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Layout design and line balancing: a case study

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Master's Dissertation

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To my parents and sister

Abstract

In a world where many businesses try to comply with evermore demanding customers, processes play a predominant role in the success or failure of a business.

To properly design and implement improved processes, an adequate balance of both resource usage and production environment design needs to be put into practice. For these reasons, layout design stands as an important issue, with great impact to organizations, as it serves as a starting point for business improvement through more efficient customer fulfilling.

Following the same idea of business and performance improvement, enhanced line balancing can allow companies to improve their resource usage, while still providing the desired results to the end customer.

Developed at INESC TEC, within the context of a project with an industrial company (ENERGIE EST), this dissertation was structured around two main components, developed to contribute for the global performance of the company.

Therefore, the main contributions of this work involve the layout redesign of the production facility, and the balancing of a particular critical assembly line. Based on the analysis of the manufacturing processes and current problems, different layout alternatives are proposed and evaluated. Some relevant performance criteria were identified, and a simple multi-criteria analysis framework was developed to assess the potential benefits of the suggested changes.

KEYWORDS: layout design; line balancing; multi-criteria decision making.

Resumo

Num mundo onde muitos negócios tentam dar resposta a clientes cada vez mais exigentes, os processos desempenham um papel fundamental no sucesso ou insucesso de um negócio.

Por forma a desenhar e implementar processos de melhoria, um equilíbrio adequado entre a utilização de recursos e o desenho da envolvente tem de ser posto em prática. Por estas razões, o desenho de *layouts* é uma questão importante com grande impacto nas organizações, uma vez que serve como ponto de partida para a melhoria dos negócios através da capacidade de satisfazer o cliente de forma mais eficiente.

Seguindo a mesma ideia de melhoria de negócio e respetiva *performance*, o balanceamento de linhas faz com que as empresas melhorem a utilização de recursos, permitindo em simultâneo satisfazer melhor os clientes.

Desenvolvida no INESC TEC, no contexto de um projeto com uma empresa industrial (ENERGIE EST), esta dissertação foi estruturada em torno de dois componentes principais, desenvolvidos com vista a contribuir para a performance global da companhia.

Nesse sentido, as principais contribuições deste trabalho são o redesenho do *layout* das instalações de produção, bem como o balanceamento de uma linha de montagem crítica. Tendo por base a análise dos processos produtivos dos problemas atuais, diferentes propostas de *layout são* sugeridas e avaliadas. Alguns critérios relevantes foram identificados, foi desenvolvida uma ferramenta simples de análise multi-critério, para avaliação dos benefícios resultantes das alterações propostas.

PALAVRAS-CHAVE: desenho de *layouts*; balanceamento de linhas; análise multi-critério.

Acknowledgments

This dissertation marks not only the end of a semester, but the end of a cycle. With that said, I would like to show my appreciation to people that, directly or indirectly, helped me along this journey.

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To the friends I made during my semester abroad, in Ghent, thank you for the good times and for making me feel at home when home was roughly 1800 kilometers away.

To my friends from MESG, thank you for these first two years of friendship.

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List of Abbreviations

ALB – Assembly Line Balancing

BPM – Business Process Management

BPMN - Business Process Model and Notation

CAPP - Computer Aided Process Planning

DHW – Domestic Hot Water

FMS – Flexible Manufacturing System

R&D – Research & Development

RDALP – Resource Dependent Assembly Line Problem

REL – Relationship

SALP – Simple Assembly Line Problem

VBA – Visual Basic for Applications

1 Introduction

1.1 Project Background

This dissertation was written in the framework of the Master in Service Engineering and Management of the University of Porto, in a partnership with the Master in Business Engineering (Operations Management branch) of the University of Ghent.

To this end, a collaboration with INESC TEC was established in order to allow the participation of the student in a project that fitted the requirements of both masters.

INESC TEC is a well-known research institute that was leading a development project with ENERGIE, an industrial company in Porto's region. The project, in its entirety, is in line with the development of a strategy for what is considered the fourth revolution in manufacturing, that is, industry 4.0.

ENERGIE is a company focused on the DHW and climatization business. Being an industrial company currently experiencing a significant growth, a natural need for reorganization of its production processes arose. In the context of this project, INESC TEC expertise followed a three-step approach which encompasses the diagnosis of the current situation, the design of a solution, and finally its implementation.

The work presented in the current report covers the design stage, with special focus on two main components, chosen among a wider set of project objectives.

1.2 Problem Description

As previously mentioned the present dissertation has two main objectives, both in line with the reorganization of the production process, in the physical sense, and less related to the digitalization part of the process.

The first sub problem concerns the *facility layout* design. Being at a stage in which expansion is a natural next step for the company, ENERGIE wants not only to extend their facilities, but also to broaden their business scope. To that end, an optimization of their operations, including both workers and equipment, is being pursued. Workers and equipment increased effectiveness depends, first and foremost, on the way the physical environment is organized as it can greatly impact the way operations are conducted inside the facility, affecting durations, productivity and, in some cases, even safety.

Currently the company has nine distinct sections, which will be described further in the present report – these sections, compose what can be called the general or global layout of the company. It is this layout that the current work aims at rearranging, so that performance can improve through improvements on a macro level layout redesign.

