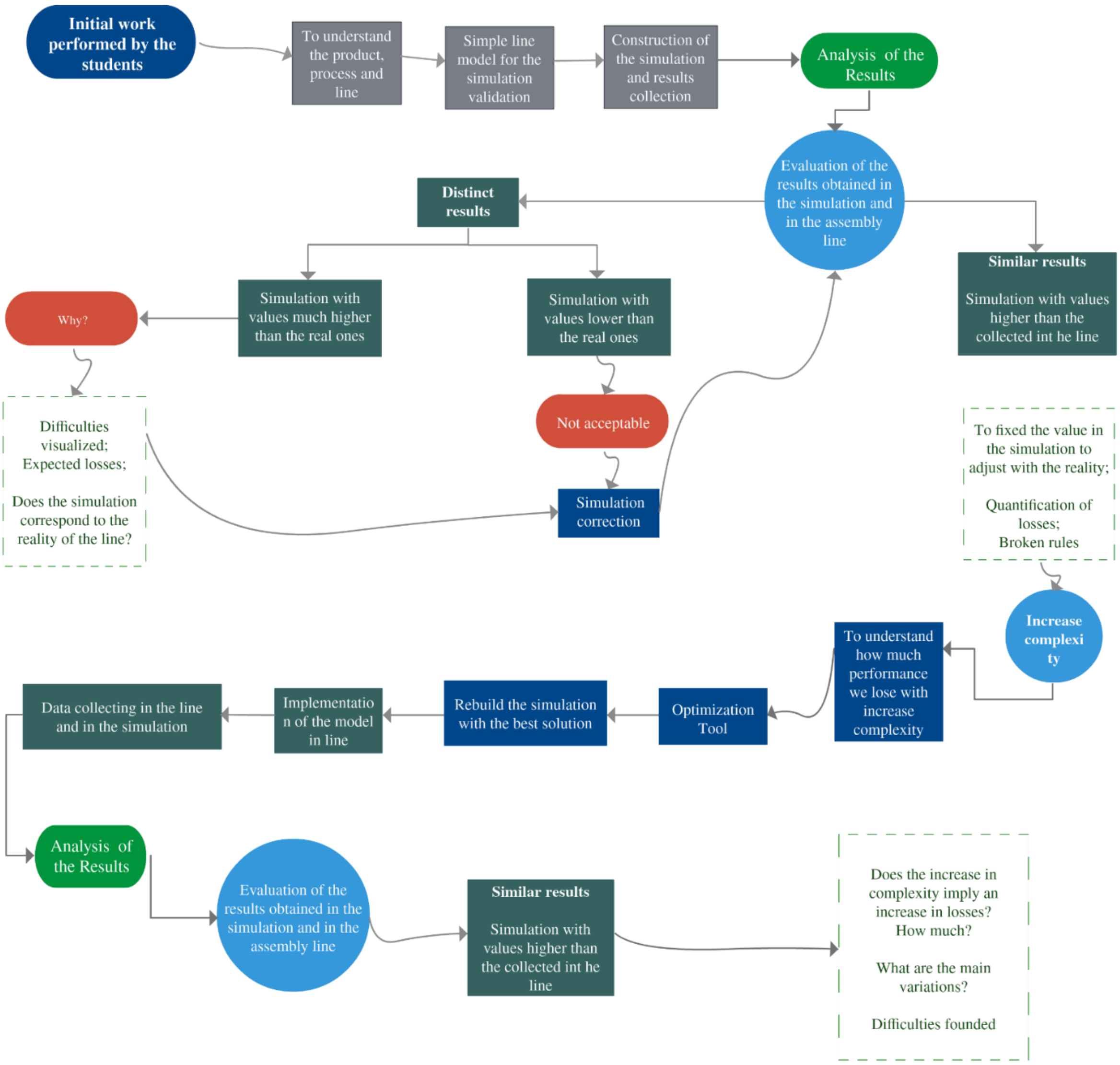


Figure 3 - Work Sequence Chart

Following the characterization of the line, it is crucial to building complexity in the simulation gradually. The gradual construction of complexity aims to validate and verify the simulation model. In terms of complexity, the problem was divided into three, Figure 4. The first phase was assumed to be the base phase and less complex. This phase consists of only three workstations and two products. The following steps are intended to characterize the real assembly line in relation to the number of workstations, and with a gradual evolution of the number of products.

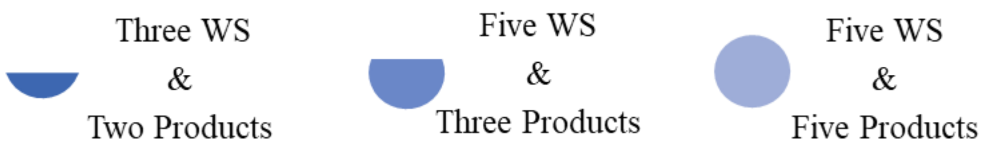


Figure 4 - Complexity levels of the models

4. DESCRIPTION OF THE CASE STUDY

The project presented in this document was performed in a laboratory assembly line, present at LISPEN in ENSAM Lille. This assembly line can be used for teaching and for research. In terms of research, the projects aim to develop novel approaches for line balancing and sequencing, seeking the development of more flexible assembly lines. This objective can be attained through the introduction of new technologies, like collaborative robots or digital twins' solutions for decision making, or through the development of new approaches for line balancing and sequencing.

The assembly line of the laboratory is a U-Shaped line composed by 5 stations. Figure 5 show the assembly line used throughout the project. In the following subsections, a description of the products to be assembled in this line is presented.

Figure 5 - Assembly line at LISPEN in ENSAM Lille

4.1. The product and the assembly process

The product used in this work is a pneumatic cylinder, and it belongs to a module-based product family. It means that the product variants are generated by selecting combinations of alternative components that could be assembled on a base product, (Wang et al., 2011).

The base consists of a pneumatic cylinder. It has six distinct components, that must respect the task's precedence in their assembly, Figure 6. The components of the base product must be assembled by screwing the back with the body of the cylinder. Subsequently, the piston stem is placed into the hole in the front part, and the final step will be to insert the piston into the body of the cylinder and screw the front section of the cylinder with the first parts assembled. Figure 7 presents the precedence diagram to the pneumatic base assembly process.

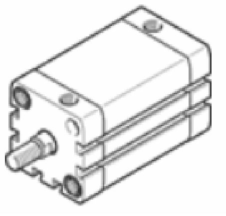


Figure 6 - Pneumatic Cylinder

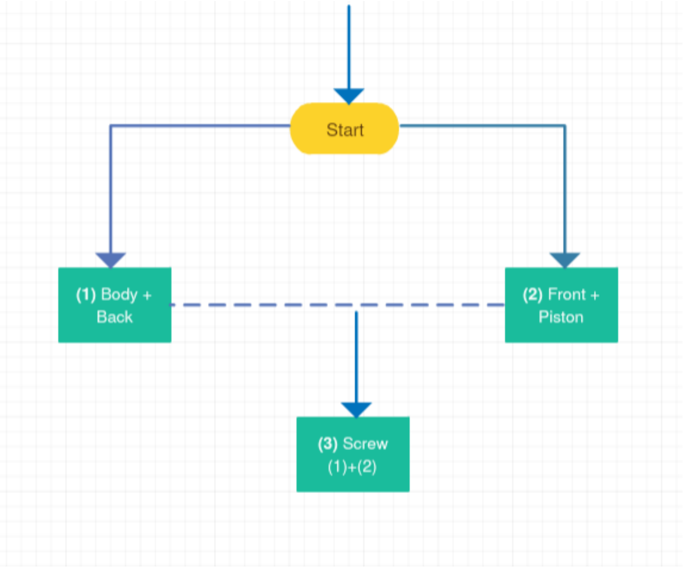


Figure 7 - Precedence Diagram to the pneumatic cylinder base

Several components can be added to the base product, the pneumatic cylinder. These components can be divided in five groups according to their function: connectors, stems, rotative joints, fixing flanges and sensors. Figure 8 presents the set of components that can be assembled to the cylinder. The maximum number of components that can be added to the cylinder are: two connectors, two stems, one rotative joint, three fixing flange and one sensor.

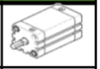
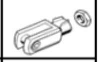
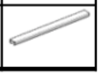
Type	N° Activity	N° Article	Nº Sub-components	Designation	3D
Base	1, 2, and 3	536297	10, 21, 22, 30, 100, 110	Cylinder	
Connectors	8	186098	41	Straingth Connector	
	7	186119	42	Elbow Connector	
Stem	5	6144	51	Rod Clevis	
	6	9261	53	Rod end	
Rotative joint	12	31761	61 or 63	Clevis Foot	
Flange	10	174405	71	Flange orientable	
	11	174391	72	Swivel Mounting	
	4	537242	81	Foot Mounting	
Sensor	9	543861	91	Proximity sensor	
		151680	93	Slot Cover	

Figure 8 - Base and the Components

The assembly tasks of the additional components do not have priorities between them. However, when the product requires the proximity sensor (Figure 8), the physical characteristics of the sensor constrain this assembly task to be the last one. The precedence diagram for the assembly of the pneumatic cylinder in is most complex form (with all the available components) is presented in Figure 9.

The subcomponents of the pneumatic cylinder are the body of the cylinder components (10,21,22,30), the hex nuts (100) and the screws (110).

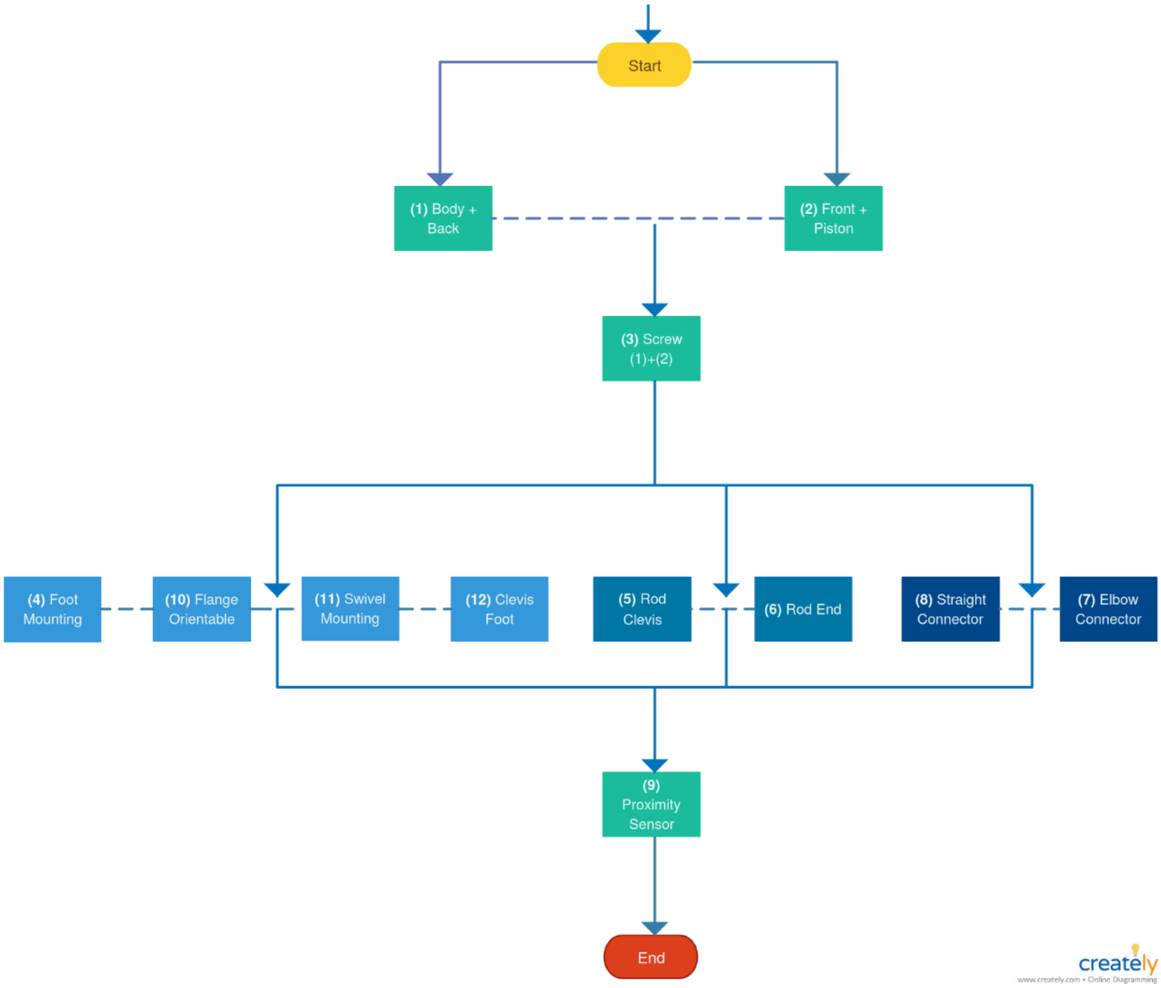


Figure 9 - Precedence Diagram of the Pneumatic cylinder

The products family can be divided into scale-based and module-base. A modular base family consists of different products but with the same product base. On the other hand, a scale-based family consists of several products but on the same scale of dimensions. In our case, it is a family with a modular base. The products are generated through the combination of alternative components that can be installed in the base product. Depending on the types of elements, the time that each one needs to be assembled differs.