The first step, in order to address this part of the problem, is to do the analysis of the current situation, to better understand how operating flows can be improved. On a second phase, possible changes must be taken into consideration, based on well-defined criteria. With these changes, and in what can be considered the final step of our approach, different layout alternatives are proposed to the decision–makers, to better accommodate various needs that the company may have, depending on which criteria are deemed more important.

The second sub problem is more closely related to one of the nine sections previously mentioned. This section is responsible for the assembly and packaging of products. Layout design does have a significant impact on the facility's productivity, but nonetheless the way each activity is carried out translates directly into performance delivery. For this reason, one of the more important sections within the facility was selected for further analysis. Improving the way it operates will hopefully translate into big changes in productivity for the company, which will consequently bring benefits of all sorts, such as increased profit, workers satisfaction as well as client satisfaction, among others.

Once again optimization is the goal here, however it is at a production level that this optimization is aimed at. By optimization, we mean that idle times should be reduced, improving the product output and resource usage.

1.3 Project Development at INESC TEC

As referred, this dissertation was done as part of a project led by INESC TEC.

INESC TEC is a private, non-profit, institution which aims to achieve advancement in science and technology, promoting science-based innovation to industry, services and public administration. It makes its presence known in various areas of activity, while placing itself right between the academic and business environments, including scientific research, technological development and advanced consulting as well as training, just to name a few.

INESC TEC has 6 sites and 13 R&D centres, structured in four domains (also known as clusters) which include:

- Computer Science;
- Industrial and Systems Engineering;
- Networked Intelligent Systems; and
- Power and Energy.

This specific project was accomplished at CESE (the Enterprise Systems Engineering Center of INESC TEC), within the Industrial and Systems Engineering cluster. This particular cluster is focused on developing systems for decision support, operations automation, management and intelligence and also on providing consultancy services and technology transfer across various activities sectors including Industry, Healthcare, Energy, Mobility among others, allowing organizations to achieve sustainable innovation and performance.

As a curricular trainee at CESE, I was challenged with a set of problems that were part of an industrial environment project in which INESC TEC is involved.

1.4 Report Outline

The present dissertation starts with this introductory chapter which aims to get the reader familiarized with the project, its origin and scope, and with what entities are involved. Moreover, it covers the current problems faced by the company, as well as the challenges proposed by this master dissertation, detailing what are the goals and desired results.

This introduction is followed by a literature review (chapter 2), that gives a general idea on how problems are dealt nowadays, by briefly describing some relevant methodologies, their current applications and concepts. Also, a view on how process design is carried out is included, as this is a decisive component in terms of the success rate of optimization problems such as the ones addressed in this work.

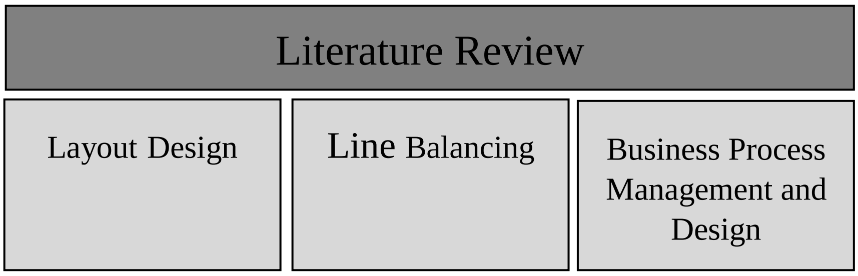

Figure 1.1 – Literature review contents

Chapter 3 starts with a description of the company under analysis, explaining what the business is about, how it operates and its current goals. Furthermore, a description of the problem at hand is made. The goal is to make it clear to the reader what information is available and what are the constraints to be taken into account.

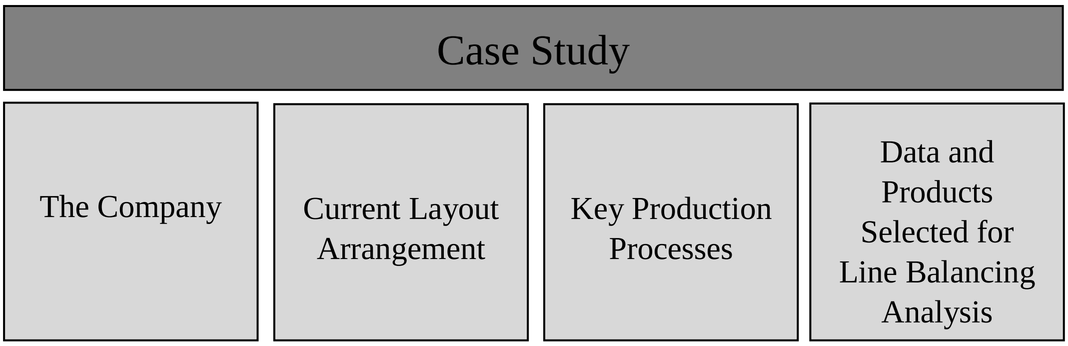

Figure 1.2 – Case study contents

Before the methodology is applied it needs to be defined and explained. Therefore, chapter 4 explains in detail why the methodologies were used for this particular problem, while also giving a step by step guide on how they are to be applied.