Depending on the type of parts associated with a product, it can be categorized into four different configurations. The feasible categorization is A, B, C, and D configuration. This creation of categories is artificial, established to mix similar kinds of components and obtain different work contents. The D configuration is the group of the base product, so this group only contains one product and is the base module for the others. Figure 10 represents the variants that may exist in the production.

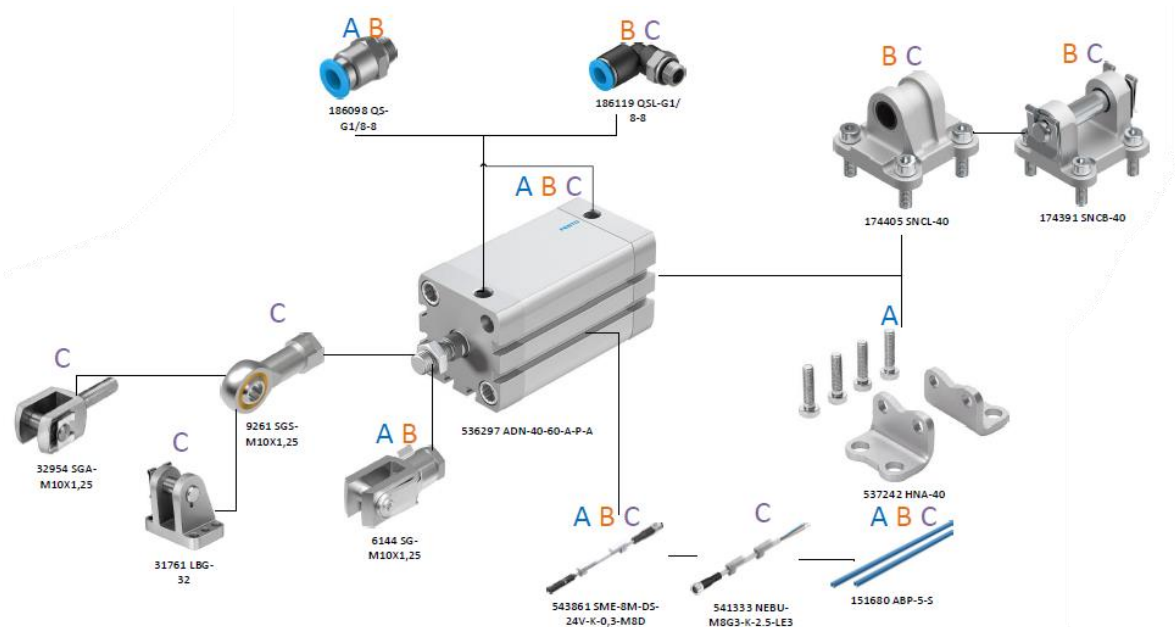


Figure 10 - A, B and C Configurations

The C configuration is the most complex product family. Thus, the following precedence diagram concerns a product of the C configuration, Figure 11.

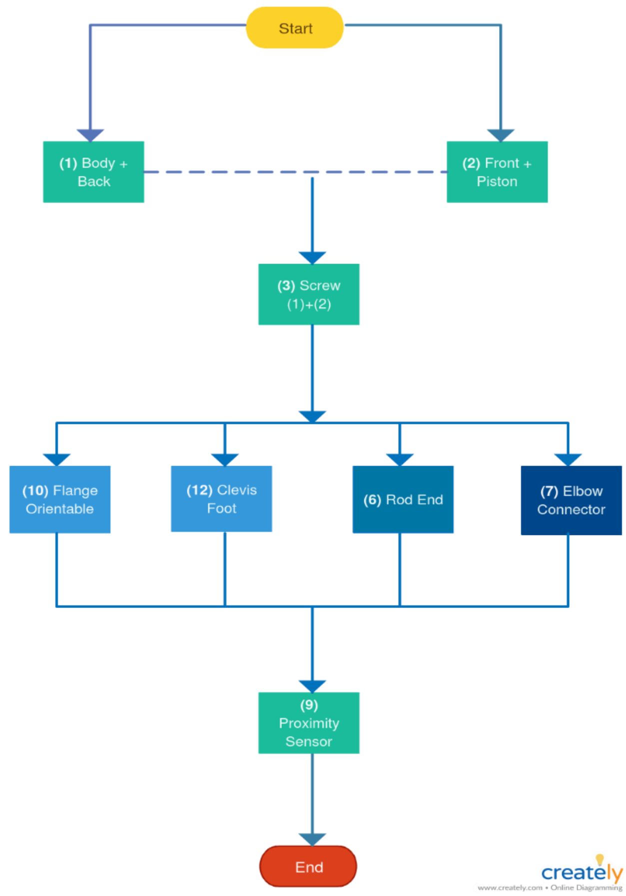


Figure 11 - Precedence diagram for one product of the C configuration

4.2. Problem Description

Different models throughout the production sequence characterize the production of mixed models,(Papakostas et al., 2014). When considering the problems of balancing assembly lines for mixed models, the objective consists in determining how tasks will be allocated on the line, i.e., which tasks will be performed in each workstation and defining the sequence by which the different products will be produced, (Sparling & Miltenburg, 1998).

In mixed-model production, there are more difficulties in line balancing compared to single model production. A production of mixed-model products consists of the creation of distinct product units on the same line without the constitution of production batches. The first adjustment that directly influences the system is to remodel the physical arrangement of the production line from a typical straight shape to a U shape, (Miltenburg, 2001).

U-shape lines are widely adopted for this type of production. According to several authors, the U-shaped lines have several positive factors compared to the more traditional ones. The elements are greater volume flexibility, the flexibility of operations, reduced number of stations, convenient transport of material, and visibility and teamwork, (Cheng et al., 2000).

The problem in question reflects a U-shape line with mixed-model production. Since we suggest a solution to solve a problem declared as a mixed model assembly line that breaks the weight of a single product in line with the SALBP premise, our problem is considered a GALBP.

The purpose of this work is to maximize the operational ratio (OPR) of the line. The OPR shows the difference between actual production and expected production. This indicator means that the maximum performance of the line is expected to be the most beneficial one, already contemplating the necessary stops.

The cost of producing several products on the same line should not be directly related to the number of different products, just as the number of different products on the assembly line should not depend on the number of quality problems in the final product.

Accordingly, this operational goal will make it possible to understand how much the line diverged from the projected objective. Just as accounting for the line output does not require any new measurement on the line. It is only necessary to collect this data at the end of the working day, or within a specified time interval.

5. METHODOLOGICAL APPROACH

In this chapter, the approaches taken during the development of this work will be presented. To starting was essential to understand how the tasks were assigned to the workstations. Through three key indicators, it was verified if the line was balanced, and then the simulation model was developed. For the development of the simulation model, the complexity was gradually increased, and the simple model was validated and verified through a manual resolution. After the model is built, it is crucial to format the values collected from the simulation. The implementation of the results on the line will be the final stage of the entire development of this work.

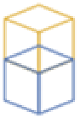
5.1. Understanding Product Assembly

The simulation can be difficult to develop when it is proposing to describe complex circumstances. Also, our purpose was to familiarise with the tool and allow yourself to check the model — a simple model for which the exact solution can be found manually. In this way, the case study will be simplified at an initial stage.

Accordingly, the simulation will not have errors if all versions are validated. Even the simplest ones require to be correct, only then it is possible to improve the scenario of the simulation without mistakes.

The assembly line consists of one worker per station and a stock unit between stations. These are some of the characteristics of a SALBP problem. What makes this problem a GALBP is that the line will have more than one product.

The case study starts considering one straight assembly line with three workstations and two different products. These two products were created to allow a perfect theoretical line balance. The time required to execute the assembly tasks for each product in each workstation are presented in Figure 12. Product 1, with configuration A, will take 18s in WS1, 45s in WS2 and 28s in WS3. It can also be observed that in this simplest problem it is intended to produce 50% of each product.



	WS 1	WS 2	WS 3	Production
1_A	18	45	28	50%
2_B	42	15	32	50%

Figure 12 - Three WS and two products

Subsequently, the real case study will consider one U-shape assembly line with five workstations and three different products, Figure 13.

	WS1	WS2	WS3	WS4	WS5	Production
1_A	25	35	26	51	22	30%
2_B	25	20	26	20	37	40%
4_C	35	34	26	20	22	30%

Figure 13 - Five WS and three products

The product families were created in such a way that the most extended tasks are split into different product families. Therefore, the activities with the lengthiest duration of which product will be attributed to different workstations.

5.2. Balancing

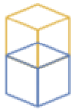
It is essential to understand what shows us that the line is balanced or has the desired characteristics for the analysis. For this, we will calculate the weighted average cycle time, the smoothness index, and the balancing delay.

The weighted average cycle time (WACT), of the assembly line, describes an indispensable factor since it provides a representational average cycle time for a mixed model context, (Rabbani et al., 2014).

Different products may have distinct task times at the same workstation, and in that way, the cycle time for each product will change. In this case, the WACT was related to the workstations, assuming that there is no change in the task time with the different operators. An objective that is intended to be achieved is that the WACT becomes equal to the *takt time*.

However, as this is the average representative of the cycle time, a variation in the product mix or the production proportions leads to changes. The variations that can occur in the line, lead to the need for a new balancing optimisation.

The WACT depends on the quantities produced per product. For this phase, the volumes produced will be 50% of each configuration. The product with the task with the longest duration belongs to configuration A, Figure 14.



	WS 1	WS 2	WS 3	Production
1_A	18	45	28	50%
2_B	42	15	32	50%
WACT	30	30	30	

Figure 14 – Weighted average cycle time calculation

In this case the WACT of the line will be 30s. For example, for WS1 we have 18s x 50% + 42s x 50%, Figure 15.

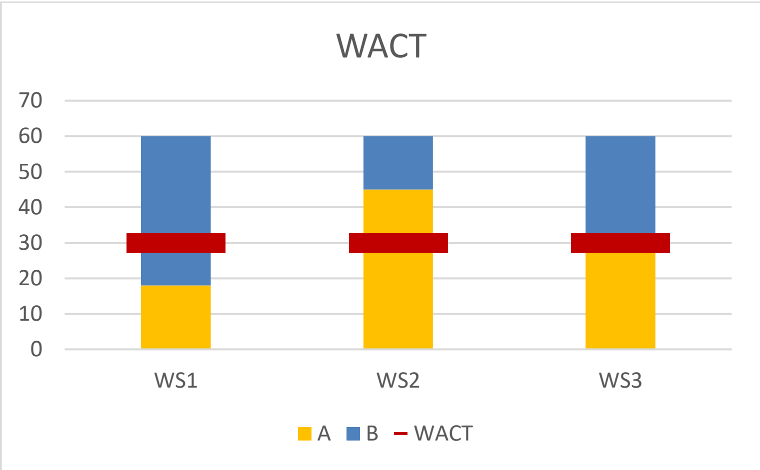


Figure 15 - Graphic representation of the WACT

WACT can help to understand where the assembly line is unbalanced and support to detect the most advantageous changes when adjusting activity allocations. However, it should not be used exclusively because the WACT is calculated with a proportion. When products are shipped into line, the balance is not necessarily verified, Figure 16.

	Day	Hours	Minutes	Seconds
Simulation time	1	8	480	28800

Production	820		WS1	WS2	WS3
1	446	54,4%	18	45	28
2	374	45,6%	42	15	32
		REAL WACT	28,946	31,317073	29,824

Figure 16 - Weighted average cycle time recalculation

To ensure that the line is balanced, other agents are essential in addition to a good WACT. Other factors can be, for example, proper planning and not having a big difference between the time of activity in each station. The indicators that complement the analysis of the line will be the smoothness index and the balance delay.

Smoothness index (SI) is an indicator that is associated with the balance

$$SI = \sqrt{\sum_{k=1}^{m} (WACT_{max} - WACT_k)^2} \qquad (5.1)$$

provided to the assembly line. An index closer to zero indicates a perfect smoothness.

Balance delay (BD) is the quantity of idle time on the assembly lines caused by the uneven division of activities between stations and operators.

$$BD = \left[\left\{ (m) * (\overline{TaktT}) - (\sum_{k=1}^{m} WACT_k) \right\} \Big/ (m) *) \overline{TaktT}) \right] * 100\% \qquad (5.2)$$

The formulas (5.1) and (5.2) are an adaptation from the Smoothness index and Balancing delay, of (Kumar & Mahto, 2013). The alterations aim a more advantageous adjustment to this case study.

5.3. Construction of Gradual Complexity Simulation

The simulation is a tool that allows to analyse the performance of a model. The model must reproduce the real characteristics of the system as faithfully as possible. Only in this way will the model allow conclusions to be drawn that are valid and applicable.

The gradual construction of the simulation serves to allow a better perception of a more complex model, as well as the validations, become more natural. Progressive development will also permit a definition of the complexity of the model to be achieved.

In an initial phase, the model is simple enough to be able to be developed analytically. The initial results serve to focus on the results of the problem. In this way, the most complicated issues will not become abstract. Only then will the modelling of a problem become concrete, and its analysis more accessible.

Accordingly, several models were used for data analysis. The first model built represents, in a simplified way, the assembly line. With only three stations and two products, it will allow a straightforward analysis of the data obtained as well as the validation of the results, Figure 17.

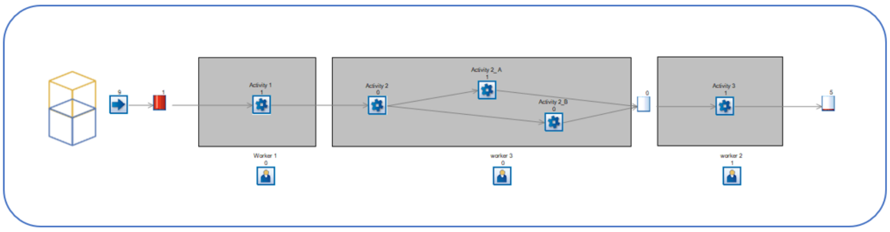


Figure 17 - Simulation model with three WS and two products

The second model will represent the real line. However, it does not represent the actual quantity of products produced in this line, Figure 18. Later, after understanding it, it will be easier to increase the degree of complexity, Figure 19, to represent the actual quantity of products.

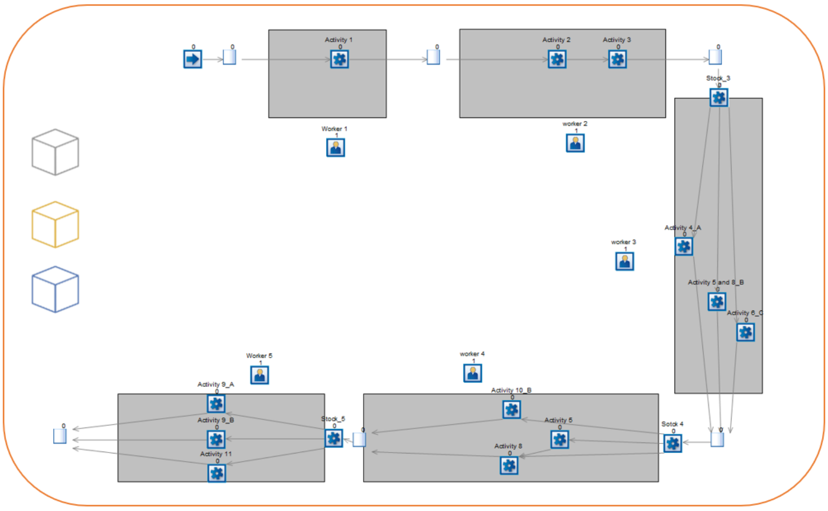


Figure 18 - Simulation model of the real line with fewer products

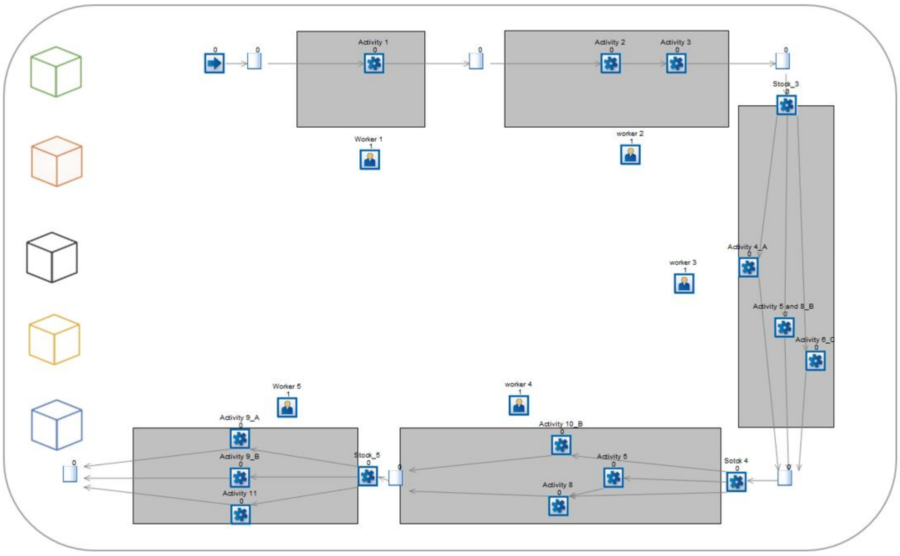


Figure 19 - Simulation model of the real line

5.4. Simulation Validation/Verification

The validity of the model data and the identification of possible associated failures is vital to guarantee the credibility of the data obtained.

To validate the model two experiments were generated. These experiments were very simple to allow the realization of a manual simulation. With the results of this experiments it was possible to verify if the simulation model developed represented conveniently the real scenario and if it would be easy to collect the necessary indicators.

Two hypothetical products were created in which only one time of a task is different from the time of the other tasks. This task has a lower value than the others and it can occur in workstations 2 and 3, distinctly for each experiment. The tasks time for each hypothetical product are presented in Figure 20 and Figure 21.

	WS 1	WS 2	WS 3	TOTAL
1_A	60	60	60	180
2_B	60	45	60	165

Figure 20 - Task Times for experience 1: validation the Blocked time

	WS 1	WS 2	WS 3	TOTAL
1_A	60	60	45	165
2_B	60	60	60	180

Figure 21 - Task Times for experience 2: validation the Starved Time

A simulation model was built for each experiment, see Figure 22, and Figure 23. In the simulation, the different duration of tasks is represented by the division of labour into product A and B for the WS2 and WS3, respectively.

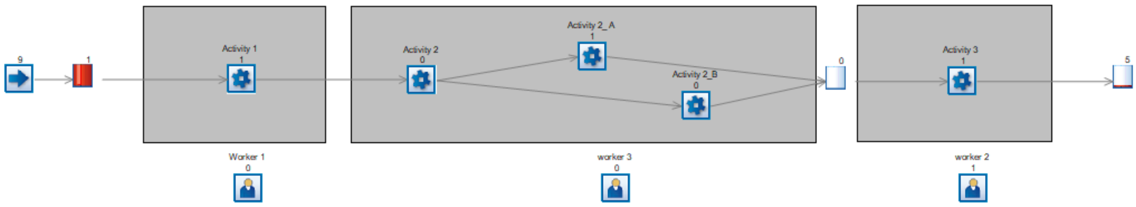


Figure 22 - Model for the simulation of the experience 1

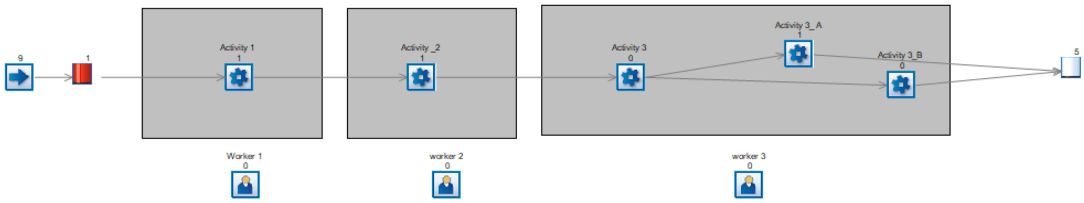


Figure 23 - Model for the simulation of the experience 2

Figure 24 represents the production sequence in which the yellow cube represents a type 1_A product and the blue cube represents a type 2_B product.

Figure 24 - Sequencing for the validations

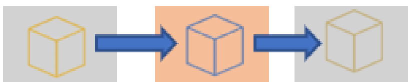


Figure 25 - Assembly line of the experience 1

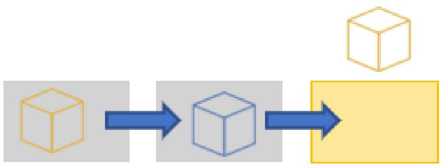


Figure 26 - Assembly line of the experience 2

The layout of the assembly line, for experience 1 and 2, composed by 3 WS are represented in Figure 25, and Figure 26. The WS represented in orange and yellow indicates the stations that are expected to be blocked or starved in each experience. In experience 1, WS2 will be blocked each time it produce a product 2_B, since it processing time in this station is lower, meaning that it will be completed before station 3 becomes available to receive it. In the experience 2, WS3 will be starved each time a product 1_A will be produced because to perform the second task to the product 2_B take more time, than the third task of the product 1_A.

Figure 27 represent the manual simulation conducted for each of the previously defined experiments.

Clock	Blocked	Starved	Lead time
0			
60			
105			
120			
165			165
225	15		
240			180
300			180
345	15		
360			180
420			180

Clock	Blocked	Starved	Lead time
0			
60			
105			
120			
165		15	165
180			
240			180
285		15	165
300			
360			180
405		15	165

Figure 27 - Simulation time Experience 1 and Simulation time Experience 2

The Figure 27, show the simulation time count in seconds. The remaining columns refer to blocked, starved, and lead time. The green colour represents a finished product. Through the analysis of these, it is noticeable that when blocking occurs the lead time tends to remain equal to the longest. The experience 2 presents 45s of starved time but has a higher production for the same time interval compared to experience 1.

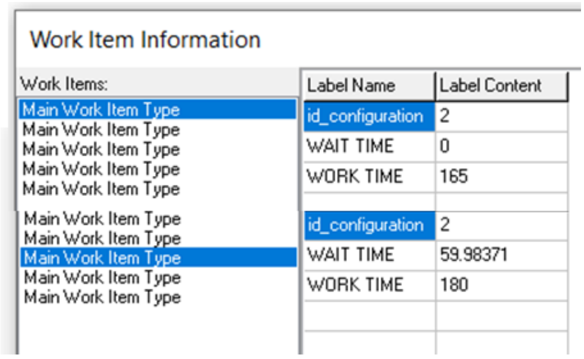


Figure 28 - Simulation Results of the experience 1

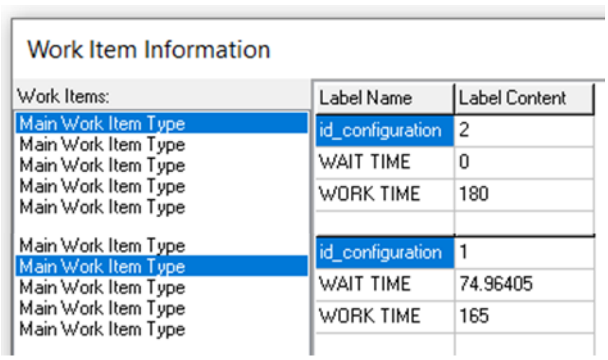


Figure 29 - Simulation Results of the experience 2

The simulation allowed to verify that calculated data were easily visualised in the simulation. With special labels in simul8, the lead time is easily identified. These values will reflect the blocked and starved time, Figure 28, and Figure 29.

Figure 28, it appears that the product 2_B despite having a total time of 165 seconds in the beginning and after has a lead time of 180. This lead time is represented by the automatic label Work time. The addition of 15 seconds means that the workpiece is blocked for 15 seconds.

5.5. Simulation Data Collection

The simulation concedes data collection directly and indirectly. At the end of the simulation, it is possible to collect data that enable the analysis of performance indicators of the line.

It is directly possible to collect the entry, exit, and processing times for each production unit, as well as the time of use of the resources available for each workstation. Thus, lead time and exit time are obtained directly from the simulation.

Indirectly and through the list of values collected in excel, the remaining indicators are extracted. Such as idle time, *takt time*, cycle time, smoothness index, balance delay and operational ratio. The data analysis was conducted with workstations k = 1, ..., m, and products i = 1, ..., p.

Lead time is the time the product spends in the system. This includes the effective assembly time and the time the product spends in queues.

$$\textbf{Lead time = Waiting Time + Production time} \qquad (5.3)$$

In the simulation, the lead time is the time that the product takes between the entrance of workstation one and the exit of station m. This is easily obtained from simul8 through the detailed Transaction Log by Area. It allows to collect a large volume of exact timing and Label value data.

Exit time is the time when the product is finished on the assembly line. Then it passes to the quality control and packaging station. While this study does not become a relevant circumstance, only product assembly stations are contemplated. In the simulation, it is the time in the simulation clock that a product enters the end point.

Idle time is the time specified as a period when the system is not in use but is fully functional within the desired parameters. In a simulation, when a workstation is not performing, it is called blocked or starved.

$$\textbf{Idle time = Blocked time + Starved Time} \qquad (5.4)$$

The station is blocked when a task finished, and the product still in there. This scenario does not permit the entry of the next reference. Starved time refers to the time the worker is waiting for the following reference. At that moment on the worktable, he does not have any products; it is empty.

Waiting Time = Blocked time + Queue time (5.5)

Blocked Time = Time at the station - Time needed to perform a task (5.6)

Idle time is equal to the time that resources are available. Since in this case, each station has a worker, and when the worker is available, the system is idle.

Takt time is the measure/rhythm of the line. It is the rate at which a product reaches the end of the line. It is an essential tool in ensuring that goods flow through each station in an efficient mode. In the simulation, it is the difference in time/label, that is, the exit time, between two consecutive products.

The cycle time is the maximum time spent at each station. The average cycle time is the average time spent at the station by product. More prolonged cycle times than the tasks times for the workstation intend waste and inefficiency.