Chapters 5 and 6 (layout redesign and line balancing, respectively), give an analysis of the application of the methodology and more importantly what came as a result of its application. Both provide a reflection and critique on the results obtained, as results can never be deemed as definitive and absolute.

To finalize this work a conclusion is presented (chapter 7), including a full review and summary of the contents developed and goals achieved, while presenting suggestions for possible future developments.

Figure 1.3 presents a general overview of this report, to provide a better understanding of the workflow previously described.

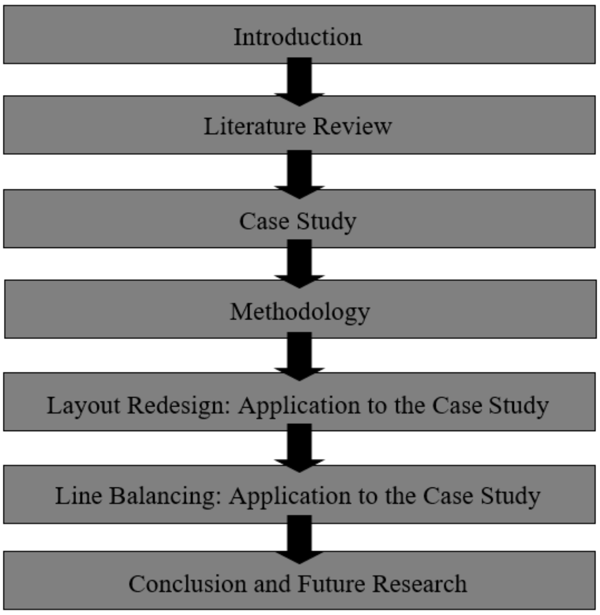

Figure 1.3 – Report workflow overview

2 Literature Review

In this chapter topics directly related to the work will be explored, covering current applications, concepts and terminology in use, as well as some key ideas of our approach. These topics include layout design, line balancing, and business process design and management.

Layout design is a crucial topic to address, as it is an important part of this dissertation. In this dissertation an industrial facility layout is to be redesigned, and to that end it is important to understand the basic principles on layout design and what kind of work has been done regarding this subject.

Another important part of this dissertation has to do with *line balancing* of a particular section of the production line. Therefore, the concept of line balancing, as described in the literature, and its applications are included in section 2.2.

Despite not being directly addressed in this dissertation, *process management and design* are a fundamental part of the work developed in this document. Prior to all analysis, process surveying was performed, to ensure that the facility's working process was fully understood. Furthermore by redesigning the layout, process management must be taken into account as they have mutual influence. Any change done, could require the other to be reviewed.

2.1 Layout Design

One important part of this work regards layout design and, on a bigger scale, facility layout decisions. Layout planning is the basic activity, enabling maximum efficiency in the way workers and equipment operate in a given facility, through the improvement of the physical arrangement of economic activity centres (Krajewski and Ritzman 1996). This should be done without disregarding the structural design constraints that come with a facility.

Layouts and their performance can be evaluated through different measures, however material handling cost proves to be decisive, since it makes up for up to 50% of the total manufacturing costs with a margin of 30% improvement through layout design optimization alone (Neghabi, Eshghi et al. 2014).

Studies have been made with the goal of displaying the steps that lead to a layout redesign, while proving that it leads to reduced floor space need, and simultaneously brings efficiency to a real manufacturing system (Kovács and Kot 2017).

When starting a layout planning process various aspects and concepts should be considered. Furthermore, layout choices are not standalone problems, as the strategic decisions of a business may be deeply connected to such choices.

The above-mentioned economic activity centres (or sections) can have multiple possible locations, however two key concepts are *relative location* and *absolute location*, as both of these have an effect on the performance of a centre. Relative location is often taken into account when travel time, material handling cost and communication effectiveness are crucial criteria (Krajewski and Ritzman 1996). The relative location may stay the same, even if the absolute location is changed.

Depending on a company's strategy, different types of layout can be considered. In the facility presented in this dissertation (our case study), product, process and fixed position layouts are considered. Below follows a brief description of these layout types, as well as a reference to hybrid layouts.

Product Layout

Also known as production or assembly line, this is one frequently used layout in the industry sector, whenever there is a need for continuous or repetitive production. The first production line, created by Henry Ford in 1939, followed a product layout.

This type of layout is characterized by an organization of equipment and work stations in a way that a linear production sequence, with no alternative pathways, is followed. In this layout type, the product or customer is the moving piece (Graeml and Peinado 2007), that is moved from station to station until production is completed or service is delivered at the end of the line. Each station operates independently, as almost no inventory is built between stations. For this reason the line's unit output is only as fast as its slowest station (Krajewski and Ritzman 1996).

Characterized by a division into low complexity and repetitive operations, these layouts enable high productivity mass production. However, there are some disadvantages in this particular layout type. One of them is vulnerability to line stoppage, which has to do with the fact that, if an operation stops, the entire line has to stop. Other disadvantages include the lack of flexibility to deal with production volume changes or change of products, as well as lack of motivation felt by operators that, due to the way operations are divided, have to perform very repetitive work (Graeml and Peinado 2007).