Operational ratio measures the ability to reach the requested quantities within the programmed time. Ideally, the OPR is between 95 and 98%. It is not the efficiency of the line since the quantity of finished product defined as target already considers the planned stops. The OPR returns the ratio between actual production and expected production with the scheduled breaks. It becomes relevant to understand what the unscheduled losses are, when they occur and their weight in manufacturing.

In the simulation, the OPR can be determined by dividing the quantity produced by the amount expected.

$$Targets = 1 + \frac{(Simulation\ time\ - Warm\_up\ period)}{Target\ Takt\ time} \quad (5.7)$$

$$OPR = \frac{Actual}{Targets} * 100\%. \quad (5.8)$$

5.6. Implementation and Collection of Line Data

Due to the pandemic situation lived during this project it was not possible, as it was intended, to make experiments in the real line. Nevertheless, a brief introduction of what was intended to do is presented next. Experiments in the real line will be made during the next academic year.

Some of the indicators serve to perceive the balance of the assembly line, and if the adjustments presented will not affect the balancing. As part of another project developed in the laboratory, an optimization tool to balance the line is being developed. Thus, when experimenting in the real line it will be possible to assume that it is optimally balanced. Consequently, the implementation on the line will be executed in such a way that it is only necessary to check the total production in a period. When collecting this value, it is possible to know if it corresponds to the simulated result and if there occurred unexpected stops on the line.

At the same time, it is intended to develop an automated monitoring system on the line. With this system it will be possible to understand when, where and how long the stops occur. Collecting data on the assembly will also allow the use of time variation in the simulation. These will turn the simulation into a stochastic analysis, which will allow an excellent approximation of simulation and reality.

6. RESOLUTION AND DISCUSSION

As a first step it was decided to consider a simple problem, considering only two products and a straight line with 3 WS. This option was taken to gain even more confidence in the model developed and to facilitate the interpretation of the results. The two considered products will be denoted 1_A and 2_B and their tasks time in each WS is given in Figure 30 and Figure 31. In each WS there is a single operator and an intermediate stock of one unit is allowed between two WS.

The time each product will take to be processed in each WS were chosen to assure a perfect line balancing. As it was referred previously, in a line, idle times can occur due to unbalanced WS or, in the case of mixed-model lines also due to sequencing decisions. Thus, the time chosen will allow to concentrate the attention in the sequencing impact on assembly lines idle time.

	WS 1	WS 2	WS 3	Production
1_A	18	45	28	50%
2_B	42	15	32	50%
WACT	30	30	30	

Figure 30 - Activity times and percentage of production

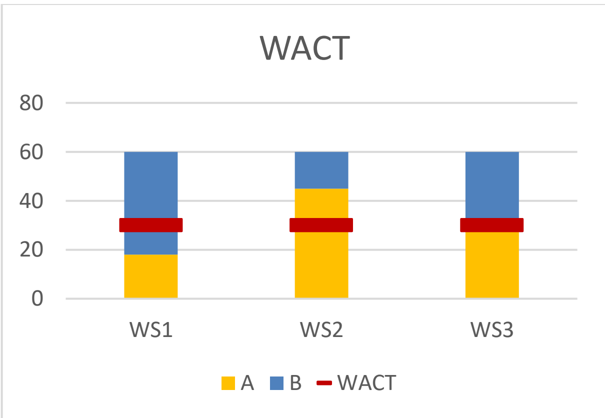


Figure 31 - WACT

The simulation model developed for this problem is presented in Figure 32. The indicators intended to be collected by the simulator are:

- **Operational Ratio (OPR)** (5.8)
- **Lead time** (5.3)

- **Blocked time** (5.6)
- **Idle time** (5.4)
- **Starved time = Idle time – Blocked time**
- **Usage of resources: Since there is a single** worker per workstation, when a resource becomes available that means that the workstation is starved or blocked.

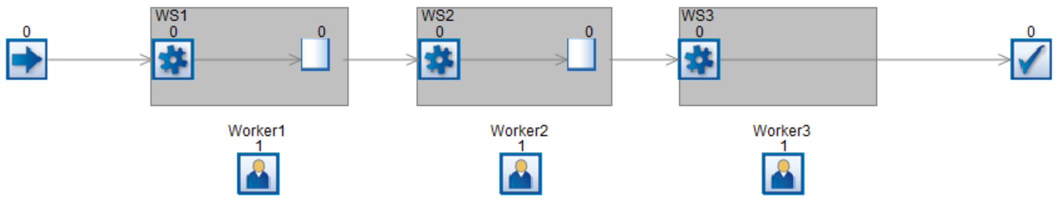


Figure 32 - Simulation model three WS

Four experiments were conducted with the developed simulation model: A, B, C and D. In experiments A, B and C the production sequence were randomly generated, while in experiment D the production sequence was defined as [(2_B)-(1_A)-(2_B)-(1_A)-…]. The results obtained for each experiment are presented in Figure 33. The collection period corresponds to a working day, as the task time is given in seconds, a working day have 28800 seconds. The simulation was only run once for each experiment as the times considered are deterministic and its repetition does not change the results.

It can be observed that for the imposed sequence [(2_B)-(1_A)-(2_B)-(1_A)-…], experiment D, the maximum OPR (99,79%) was obtained. In fact, a production of 956 products were achieved for an expected production of 958. This OPR is obtained because the line is perfectly balanced and there is no idle time, meaning that it is never blocked, or starved. The idle time that appears in the results for this experiment is due to the warmup period.

On the other hand, for experiments A, B and C, with a randomly generated production sequence, the OPR is around 85%, 15% lesser than the one obtained for experiment D. This lower OPR can be easily explained by the presence of Idle time, resulting from the fact that in some period the line will be blocked due to the combination of products present in the line.

Since the line is perfectly balanced in all experiments, it can be concluded, as expected, that the OPR of a mixed-model assembly line, depends not only on the balancing decision, but also on the sequencing decision. In sum, it can be said that the idle time has a component that concerns balancing and another that is related to sequencing. It is also important to understand that a bad sequencing decision can result in important losses of productivity in the assembly line, in this case up to 15%.

A		
Production	820	
TARGET	957	
1	446	54,39%
2	374	45,61%
OPR		85,68%
idle time		12264
blocked time		5009
starved time		7255

B		
Production	831	
TARGET	958	
1	418	50,30%
2	413	49,70%
OPR		86,74%
idle time		11379
blocked time		3965
starved time		7414

C		
Production	840	
TARGET	957	
1	428	50,95%
2	412	49,05%
OPR		87,77%
idle time		10470
blocked time		3749
starved time		6721

D		
Production	956	
TARGET	958	
1	478	50,00%
2	478	50,00%
OPR		99,79%
idle time		118
blocked time		0
starved time		118

Figure 33 - Characteristics of four distinct analyses

Considering the OPR, and the blocked and starved time. The longest blocking time is usually located before the bottleneck of the line and the longest starved time after. The blocked time is the one that is most easily extracted from the line, as it is related to the time that the product spends in a specific station and exceeds the task time. For this reason, the most crucial factor for the analyse is the blocked time. The decrease of the OPR can be related to the blocked time when the blocking time decreases, the OPR value increases. The same correlation cannot be made with starved time.

The described experiments were also important to validate the model. In fact, it was possible to observe that the first WS never stays starved, because the product integrates the line whenever the line needs it and that the last station never remains blocked because there are no subsequent stations.

The blocking time depends on several factors which makes it difficult to calculate for multiple products. The blocked relies not only on the uptime of the product in question but also on the uptime of precedent products.

To understand and anticipate line blockages the concept of phenomenon will be introduced. The term phenomena are utilized by (Tiacci, 2017)in a paper about the mixed-model U-shaped assembly lines. We will consider a list of size n as a subset of the main production sequence. This concept is illustrated in Figure 34. In a sequence of 5 jobs, we can obtain 3 lists of size 3. In the proposed example the list is [2,1,1], [1,1,2] and [1,2,1].

A phenomenon can be analysed to verify if it will cause a blocked time in the line. If it is the case, this list will be referred to as a phenomenon. In a Phenomena the blocked time will always be associated to the product i+(n-1) in the list.

Consider for example the list [2,1,1] in the example of Figure 34. The first product to enter in the assembly line is 2, that is, the production flows from left to right in the list. If we consider that the list [2,1,1] is a Phenomena, this means that whenever producing [2,1,1], the last job of the list will get blocked at a given workstation. This blocked time depends on the last product tasks time in each WS and on the tasks time of its predecessors.

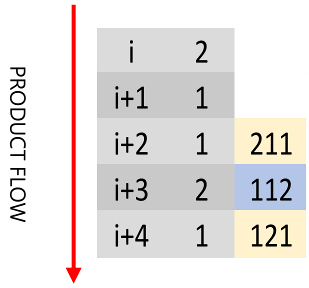


Figure 34 - Example of a sequence of products

Thus, it is crucial to understand how we can collect the values of the simulation and understand where the problem is occurring and what factors are associated with it.

For a manual resolution of the problem, the following decision variables were used:

$t(WS_k)_i$ – Task time in the workstation k and for the product i.

$C_S(WS_k)_i$ – Clock when the product i starts at the workstation k.

$C_F(WS_k)_i$ – Clock when the product i finishes the task at the workstation k.

$C_S(S_{k,k+1})_i$ – Clock when the product i enter in the stock between the stations k and k+1.

$C_F(S_{k,k+1})_i$ – Clock when the product i leaves the task at the stock between the stations k and k+1.

$t(S_{k,k+1})_i$ – Time in stock between the stations k and k+1 for the product i.

The indexes are:

$$i = \text{products } 1 < i < p,$$

$$k = \text{workstations } 1 < k < m.$$

Initially, when the intermediate stock of stations is empty, the product don't need to stay in the stock if $t(WS_k)_{i+1} \geq t(WS_{k+1})_i$ and the $C_F(WS_k)_{i+1} = C_S(WS_{k+1})_{i+1}$.

The product i+1 go to the stock when $t(WS_k)_{i+1} < t(WS_{k+1})_i$.

The product goes to the stock when $t(S_{k,k+1})_{i+1} = C_F(S_{k,k+1})_i - C_S(S_{k,k+1})_{i+1}$ and the product are blocked when the $t(WS_{k+1})_i > t(S_{k,k+1})_{i+1}$.

During the analysis of the results, three aspects are essential to contemplate. The impact of to remove a phenomenon of the line. The effect on the line's operability when we exclude a phenomenon. After that, it is vital to be aware of the difficulty/benefit. This proportion can help to choose the desired level of complexity.

6.1. The analytical results of the first experiments

The combination of three products is short and straightforward to solve analytically. What we want to answer is which specific product sequences block the line.

When considering a combination of four equal products of type A, it turns out that there is a blocked time in the third type A product between the WS 1 and 2. This circumstance means that this product combination tends to accumulate stock between the WS 1 and 2. Also, the last WS is always starved, Figure 35. On the other hand, when we analyse a combination of three type B products, as the first task is the longest one, we only observe starved times in the remaining stations, Figure 35.

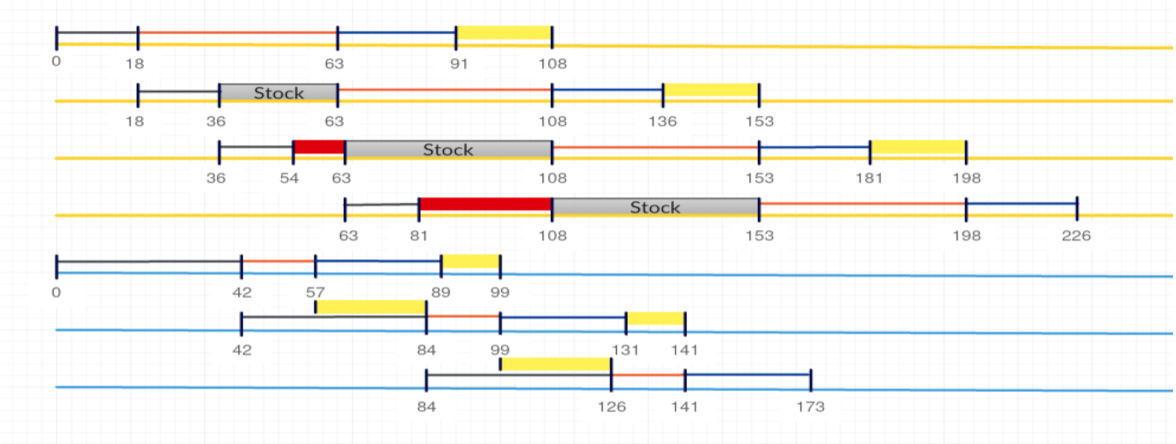


Figure 35 - Sketch of the behaviour of the lists [A-A-A-A], and [B-B-B] on the line

Taking the [A-A-A] sequence because it is the worst and trying to avoid blocking. We change the last A to B, getting the combination [A-A-B]. After that change, the only products that will not cause the blockage is the B-A successively. The sequence [A-A-B-B-A] is obtained. The sixth product that enters the line will always stop up regardless of the type of product.