Process Layout

These layouts are associated with high product variety and lower volumes of production, where sections are created based on function. This kind of layout provides more flexibility as resources are seen as general purpose, enabling shifts between different products (or customers) (Krajewski and Ritzman 1996). Product and materials go to the different processes that require them, in all the areas of the layout.

Contrary to what happens in a product layout, a process layout offers flexibility that enables this kind of layout to promptly respond to market changes. Furthermore different product types and quantities can be produced simultaneously, due to its function based sectioning.

On the negative side, long flows are frequently given that, as previously mentioned, products and materials have to go to the processes, which could generate inefficient movements. It is also more difficult to balance the workload, due to the product changes that take place. Higher product changes mean that volumes produced are lower, which also requires more frequent machine setups and preparation (Graeml and Peinado 2007).

Fixed Position Layout

As the name implies, here the product is in a fixed position and it is the worker that goes to the product's position to work on it, minimizing the number of times a given product has to be moved (Krajewski and Ritzman 1996).

The biggest advantage of this layout type is the lack of movement it requires. On the other hand, it typically requires an additional area next to it for materials and components storage (Graeml and Peinado 2007).

Models have been developed to enable dynamic scheduling, having in mind this type of layout, which resulted in an applicable strategy in real world assembly for complex products (Qian, Zhang et al. 2020).

Hybrid Layout

This type of layout is the result of a combination of layouts, more specifically the two previously mentioned, product and process layouts. Whenever raw material is used the layout is more process oriented. On the other hand, when assembly of components is the operation in question, then the layout is product oriented. These layouts are normally created by operation managers when a FMS is implemented (Krajewski and Ritzman 1996).

Layout design is a vast research and application area that was addressed in multiple surveys. There is, in fact, an extensive literature on these topics, highlighting their practical relevance, from broad literature surveys (Drira, Pierreval et al. 2007), to more recent analysis of both layout design and facility planning for different manufacturing processes, including various techniques and algorithms (Jain, Khare et al. 2013).

Many papers review works on more specific, yet relevant, topics such as developments in multi-criteria facility location problems (Farahani, SteadieSeifi et al. 2010).

2.2 Line Balancing

Associated to the mentioned product layouts, comes a set of other relevant problems. Since the product moves from one station to the next, until it reaches the end of the line and given that there is little to no inventory generated in between stations, these cannot operate independently, which means that the line is only as fast as its slowest station. The goal of line balancing is to level the workload across all workstations in a line, which is done by assigning each of the operations in a process to the minimum number of stations, while ensuring that the desired output rate is met (Krajewski and Ritzman 1996).

For this reason line balancing proves to be crucial for productivity improvement and minimization of production costs. In order to address line balancing in an efficient way, different approaches have been developed throughout time. From software that implements simple heuristics, to the proposal of metaheuristics that improve upon classical heuristics, including real world industrial applications (Lapierre, Ruiz et al. 2006)**,** all of them are attempts of simplifying and optimizing line balancing. More recently computer simulation has been systematically used by manufacturing companies to design and analyse manufacturing systems and, in particular, to address these types of problems.

"To efficiently do the line balancing process a good observation of the overall system is required."(Sime, Jana et al. 2019)

It has been stated however that most ALB problems across various industries can be treated as RDALP. This variant of the problem does not follow the assumption that processing times are fixed SALP. Research work has been developed regarding this topic, adapting the RDALP to

U-shaped lines (Kara, Özgüven et al. 2011) and more recently it has been applied to the concept of Parallel Assembly Line Balancing (Kara and Atasagun 2013)**.**

2.3 Business Process Management and Design

Alongside many process improvement tools that have been created from industrial settings, such as Lean and Six Sigma, there are many organizations which currently make use of BPM.

The tendency is for individuals in an organization to try to optimize the work/task they are responsible for. However most of the times the improvement of a small part of a system does not translate into an overall improvement, and on the contrary it may lead to worse results.

Currently we are in a process oriented era, which is characterized by a work organization that takes into account the various departments involved in the global process, having always in mind the final customer (Sharp and McDermott 2009).

This is why nowadays businesses are viewed as systems, where everything is connected and processes are modelled considering flows and feedback. This idea of system puts an emphasis on links, relationships and flows, meaning that each singular portion of the business is part of a bigger whole and must be dealt with as such.

In order to execute business process modelling (in the graphic sense), adequate notation is necessary. Such standardized notation exists to clearly define the adequate symbology and the meaning given to the different types of processes and their combinations, thus enabling everyone who knows the notation to have an understanding of a model. BPMN is currently the leading standard for business process modelling (Allweyer 2016).

Another concept closely related to process modelling is process planning. Defined as complex and dynamic in nature, process planning can include different activities, strategies and methodologies, having no standardized definition for what should or should not be included. There have however been attempts to develop systems for computer aided process planning (CAPP) to be implemented in the industry, although not successfully. One reason is that there is a significant difference between this sort of systems and the practical execution of process planning in the industry (Bagge 2014).

Other works have focused more on process design, as a component in the process planning process, as well as on the human contribution side, where expertise plays a role. CAPP systems support on human decision making was also analysed (Lundgren, Hedlind et al. 2018).

Given process design complexity as it integrates different elements such as product analysis, market research, capital intensity and resource flexibility, work has been developed to extract process design rules for the manufacturing process, not including environmental factors (Song and Jeong 2019).

With this very brief literature review, we aim to provide a context for the work presented in the subsequent chapters. The following chapter gives the reader a full understanding of the problem at hand, with all the necessary information for the analysis performed in later chapters.

3 Case Study

This dissertation was done around a case study carried through a project between INESC TEC and ENERGIE, an industrial company that is now briefly described (section 3.1).

Furthermore, to provide context for the chapters to come, this chapter also describes the *as-is* situation of the production facility, considering the layout and key processes (section 3.2 and 3.3, respectively), as well as relevant information to be used in the line balancing of a specific section's line (section 3.4).

3.1 The Company

Founded in 1981, ENERGIE EST is a Portuguese owned company that was created to fill a gap in the market for hydraulic components. In 1990, ENERGIE became the exclusive holder of the patent and manufacturer of thermodynamic solar systems, with a mission to enter and establish a solid position on new markets all over the world, while following a social responsibility demeanour in all its actions.

Building up its status and becoming a reference both on a national and international level, it has a Department of Research and Development, ensuring that scientific advances and industrial process integration are always matched. This is possible through collaborations kept with prestigious universities and national, as well as international, research and development centres. Such focus on research is, for the company, a strategic pillar of growth. On the other hand, having such a collaborative structure is something that is aligned with the company's vision:

"We believe that by developing innovative technologies and effective processes we will find the solutions required to meet the challenges of the future, thereby making the planet more economically stable by making full use of natural resources."

This work was developed at the facility in Laúndos, Póvoa de Varzim that is going, as mentioned previously, through an expansion process. Furthermore, there is a need that comes with this expansion, which is the reorganization of the productive process.

ENERGIE offers a vast array of products and models, which are made available through essentially two types of distributors, small and big. This dissertation will be focusing on three models – ECO, ECO TOP and MONOBLOC. Products are made for both domestic use and professional use, which includes hotels, hospitals, sports and industrial facilities.

Now an analysis of the current situation will be done, to further understand the case at hand, and in particular, an explanation of the Laúndos' facility layout arrangement is presented in section 3.2.

3.2 Current Layout Arrangement

The before mentioned project targets the improvement of the productive process of the company, dedicated to the production of water heating equipment, which includes the rearrangement of the current layout. Moreover, it was mentioned that the factory is going through an expansion process, something that has to be taken into account since it provides more room for alternative solutions.

The rearrangement of the factory as a whole, is the macro scale component of this dissertation which consists on a *layout redesign*. Currently the layout is divided in 9 sections, which are described below.

Pallets and metalwork storage

In this section pallets are stored and perforated, to be used for the transportation of the finished product. Currently this section consists of a container located outside the facility.

Finished product storage

Place where the product that comes from the assembly and packaging line goes to, before expedition. Alternatively, products that enter the facility and do not require any transformation go directly to this section.

Laboratory

Mainly engineering offices, where the development of new products, software and electronics takes place. Testing is done prior to production in this section.

Raw material and components storage

Includes all the material and components needed for the productive process, including water heaters production materials, components for heat pump production, components for the final assembly and packaging material for finished products.

Water heaters production

Where production of water heaters takes place, following a procedure divided in six steps which will be detailed in the next section (section 3.3). The production is done following a product layout.

Assembly and packaging

In this section, the final product is put together and packed before being prepared for expedition. Similarly to the water heaters production, this process will be detailed further.

Heat pump production

Fixed-position layout section where assembly benches serve to produce heat pumps and also as storage prior to assembling. This production process will also be detailed in the following section.

Storage and production of other products

Besides the main products for water heating, ENERGIE also produces other types of products such as solar panels and geothermic products. These are the areas reserved for their production, and for the storage of some of the components needed.

Tanks storage

There are two types of tanks available, based on material, stainless steel and enameled steel. The first type can be and is stored outside the building. The second type is stored inside.

Figure 3.1 is a representation of the main sections within the facility. However this layout representation already accounts for the expansion of the facility. The red lines represent the expansion area. This enables a clearer perception of how the new available space is being used if the current sections layout was to be kept.

The original facility has around 4,015 square meters, while the expanded one has around 5,205 square meters, accounting for an expansion of roughly 1,190 square meters. This expansion was made in order to increase the space available for storage.