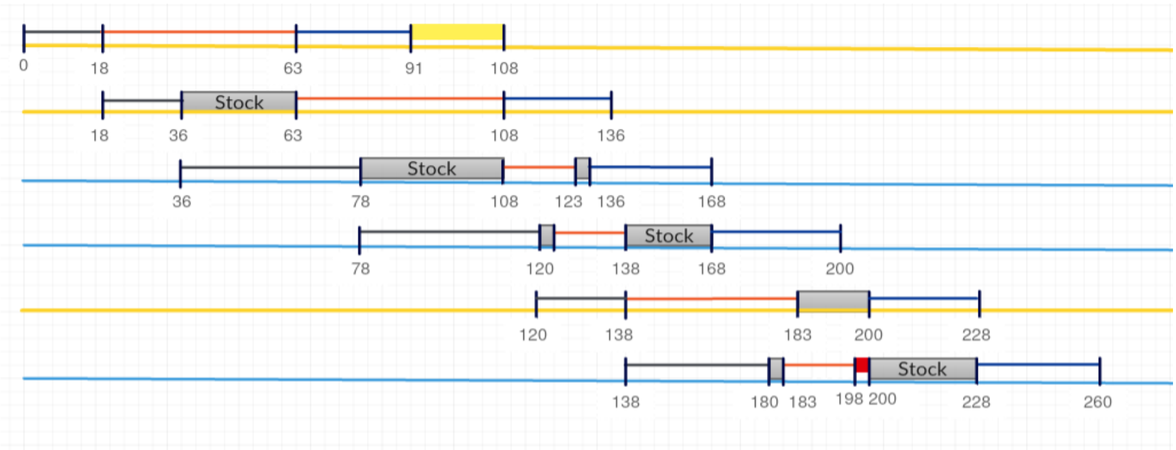


Figure 36 – Sketch of the behaviour of the list [A-A-B-B-A-B] on the line

The block will appear between WS 2 and WS 3 for two seconds, Figure 36.

6.1.1. The results of the first experiments in the simulation

To the previous experiments A, B, C, a new random experiment was added. These started to be called experience 1, 2, 3, and 4, respectively.

The line has a uniform WACT of 30 for all stations when production is precisely 50%. With a slight variation, the bottleneck at workstation 2 appears, Figure 37. This workstation is the one causing the blocked time in the WS 1, and the starved to the WS3. As station 1 has the longest blocked time, Figure 38. The focus will be to reduce this, analysing the phenomena.

				WS1	WS2	WS3
Product_ID	A	1	50,3%	18	45	28
	B	2	49,7%	42	15	32
	WACT			29,9	30,1	30,0

Figure 37 - Variation of the percentage of production and respective change of WACT

	WS1	WS2	WS3	TOTAL
idle time	3826	3709	3844	11379
blocked time	3826	139	0	3965
starved time	0	3570	3844	7414

Figure 38 - Idle, blocked, and starved time for each workstation

Figure 37 shows that the bottleneck will be WS 2. Thus, WS2 will not be considered for this analysis of the blocked and only the combinations that cause the block in WS 1 will be studied. Considering two distinct products grouped in combination of 3 products we can obtain $2^3 = 8$ possible combinations. Analysing the impact of these eight combinations it was verified that 4 of them never caused blockage in WS1. Figure 39 presents the number of times each of the 4 combination that cause blockage occur during the simulation and the number of times they cause blockage.

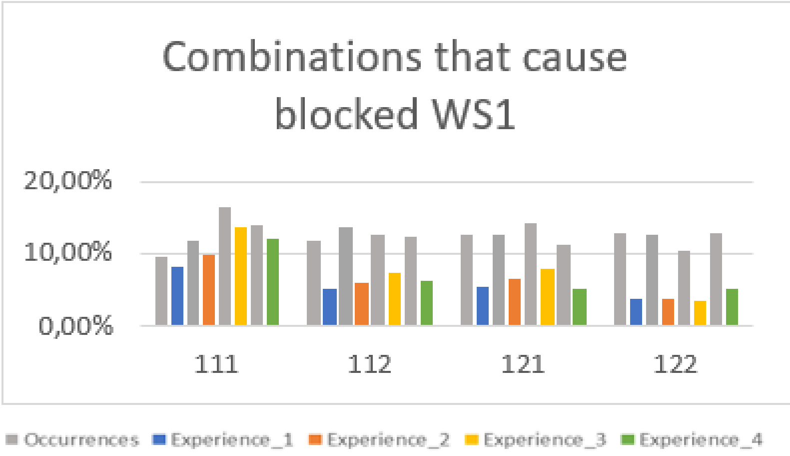


Figure 39 - Block and Occurrence relation for four random experiments combination of three

The number of occurrences, of each combination in each experiment, is represented in grey. The colours represent the number of times the combination leads WS1 to be blocked in the respective experiment. Observing the grey column with the adjacent coloured column, we get the relationship of occurrence with the blocked. We can conclude that the combinations of 3 products are inconclusive. No combination blocks the line whenever it occurs.

For the combination of 4 products, in the total, we have $2^4 = 16$ distinct combinations to analyse. In Figure 40, it is possible to observe the five combinations that caused the blockage of the line. The combination of 4 products enables to visualise two phenomena. The combinations 1111 and 1112 always cause blocked time.

In the combinations of five products, there are already known phenomena. The known phenomena are 11111, 11121, 11112, 11122, 21111, 21112. These are a result of the allocation of one product to the phenomena obtained previously. They need to be a phenomenon in the results for the combinations of five products.

The other three combinations need to evaluate for a combination of five products. However, to reduce the complexity and the resolution time, only a different product will be added to the three combinations at the beginning. This reduction is possible because the factors that imply to obtain a phenomenon are related to the production sequence. That is, with the previous products and not with the subsequent ones.

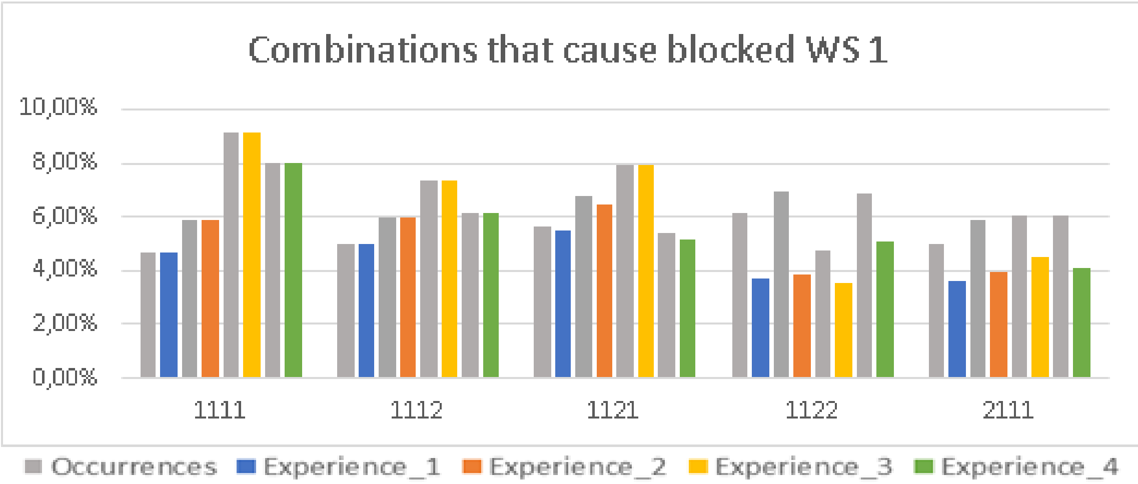


Figure 40 - Block and Occurrence relation for four random experiments combination of four

What had been predicted following the phenomena of the combination of 4 can be seen in Figure 41. It shows the occurrence of the blocks of the $2^5 = 32$ combinations of 5. Furthermore, a new phenomenon occurs from the previous inconclusive combinations, and remain three inconclusive combinations.

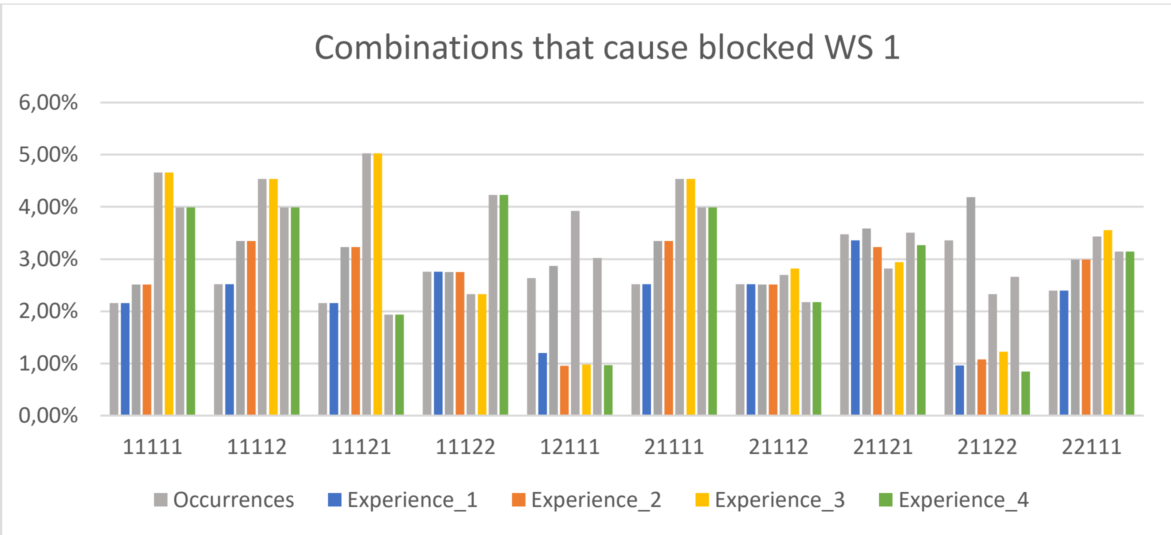


Figure 41 - Block and Occurrence relation for four random experiments combination of five

In most experiments, combinations of 9 products were the maximum number of combinations needed to find all the phenomena. Figure 42 shows the conclusions of the four experiments. In this figure it is possible to observe, for each experiment and each identified phenomenon the resulting percentage of blocked time in the line. There are phenomena common to all experiences and other phenomena that occur only in some. This situation occurs because the values were generated randomly, there are combinations that do not happen in all experiments. This factor can create the appearance of small changes in the phenomena found.

	Experience_1		Experience_2		Experience_3		Experience_4	
Comb_4	1111 1112	9,70%	1111 1112	11,83%	1111 1112 1121	24,48%	1111 1112	14,13%
Comb_5	11121 11122 22111	7,31%	11121 11122 22111	8,96%	11122 22111	5,88%	11121 11122 22111	9,30%
Comb_6	121121	1,80%	121121	1,9%			121121	1,2%
Comb_7	1121122 2212111 2221121	2,63%	1121122 2212111 2221121	2,27%	1121122 2212111	1,35%	1121122 2212111 2221121	2,4%
Comb_8	21212111 21221121	0,96%	21221121	0,24%	21212111	0,37%	21212111 21221121	1,1%
Comb_9	211221121	0,12%	112121122 211221121 221212111	0,84%	112121122	0,37%	112121122 122121122	0,4%
Comb_11					11212121122	0,1%		

Figure 42 - Summary table of the phenomena in the four experiences

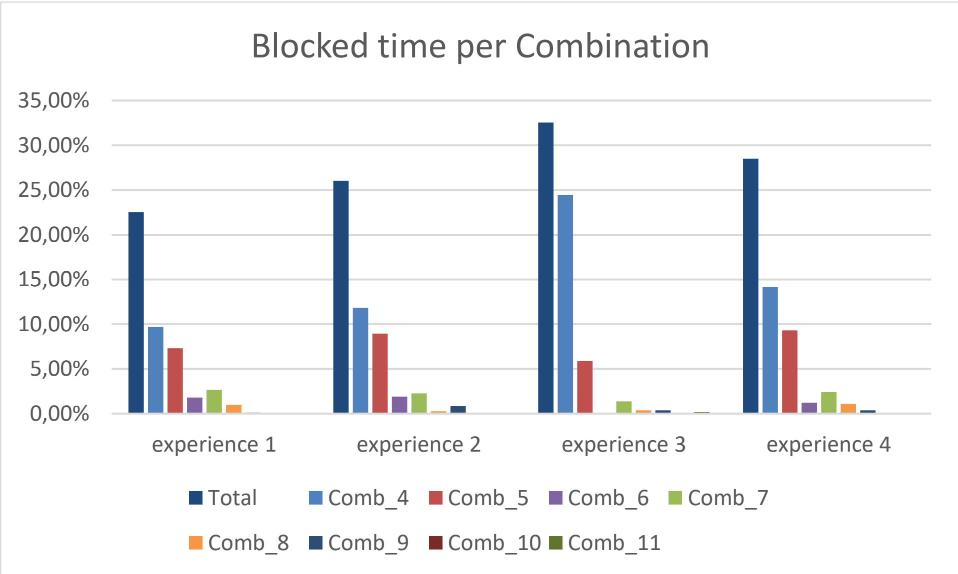


Figure 43 - Percentage of time blocked in each combination

Figure 43 compares the percentage of total block with the percentage of blocked time for each type of combinations. The last step is to remove the phenomena from the production sequence. Figure 44 summarises the results obtained.

	1111	4,67%	Removed						
	1112	5,03%	1112	2,33%	Removed				
							1121	2,55% Removed	
	11121	2,16%	11121	0,70%					
	11122	2,75%	11122	1,63%					
	22111	2,40%	22111	1,05%					
	121121	1,80%	121121	3,26%	121121	3,24%	Removed		
	1121122	0,96%	1121122	0,81%	1121122	0,46%	1121122	0,12%	
	2212111	0,84%	2212111	0,58%	2221121	0,93%			
	2221121	0,84%	2221121	0,93%	2221121	0,93%			
	21212111	0,36%			21212111	0,81%			
	21221121	0,60%	21221121	0,81%	21221121	0,81%			
	211221121	0,12%							
			2211221121	0,12%	2211221121	0,12%			
			11212121122	0,23%	11212121122	0,23%	11212121122	0,23%	
			1221212121122	0,12%					
Blocked	23%		12,6%		5,44%		2,9%		0,00%
Finished	838		862		867		866		871
Reduction of blocked time			9,94%		7,13%		2,54%		2,90%

Figure 44 - Results of the elimination of phenomena in the production sequence

With the elimination of a phenomenon, the improved percentage was more significant than the portion of blockage caused by it. This reduction occurs because there are associated phenomena.

The elimination of [1,1,1,1] the blocked time in global reduced more than the % of the blocked time that this caused. Another combination that causes every time block is [1,1,1,2]. After the sequence [1,1,1,1] can appear the product 2, and with this will generate the combination [1,1,1,2]. When the combination [1,1,1,1] is removed from the planning, the percentage of occurrences of [1,1,1,2] combination will be reduced too.

Another factor that is observed by the analysis of figure 33 is that the phenomenon [1,1,2,1], which occurs only in experiment number 3 (Figure 42), is due to the absence of the combination [1,2,1,1,2,1].When the combination [1,2,1,1,2,1] is removed, the phenomenon [1,1,2,1] appears, and its elimination solves the balance of the line.

After the elimination of 4 phenomena, the line is out of blocking time and at maximum production. In other words, with an OPR of 99.9%. The relationship between OPR and the blocked time is not direct. The value of the blocked time has always reduced, but the number of finished products does not increase linearly.

6.2. Three products and five WS

In the previous section an analysis of a simplified version of the considered assembly line was performed. In this section we will consider the real-life assembly line, Figure 45. This line is composed by 5 WS and can produce a large set of different final products, depending on the components assembled to the base product (the pneumatic cylinder). From this large set of final products, 5 different products were chosen to be produced. Note that in this new experiment the task times are no longer defined to obtain a perfectly balanced line, they are the real time necessary to perform the operations and they were collected in the real line.

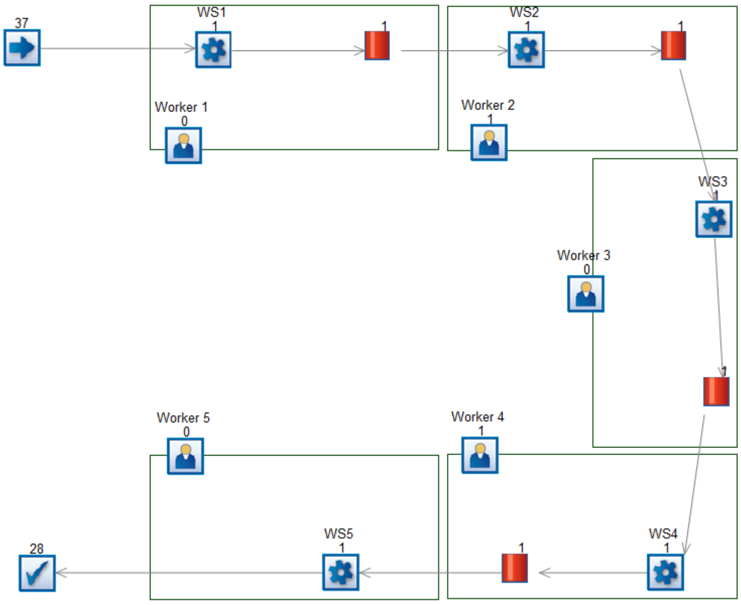


Figure 45 - Simulation model five WS

It is inherent to realize that products considered as more uncomplicated, that is, that require fewer components in their configuration, are not necessarily the products that have less total assembly time, Figure 46.

The choice of the three products

Configurations A, B and C, group numerous different products. However, in the simulation, the products are only different when they have different assembly times. Thus, the 5 selected products can be grouped in just 3 different configurations.

	WS1	WS2	WS3	WS4	WS5	Production %	Production time
1_A	25	20	26	51	37	30%	159
2_B	25	20	26	20	37	20%	128
3_B	25	20	26	15	37	20%	123
4_C	25	20	26	20	46	15%	137
5_C	25	20	26	15	46	15%	132
WACT	25	20	26	27,55	39,7		

Figure 46 - Tasks and Total production time for each product

The product 1_A belongs to the A configuration, 2_B and 3_B to the B configuration and the other two belongs to the C configuration.

The components that will be assembled in each WS for each product and the respective WS, and activity time are presented in Figure 47. Figure 47 represents the task allocation established by the group of students. The group of students developed their balance manually, obtained this solution for the balance of the line.The sub-components 110 and 100 are the screws, and the cylinder body have four screws. The assembly of them are divided between WS1 and WS2, it means that two screws will be screwed in the WS1 and the other two in WS2. The sub-components are described in Figure 8.

1_A		30%
Station	Assembly time	Config A Sub-component
WS1	25	10
		22
		30
		110 and 100
WS2	20	21
WS3	26	41 *2
WS4	51	81
WS5	37	51
		91
		93

2_B		20%	3_B		20%
Station	Assembly time	Config B Sub-component	Station	Assembly time	Config B' Sub-component
WS1	25	10	WS1	25	10
		22			22
		30			30
		110 and 100			110 and 100
WS2	20	21	WS2	20	21
WS3	26	41	WS3	26	41
		42			42
WS4	20	71	WS4	15	72
WS5	37	51	WS5	37	51
		91			91
		93			93

4_C		15%	5_C		15%
Station	Assembly time	Config C Sub-component	Station	Assembly time	Config C' Sub-component
WS1	25	10	WS1	25	10
		22			22
		30			30
		110 and 100			110 and 100
WS2	20	21	WS2	20	21
WS3	26	42*2	WS3	26	42*2
WS4	20	71	WS4	15	72
WS5	46	53	WS5	46	53
		61 or 63			61 or 63
		91			91
		93			93

Figure 47 - Regrouping of products for simulation

As can be seen from Figure 46, the line is not balanced. In this way, what will result will be a very high idle time, which in turn will represent a reduced line efficiency.

To analyse the impact of an unbalanced line versus a balanced line, the simulation results for both balances were collected and analysed. A product of each configuration was considered, being product 1, 2 and 4, respectively. The probabilities of originating each product were 30, 40, 30, respectively.

The tasks were initially evenly distributed, even when precedence was not required. For example, the assembly of sub-component 21 would always be performed at WS 2 regardless of the configuration, and the remaining assembly times. In Figure 48 and Figure 49, it is possible to observe the changes made in terms of task allocation.

			WS1	WS2	WS3	WS4	WS5
A	1	30%	25	20	26	51	37
B	2	40%	25	20	26	20	37
C	4	30%	25	20	26	20	46

Figure 48 - Allocation of tasks without balance

			WS1	WS2	WS3	WS4	WS5
A	1	30%	25	35	26	51	22
B	2	40%	25	20	26	20	37
C	4	30%	35	34	26	20	22

Figure 49 - Allocation of tasks with balance

The lines have a different task allocation and the same percentage of production, thus their WACT changes. For unbalanced WACT ranges between 20 and 40, Figure 50. In a balanced line, WACT varies between 26 and 29, Figure 51.

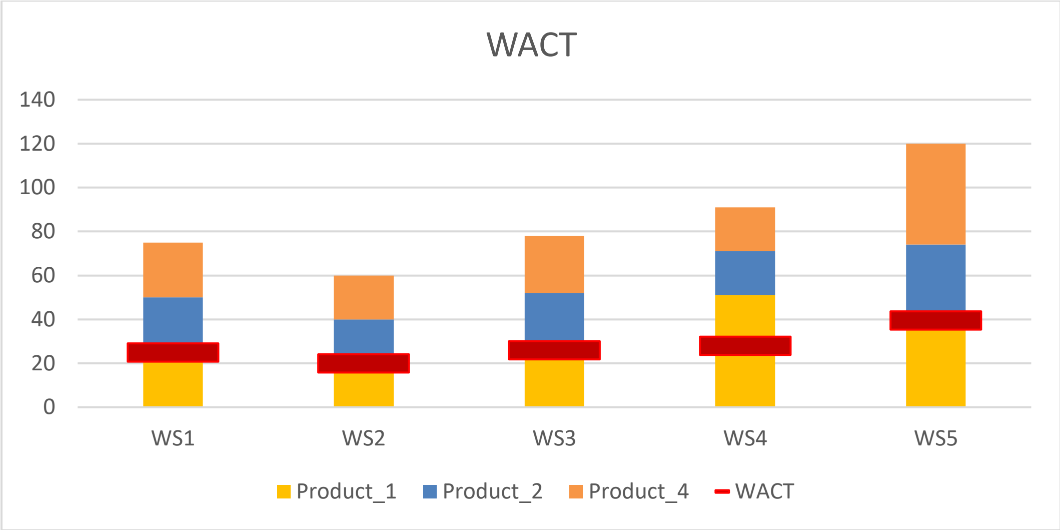


Figure 50 - WACT without balance

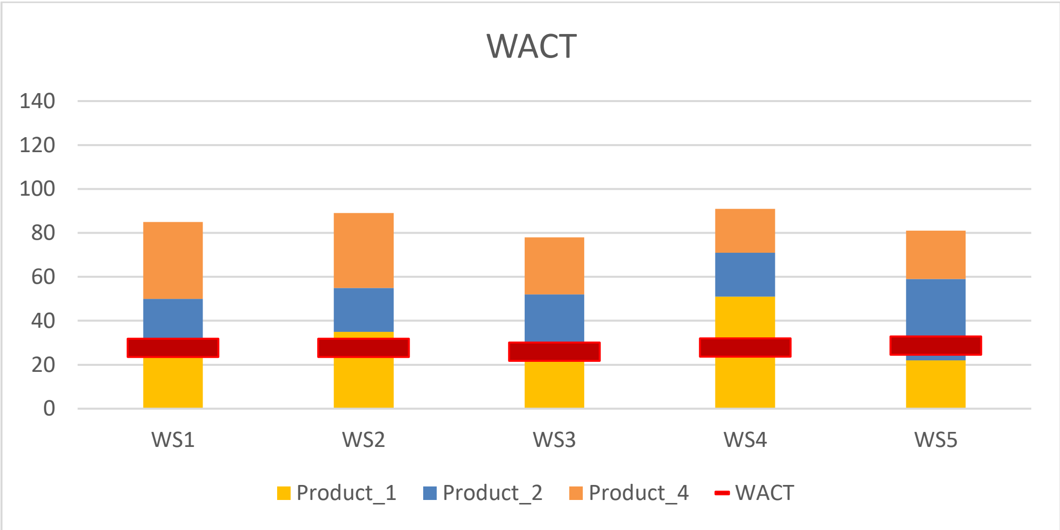


Figure 51 - WACT with balance

The unbalanced line has a more significant variation in its WACT. However, its OPR had a good value. This happen because the OPR is calculated considering a *takt time*. This ideal *takt time* comes from the higher WACT value. When the line is unbalanced, the higher value of the WACT makes the target *takt time* higher and thus the expected production smaller. When the production target becomes smaller it will be more easily achieved, but the line will be working with low efficiency. The variable such as idle time and smoothness index will also be higher.

Considering the efficiency of the stations it can be concluded that the line has an average efficiency of 70%, where station two is using only 50% of its capacity. In the balanced assembly line, the average line efficiency is around 87%. The efficiency of each station reaching a minimum of 81% and a maximum of 90%. The OPR of the unbalanced line is higher than 9%. However, the production in the balanced line is more elevated 169 units per day, Figure 52 and Figure 53.

Regarding the smoothness index and the balancing delay, there can be a very strong reduction. The SI is now closer to zero, which is it an excellent value, and the BD has reduced by more than half, Figure 52 and Figure 53.

	Day	Hours	Minutes	Seconds			
Simulation time	1	8	480	28800			
Production	722						
1	186	26%					
2	330	46%					
4	206	29%					
WACT		25	20	26	28	40	
		WS1	**WS2**	**WS3**	**WS4**	**WS5**	
Idle time		10525	14220	9898	8534	160	
Cycle time		51	51	51	51	46	
Average Cycle time		39	39	39	40	40	
WS EFFICIENCY		63,5%	50,6%	65,6%	70,4%	99,4%	70%
Smoothness index			30				
Balancing delay			30,1%				
Average Takt Time		39,667					
Actual		722					
Target Takt Time		39,57					
Targets		725,63					
OPR		0,995	99,50%				

Figure 52 - Assembly line results without balancing

	Day	Hours	Minutes	Seconds			
Simulation time	1	8	480	28800			
Production	891						
1	263	30%					
2	391	44%					
4	237	27%					
WACT		27,7	28,2	26,0	29,2	28,6	
		WS1	**WS2**	**WS3**	**WS4**	**WS5**	
Idle time		3925	3575	5521	2741	3298	
Cycle time		51	51	51	51	37	
Average Cycle time		32	32	32	32	29	
WS EFFICIENCY		86%	88%	81%	90%	89%	87%
Smoothness index			4				
Balancing delay			13%				
Average Takt Time		32,172					
Actual		891					
Target Takt Time		29,15					
Targets		984,59					
OPR		0,9049	90,49%				

Figure 53 - Assembly line results with balancing

Notwithstanding being the balanced line that presents a more favourable result, an initial analysis of the phenomena present in the unbalanced line was made. Following the same line of thought adopted for the simplified line, all combinations of 3 products for the three products were analysed, thus obtaining $3^3 = 27$ combinations. Note that the degree of complexity has increased, Figure 54 shows the increase in the number of combinations considering the increase in products in the line.