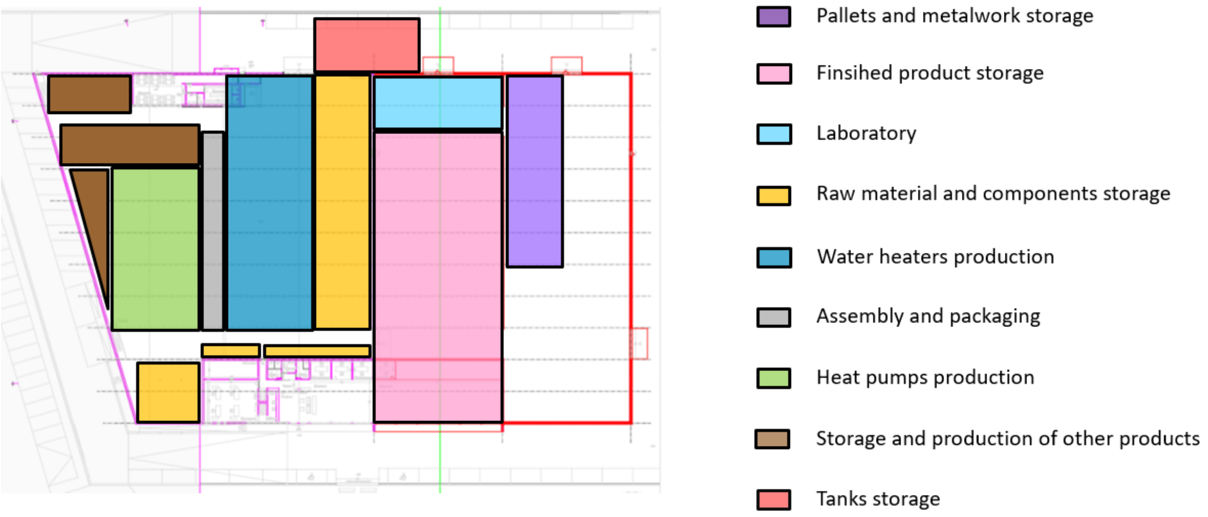

Figure 3.1 – Current layout

Currently the facility has two entrances being used, one for the entrance of tanks (entrance A), and another for entry and exit of components, raw material and finished product (entrance B), as identified in figure 3.2.

The information above would be incomplete without an understanding of the basic flow of materials and products. When materials and components enter the facility, they are to be stored in the raw material and components section. From there, they are taken to the respective production sections. From the production sections results the finished product that goes to the finished product storage area and then, after some additional procedures, outside the facility. This represents the "macro flow" within the facility and will serve as starting point for the layout redesign to be performed later.

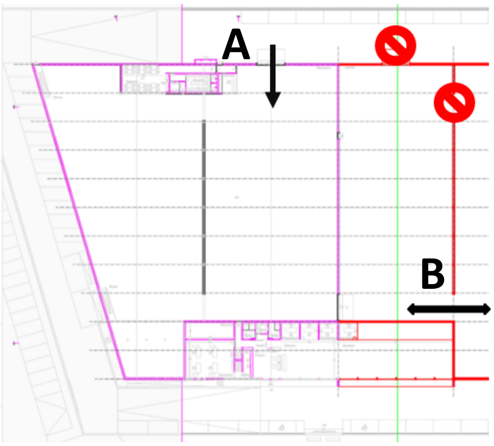

Figure 3.2 – Facility's entrances

As presented, this *as-is* layout is composed by 9 distinct sections, that were briefly described in order to give the reader an understanding of the role of each one in the global productive process. This description, combined with an understanding of the facility's material and product flows, serves as a starting point for the analysis presented in the remainder of this dissertation.

The layout and associated sections and flows can be considered higher level information. However, to further understand how the main production sections interact with each other, an overview of key production processes is presented in the next section.

3.3 Key Production Processes

Besides the layout positioning it is important to understand the flows of both product and materials. Furthermore, it is key to understand how the production process is carried out so that the main interactions can be pinpointed and analysed in the following chapters.

The main production process starts with the water heaters production. Operations are carried out as represented in figure 3.3.

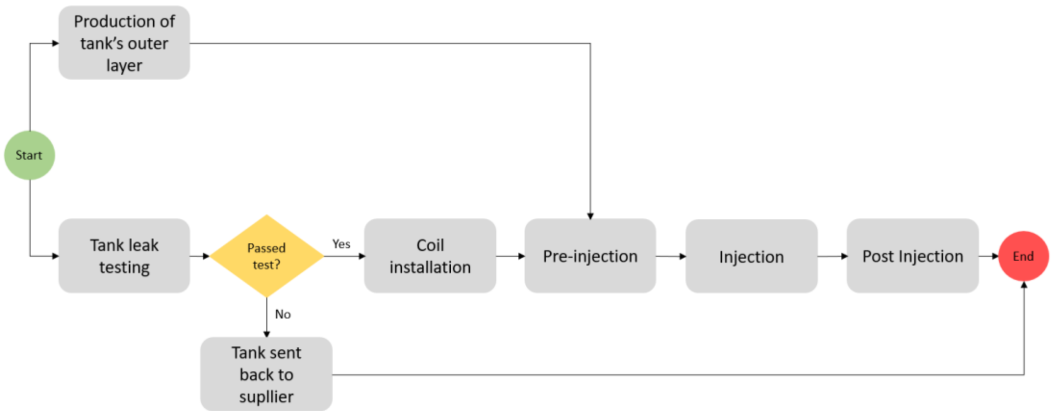

Figure 3.3 – Water heaters production process diagram

The process starts off with the tanks having to be tested for leakage, which is done inside the building, next to the enameled steel storage. Currently, only two tests are performed simultaneously, although there is capacity for four tests at a time. This happens because the following task is not able to handle all four tanks at once. In the meantime the tank's outer layer starts being produced in what is a multi-phased procedure.

Once the tanks are fully tested, they are moved to the coil installation area and fixated on a reeling machine, so that the coil is rolled around the tank.

After the coil installation around the tank and the outer layer are ready for installation, the product enters the pre-injection phase, where part of the outer layer is installed around the tank (the top part is to be installed at a later stage). After completion, as the name of the phase implies, the product is ready to proceed to the injection phase.

The injection phase is when polyurethane is injected to guarantee the insulation of the final product. This step is performed while the tank is locked in an equipment that stops the metal sheets from rupture.

To conclude the water heaters production, there are some operations which are performed after injection. These include polyurethane's chips cleaning, tube preparation, insertion of the electrical power cable and lids.

Simultaneously heat pumps are produced, following the sequence shown in figure 3.4.

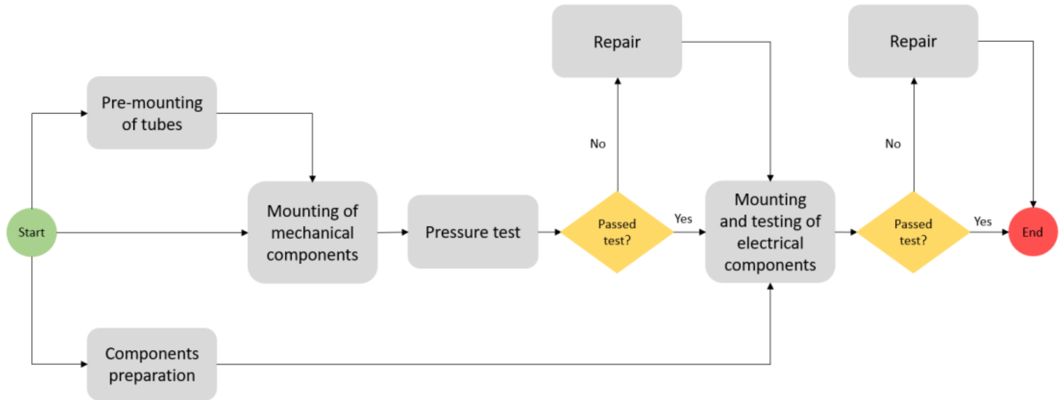

Figure 3.4 – Heat pumps production process diagram

In a first phase tubes are produced to be incorporated in the heat pumps. Following this operation is the mounting of mechanical components, which starts from the support plate that serves as base for the heat pumps. After the metal support plate is in place, compressors are brought and the components (including the tubes) are mounted.

Once the mechanical part is mounted, a 48 hours pressure test is done to ensure that the equipment is functioning properly. In the meantime, electrical components are prepared and brought to the assembly bench to be later installed and tested, similarly to the procedure sequence followed for the mechanical components.

When both water heaters and heat pumps have been produced, assembly and packaging (figure 3.5) can begin.

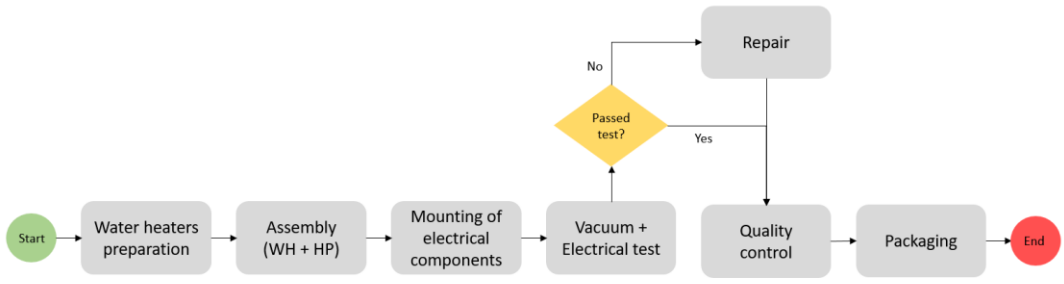

Figure 3.5 – Assembly and packaging process diagram

The first step is to make sure the water heaters are ready for the final assembly, checking everything is as required from the water heaters production. This includes checking the tubes, cutting and putting on rubbers in the tubes that connect to the heat pumps, cleaning any remains of polyurethane and placing lids.

The assembly of the water heaters and heat pumps is then executed, followed by the mounting of electrical components.

Then a vacuum test using nitrogen is performed, followed by an electrical test. In case there is any sort of leakage or failure, the system needs to be removed from the line and the situation rectified.

Prior to packaging and after tests are executed, a quality control check is performed on all systems.

Packaging includes screwing the systems to pallets to ensure they are secured for transportation, putting labels and the box.

This overview of the main production processes will hopefully provide a better understanding of the assembly and packaging line procedures, serving as a basis for the line balancing component of our work. The next section addresses what type of information is available and what type of products will be included when performing line balancing on the assembly and packaging line.

The next section addresses what type of information is available and what type of products will be included when performing line balancing on the assembly and packaging line.

3.4 Line Balancing Analysis

There is a second problem addressed in this work that, as already mentioned, has to do with the distribution of the workload, more specifically in the assembly and packaging section. The way this section operates, in general terms, was already discussed in the previous section, however is important to understand what data is available and what changes from model to model.