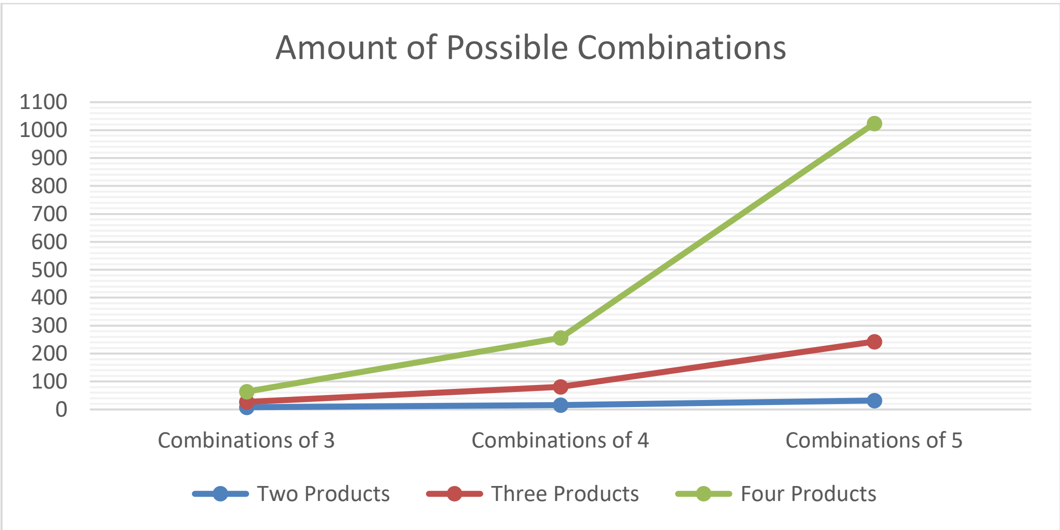


Figure 54 - Increase in the number of possible combinations

6.2.1. Analysis of phenomena's

Due to the increased complexity, the simulation models were run for a work week, 144 000 seconds. This measure was due to the increase in the number of possible combinations compared to the combinations with only two products.

With a more significant number of products, the number of combinations increases exponentially. Thus, it becomes essential to increase the spectrum of data collection. For a simulation with only 28800 seconds, it was found that most combinations did not occur, which means that not all factors were analysed to find the phenomena.

Figure 55, and Figure 57 show that the results are different. The blocking percentages are expected to be different as the values are generated randomly. However, what happens is that not all combinations that are considered phenomena when the spectrum of results is widened. For example, in the list of combinations of 3 products, with the increase in the data analysed, it stopped showing phenomena.

Figure 56, and Figure 58 allow us to observe that there are similar phenomena for WS 3 and 4. In WS 1 and 2 we observe the similarities in the phenomena, however they are all different.

		WS1	WS2	WS3	WS4
Comb_3	Blocked	330	336	322	294
		37,1%	37,8%	36,2%	33,1%
	Phenomena	0	0	104	0
		0,0%	0,0%	11,7%	0,0%
Comb_4	Blocked	330	336	218	294
		37,1%	37,8%	24,5%	33,1%
	Phenomena	27	32	78	198
		3,04%	3,60%	8,77%	22,27%
Comb_5	Blocked	303	304	140	96
		34,1%	34,2%	15,7%	10,8%
	Phenomena	62	86	46	40
		7,0%	9,7%	5,2%	4,5%

Figure 55 - Blocking data and phenomena for the spectrum of a 28 800 seconds

Occurrence	WS1	Occurrence	WS2	Occurrence	WS3	Occurrence	WS4
0,9%	1 411	3,6%	2 222	3,8%	121	3,6%	2 222
0,4%	1 421	0,3%	11 112	5,6%	122	2,2%	2 224
0,9%	1 422	0,1%	11 124	2,2%	142	2,6%	2 242
0,8%	4 412	0,1%	11 142	1,0%	1 112	1,5%	2 244
0,1%	11 241	0,7%	11 222	0,4%	1 114	2,8%	2 422
0,2%	11 441	0,1%	11 241	1,1%	1 121	1,2%	2 424
0,6%	11 442	1,1%	12 122	1,8%	1 122	1,5%	2 442
0,4%	12 121	0,1%	12 144	0,9%	1 124	0,8%	2 444
0,1%	12 414	0,4%	12 211	0,4%	1 141	2,2%	4 222
0,1%	14 141	0,3%	12 241	0,9%	1 142	2,0%	4 224
0,4%	14 142	0,1%	12 244	1,1%	1 144	1,1%	4 242
0,1%	14 214	0,2%	12 411	0,9%	2 114	0,7%	4 244

Figure 56 - Percentage of occurrence and phenomena associated with each workstation, spectrum of 28 800 seconds

		WS1	WS2	WS3	WS4
Comb_3	Blocked	1576	1467	1543	1314
		34,9%	32,5%	34,2%	29,1%
	Phenomena	0	0	0	0
		0,0%	0,0%	0,0%	0,0%
Comb_4	Blocked	1576	1467	1543	1314
		34,9%	32,5%	34,2%	29,1%
	Phenomena	0	0	255	489
		0,0%	0,0%	5,7%	10,8%
Comb_5	Blocked	1576	1466	1288	825
		34,9%	32,5%	28,5%	18,3%
	Phenomena	83	64	386	290
		1,8%	1,4%	8,6%	6,4%

Figure 57 - Blocking data and phenomena for the spectrum of 144 000 seconds

Occurrence	WS1	Occurrence	WS2	Occurrence	WS3	Occurrence	WS4
0,4%	11 411	1,4%	22 222	0,7%	1 112	3,0%	2 222
0,3%	11 412	0,1%	111 112	1,1%	1 121	2,1%	2 224
0,3%	11 421	0,1%	111 122	1,2%	1 122	2,1%	2 242
0,3%	11 422	0,1%	111 124	1,0%	1 124	1,3%	2 244
0,2%	11 441	0,2%	111 212	0,8%	1 142	1,6%	2 424
0,2%	14 411	0,0%	111 214	0,9%	1 144	0,7%	2 444
0,1%	41 411	0,1%	111 221	0,3%	11 111	0,8%	12 422
0,1%	111 442	0,1%	111 222	0,4%	11 114	0,4%	12 442

Figure 58 - Percentage of occurrence and phenomena associated with each workstation, spectrum of 144 000 seconds

Returning to the previous analysis of the phenomena for a balanced and an unbalanced assembly line. In the unbalanced line, after analysing, the combination lists of 3 products, it can be concluded that removing the phenomena of this would be a complicated task. Through the analysis of the stations, Figure 52, it can be concluded that the last station would be the bottleneck of the line furthermore the station that would have more idle time would be station 2. A relevant factor is that stations 1 and 2 present high percentages of blocking, being 99.8% and 99.9% respectively, Figure 59.

	WS1	WS2	WS3	WS4
% Blocked	99,8%	99,9%	84,4%	63,5%

Figure 59 - Percentage of blockage occurrence for an unbalanced line

When analysing the 27 lists of possible combinations, it appears that of these 22 are considered phenomena for station 1 and 25 for station 2. Moreover, the two lists that are not considered phenomena have a high blocked ratio, Figure 60. This Blocked ratio is the ratio between the number of times the list blocks the station and its number of occurrences. When the ratio is equal to 1, excel is configurated to the word phenomena appear.

Comb_3	Blocked WS1 Ratio	Blocked WS2 Ratio
111	0,956	0,967
112	Phenomena	Phenomena
114	0,990	Phenomena
121	Phenomena	Phenomena
122	Phenomena	Phenomena
124	Phenomena	Phenomena
141	Phenomena	Phenomena
142	0,991	Phenomena
144	Phenomena	Phenomena
211	0,992	0,992
212	Phenomena	Phenomena
214	Phenomena	Phenomena
221	Phenomena	Phenomena
222	Phenomena	Phenomena
224	Phenomena	Phenomena
241	Phenomena	Phenomena
242	Phenomena	Phenomena
244	Phenomena	Phenomena
411	Phenomena	Phenomena
412	Phenomena	Phenomena
414	Phenomena	Phenomena
421	Phenomena	Phenomena
422	Phenomena	Phenomena
424	0,992	Phenomena
441	Phenomena	Phenomena
442	Phenomena	Phenomena
444	Phenomena	Phenomena

Figure 60 - Phenomena in the unbalanced line and in the combinations of 3 products for WS1, and WS2

The line balanced, in terms of the blocking percentage of each workstation, has a significant improvement. When comparing the blocking percentage with the total blocking time, it is observed that the highest percentage is associated with WS1, Figure 61 and the highest blocking time with WS3, Figure 53. This difference is because the blocking percentage is associated with the number of phenomena and not the weight that each phenomenon has. A workstation may have fewer phenomena, but these phenomena have a greater weight. For example, the phenomenon [1,1,1,1,1] of WS 3 occurs 13 times during the working week and the phenomenon [1,1,4,1,1] of WS 1 occurs 19 times. As the list [1,1,4,1,1] occurs more often, it will have a higher percentage of blocking, but this only causes a stop of 2s. The list [1,1,1,1,1] causes a stop of 20 seconds at station 3. In the end the list [1,1,1,1,1] will cause a block of 13 * 20s = 260 seconds compared to the 19 * 2s = 38 seconds caused by the list [1,1,4,1,1].

	WS1	WS2	WS3	WS4
% Blocked	34,9%	32,5%	34,2%	29,1%

Figure 61 - Percentage of blockage occurrence for a balanced line

Given the previous results, the increase of 1 product, increased the average of necessary combinations, to discover all the phenomena. Previously with combinations of 9 products, all phenomena are known, on average, Figure 42. For this case, combinations of up to 15 products were required, Figure 62.

		WS1	WS2	WS3	WS4
Comb_3	Blocked	1576	1467	1543	1314
		34,93%	32,51%	34,20%	29,12%
	Phenomena	0	0	0	0
		0,00%	0,00%	0,00%	0,00%
Comb_4	Blocked	1576	1467	1543	1314
		34,93%	32,51%	34,20%	29,12%
	Phenomena	0	0	255	489
		0,00%	0,00%	5,65%	10,84%
Comb_5	Blocked	1576	1466	1288	825
		34,93%	32,49%	28,55%	18,28%
	Phenomena	83	64	386	290
		1,84%	1,42%	8,55%	6,43%
Comb_6	Blocked	1493	1402	902	535
		33,09%	31,07%	19,99%	11,86%
	Phenomena	199	302	314	273
		4,41%	6,69%	6,96%	6,05%
Comb_7	Blocked	1293	1100	588	262
		28,66%	24,38%	13,03%	5,81%
	Phenomena	400	471	325	161
		8,87%	10,44%	7,20%	3,57%
Comb_8	Blocked	893	629	263	101
		19,79%	13,94%	5,83%	2,24%
	Phenomena	492	357	140	71
		10,90%	7,91%	3,10%	1,57%
Comb_9	Blocked	414	323	151	60
		9,18%	7,16%	3,35%	1,33%
	Phenomena	269	209	112	53
		5,96%	4,63%	2,48%	1,17%

		WS1	WS2	WS3	WS4
Comb_10	Blocked	145	114	39	7
		3,21%	2,53%	0,86%	0,16%
	Phenomena	91	76	30	5
		2,02%	1,68%	0,66%	0,11%
Comb_11	Blocked	54	38	9	2
		1,20%	0,84%	0,20%	0,04%
	Phenomena	37	27	8	2
		0,82%	0,60%	0,18%	0,04%
Comb_12	Blocked	16	11	1	0
		0,35%	0,24%	0,02%	0,00%
	Phenomena	9	7	1	0
		0,20%	0,16%	0,02%	0,00%
Comb_13	Blocked	7	2	0	0
		0,00%	0,00%	0,00%	0,00%
	Phenomena	0	0	0	0
		0,00%	0,00%	0,00%	0,00%
Comb_14	Blocked	1	1	0	0
		0,02%	0,02%	0,00%	0,00%
	Phenomena	1	0	0	0
		0,02%	0,00%	0,00%	0,00%
Comb_15	Blocked	0	1	0	0
		0,00%	0,02%	0,00%	0,00%
	Phenomena	0	1	0	0
		0,00%	0,02%	0,00%	0,00%

Figure 62 - Summary of the combinations that generate blocking time

In the initial analysis the elimination of the phenomena was considered a task of low complexity since there were only two products, Figure 44. Figure 63 shows that the number of combinations that block the line has increased considerably. WS 3 which is our problem station as it is the station adjacent to the bottleneck of the line. This WS has a total of 485 phenomena.

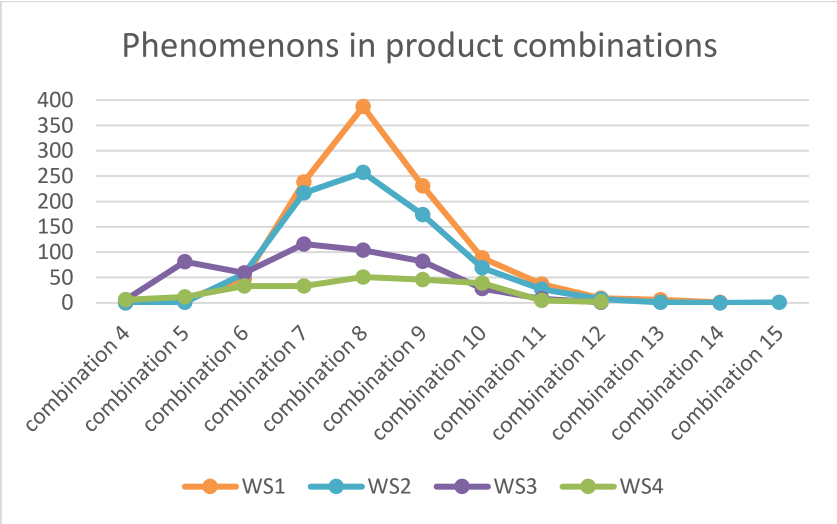


Figure 63 - Number of phenomena for each workstation

Considering the lists of less complex combinations for the WS3 how cause every time blockage, Figure 64, these have been removed from the production sequence.

WS3	
1112	33
1121	48
1122	52
1124	43
1142	38
1144	41

Figure 64 - First phenomena for the WS3

The improvements are significant. Production increased by 53 products and idle time decreased by 20% per workday. Only the production quantity of one type of product was respected but the deviations are not very high, Figure 65, and Figure 66.

	Day	Hours	Minutes	Seconds	
Simulation time	1	8	480	28800	
Production	891				
1	263	30%			
2	391	44%			
4	237	27%			
WACT	27,7	28,2	26,0	29,2	28,6
Target Takt Time	29,15				
Targets	984,59				
OPR	0,9049	90,49%			

	WS1	WS2	WS3	WS4	WS5	TOTAL	% Total Time
idle time	4146	3560	5502	2748	3294	13208	46%
blocked time	4146	3443	5188	2627	0	12777	44,4%
starved time	0	117	314	121	3294	431	1,5%

Figure 65 - Results for a simulation day without removing the phenomena

	Day	Hours	Minutes	Seconds	
Simulation time	1	8	480	28800	
Production	944				
1	252	27%			
2	378	40%			
4	314	33%			
WACT	28,3	28,7	26,0	28,3	28,0
Target Takt Time	28,66				
Targets	1001,4				
OPR	0,9427	94,27%			

	WS1	WS2	WS3	WS4	WS5	TOTAL	% Total Time
idle time	1807	1540	4140	2019	2435	7487	26%
blocked time	1807	1486	3938	1719	0	7231	25,1%
starved time	0	54	202	300	2435	256	0,9%

Figure 66 - Results for a simulation day removing the list of phenomena in the combination of four products

When analysing the last sequence, it is verified the existence of a phenomenon with a high weight, the list [1,4,4]. When trying to remove this, the phenomena that had been eliminated in the previous step always appeared. Due to this difficulty it was decided to apply *Heijunka*.

6.2.2. Applying *Heijunka*

To facilitate the process of removing the phenomena, the *Heijunka* was applied. To define a pattern that would be repeated, reverse thinking was used. The excel developed to find the phenomena was adapted to find the list of combinations that did not block the line.

The first criterion for choosing the lists was considered the number of occurrences favourable to a high number of stations, if possible, in the four stations under study, without causing a blockage. For the list of combinations of 5 products, each combination occurred several times. However, the combinations were not favourable for all WS; at most they were favourable for three WS.

The higher the number of products in the combinations, the lower as the probability that this will have occurred during the simulation of a working week. Figure 67 shows that in combinations of 8 products, the average occurrence is 0.6, with an average deviation of 0.73, which means that most combinations did not occur. To respect the production percentages, the standard chosen will be the combination of a minimum of two lists.

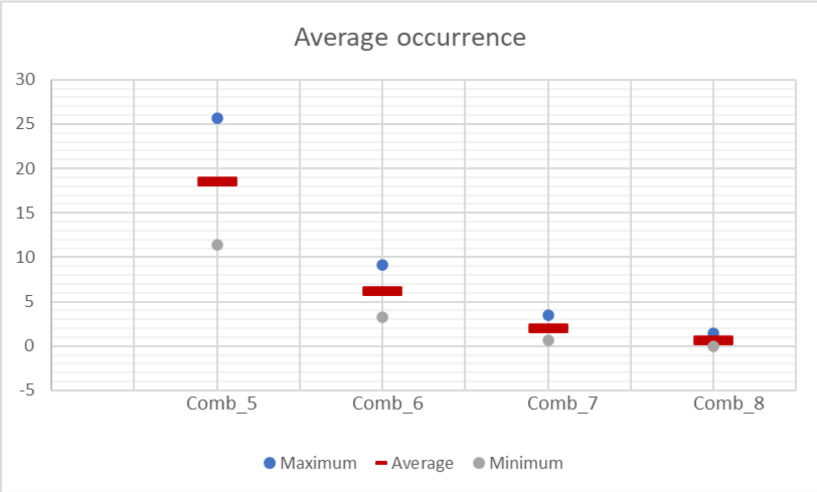


Figure 67 - Average occurrence of the combinations

It was proceeding to the analysis of the combination of 6 products. There is a total of 50 combinations that are favourable for the four WS and occur at least once. When choosing lists, problems may arise with the combinations that arise from the connection. For example, the lists [2,2,1,2,1,4] and [1,4,4,2,2,1], occur 10 and 9 times respectively, and never block any workstation. However, the union of these two lists generates ten new combinations of 6 that arise from the repetition of these two lists, Figure 68. Of these ten lists, only one is favourable to all stations, which is [1,2,1,4,1,4], in addition to the two chosen. And the list [4,2,2,1,2,2] blocks all stations.

2	
2	
1	
2	
1	
4	221214
1	212141
4	121414
4	214144
2	141442
2	414422
1	144221
2	442212
2	422122
1	221221
2	212212
1	122121
4	221214

Figure 68 - Merger of the lists [2,2,1,2,1,4] and [1,4,4,2,2,1]

One of the problems with using a fixed pattern is that the phenomena are repeated as many times as the pattern. If 1000 units are launched per day for production, the pattern, with two lists of six products, is repeated 83 times, which means that the phenomena that exist are also repeated 83 times. Another factor to keep in mind is that when changing one phenomenon, another one may be generated.

Thus, the choice of lists to incorporate the pattern becomes a complex task. To decrease the complexity, a pattern will be created based on the lists that do not block all stations and only station 3. The choice of station 3 is because it is the station with the most time blocked, and the first step is to reduce the blockage of this to achieve the production objective.

As it would be essential to understand which pattern of combinations respected the percentage of production, three analysis matrices were built—one matrix for each product. From the analysis of these, it was found that no pattern built with the favourable lists would respect the percentages of production. The production percentages for products 1_A, 2_B and 4_C would have to be 33, 42 and 25, respectively.

Even not respecting the percentages of production the lists analysed. All patterns that are generated always have lists of combinations that will generate blocking. Overall, they have lists between 4 to 5 lists that block station 3, and 3 to 4 lists at least once are favourable to all stations.

With a focus on WS 3, the lists of 10 products that do not cause blockage in any of their occurrences were analysed. A total of 9 lists are obtained, which in their occurrence never block the line and respect the production percentages. For a first attempt, the list [4,1,1,2,2,1,2,4,4,2] was placed as standard in the simulation.

Another analysis that can be done is that of all the simulations carried out when trying to adapt a sequence that will not respond to demand. There is always variation in production. Are these variations advantageous? Comparing the best OPR solution with and without the restriction of strictly fulfilling the necessary production, becomes a relevant factor.

Of all the patterns used in the simulation, the pattern where it was possible to obtain better results was a combination of three lists of combinations of 5 products, [4,1,2,4,2], [4,1,2,4,1], and [2,1,2,4,2]. When trying to extract from the standard of 15 products lists of combinations of 10, 9 or 8 products, what happened was that none of them happened during a week of simulation. Why choose these three combinations? These combinations came about to eliminate the phenomena that occurred more often and therefore, were associated with a higher percentage of blockage. On the other hand, this solution does not respond to production needs.

The number of patterns that formed the production sequences represents a small part of the existing possibilities. However, of all the sequences tested for the production of these three products, the two most beneficial ones are summarized in Figure 69, and Figure 70.

In the sequence how did not respect the production percentage, the idle time is the smallest, Figure 69. However, an attempt to improve this solution may not be easy. The list [2,4,2] is a phenomenon, a phenomenon that occurs 131 times a day of production. That is, the total time that the line spends blocked, which is 12.5% which is equivalent to 3606 seconds, which corresponds to approximately one hour of work.

	Day	Hours	Minutes	Seconds			
Simulation time	1	8	480	28 800			
Production	988						
1	264	27%					
2	395	40%					
4	329	33%					
WACT		28	29	26	28	28	
		WS1	**WS2**	**WS3**	**WS4**	**WS5**	
Idle time		566	280	2 984	774	1 096	
WS EFFICIENCY		98,0%	99,0%	89,6%	97,3%	96,2%	96%
			Smoothness index				
Balancing delay		2,8%					
Average Takt Time		29	2,8				
Actual		988					
Target Takt Time		29		2,8			
Targets		1 001					
OPR		0,9869	98,69%				

Figure 69 - Summary of results without complying with the production percentage

	Day	Hours	Minutes	Seconds			
Simulation time	1	8	480	28 800			
Production	951						
1	286	30%					
2	380	40%					
4	285	30%					
WACT		28	29	26	29	28	
		WS1	**WS2**	**WS3**	**WS4**	**WS5**	
Idle time		1 957	1 329	3 996	846	2 178	
WS EFFICIENCY		93,2%	95,4%	86,1%	97,1%	92,4%	93%
			Smoothness index				
Balancing delay		4,5%					
Average Takt Time		29	3,9				
Actual		951					
Target Takt Time		29		3,9			
Targets		979					
OPR		0,9716	97,16%				

Figure 70 - Summary of results with the expected production percentage

Comparing Figure 53 with Figure 69, it can be concluded that the change in sequence could implies benefits for the total of the units produced, OPR, line efficiency, SI, and BD.

7. CONCLUSION

The main objective of companies is to generate profits, and no company wants to lose out. Maximising profits can be done in several ways, such as increasing quality, increasing production rates, reducing idle time, among many others. Idle time is a critical aspect as it is associated with wasting available resources. With the increase in customisation required by consumers, companies have adopted lines that produce more than one product without considering lots and with a design different from the straight line. These solutions have become more flexible and economically viable. Still, they have also become a factor that reduces profits by causing difficulties in balancing and sequencing that generate a lot of idle time. Over the past few years, algorithms for solving them have been developed. But due to its complexity, practical solutions that can be easily used by companies are less addressed.

This work allowed the study of some factors that help to minimise the idle time. The idle time provides knowledge of the bottleneck and target stations. The blocking or starved time is caused by the adjacent stations, with more weight in the stations that are not the bottleneck. Target stations or problem stations are those that have the longest blocking or starved time, and these are the ones that should be studied. A perfectly balanced line achieves perfect sequencing when the blocked time is null, and the starved time only occurs in the warmup period of the line.

The operational ratio (OPR) depends on AL balance and sequencing. The OPR reflects unscheduled stops by balancing. However, the OPR should not be analysed as a single factor but must be associated with others to obtain a complete analysis of the productive efficiency of the line because a line with low efficiency will easily be closer to the ideal OPR.

The balancing method used for this type of assembly line is WACT. WACT is a very sensitive parameter. In AL, small changes in production quantities or task times cause the WACT change and, consequently, the line becomes unbalanced.

The number of existing phenomena is dependent on the balance of the line. In the case of a simple and perfectly balanced line, the removal of these allows achieving the expected OPR with high efficiency.

Noting the exponential increase of combinations that cause the blocked time when the line is not correctly balanced, becomes essential for futures works to apply an optimisation tool to find the perfect task allocation. Only then can it be concluded if the impact of a line balanced by an optimisation tool versus one balanced manually will decrease losses or complexity. When the line is unbalanced, it will be essential to understand whether blocking or idle time cannot be minimised without disrespecting production percentages. It is crucial to understand the weight of the rules for the company, as breaking some rules can be more beneficial than compliance with them. At the end of this work, some unanswered questions would be important for futures works, such as what will be the idle time goal to achieve on an unbalanced line or what the simulation time required to test all the combinations that cause blocking. In what concerns this last question, one can envisage the development of machine learning approaches to identify phenomenon and to propose an Heijunka sequence that minimize the total blocking time of an AL.

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