Data previously collected and made available consists of time measurements for each task of the assembly and packaging process, as well as the tasks that precede each one. This information was collected for the three product models selected for analysis (and mentioned before), with each of these models having two different capacities, in litres.

The sample size for the product models mentioned can be considered small, and some inconsistencies were found between the same product models with different capacities. It was initially mentioned by company members that for the same model type, regardless of capacity, the sum of task times should be the same, but that was not the case. It was not possible to determine the origin of this disparity, however it was possible to identify the error.

Given that the sum of the task times should be the same, that is something to be assumed in the following chapters, this meaning that only one capacity for each product model will be under analysis. In order to choose which capacity to work with, the criterion adopted was to choose the one which had the biggest total task time, as it can provide worst case scenario numbers for the time required for production. Comparisons between different capacities for the same model will be excluded since, as previously mentioned, they are supposed to be the same. For these reasons, the only products having the assembly and packaging process analysed are the ones highlighted in green in table 3.1.

ECO Model	250 Litres	Product 1
	500 Litres	Product 2
ECO TOP Model	200 Litres	Product 3
	300 Litres	Product 4
MONOBLOC Model	280 Litres	Product 5
	300 Litres	Product 6

Table 3.1 – Products selected for line balancing

Before having the assembly and packaging processes for each model analysed, it is important to understand the differences between different product models, as these may translate into different tasks and procedures.

The ECO and ECO TOP models present a very similar structure, composed by a heat pump, a water heater and a solar panel. One key difference between these models is that the ECO TOP model has a display. Other than that, basic functionalities and the way of operating are identical.

The MONOBLOC model has a different structure as it does not include a solar panel. The reason for this is that the MONOBLOC already has an evaporator incorporated, avoiding the need for a solar panel for transferring thermal energy. Similarly to the ECO TOP model, it has a display.

Operations' information collected for products 2, 4 and 6 can be found in Appendix A.

In this chapter the case study was presented, starting with a brief description of the company, followed by *as-is* information regarding the facility. This includes the layout arrangement and workflows, an overview of the key production processes and an understanding of the available information for line balancing purposes.

The methodology followed in this dissertation will be described in the next chapter.

4 Methodology

This chapter provides a step-by-step description of the methodology followed in this dissertation.

The first section is dedicated to the general methodology, and aims to give the reader a high-level view of the overall approach, while the following sections tackle specific tools used in our work, supported by some literature references.

4.1 General Methodology

As mentioned in previous chapters, this dissertation includes two main components, which require two distinct approaches. However, before following those approaches (as shown in figure 4.1) data had to be collected, this being the first step of the proposed methodology.

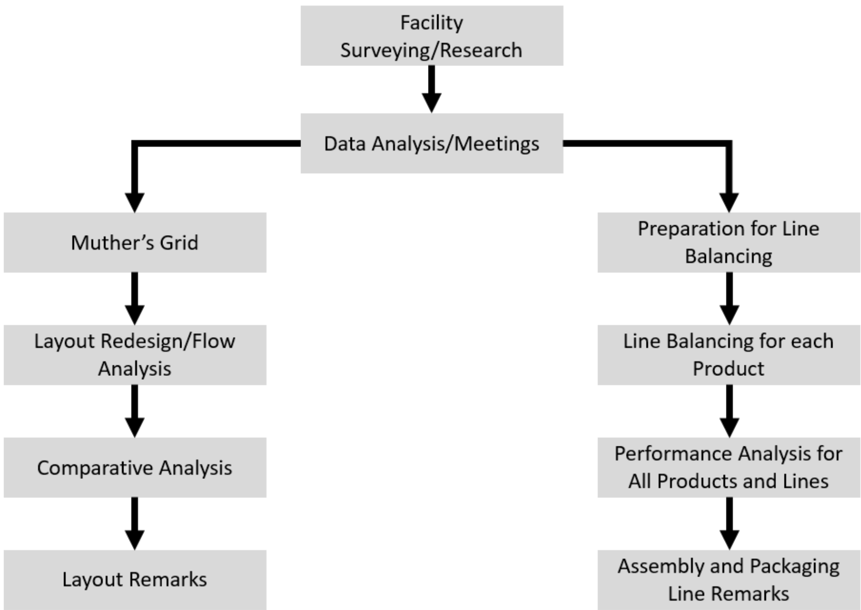

Figure 4.1 – General methodology

Data collection was performed on one hand, through facility surveying. This provided an insight into what happens inside the facility, including layout arrangement and processes, and also into problems that occur on daily operations. Furthermore, research regarding related topics and adequate methods used for the problems at hand was done.

After collecting data, a series of meetings and thorough data analysis were done, to better clarify some aspects that were not covered in the initial phase and to better understand what approach would work best, with the available information.

With this we have reached the point where the methodology is split into two distinct approaches, as mentioned in the beginning of this section.

On one hand, there is the *layout redesign* component of the dissertation, which starts with an evaluation of the current situation using a Muther's grid. This technique will be further detailed in the following section. Afterwards, with an understanding of the *as-is* situation, alternative layouts and their respective flows are presented and analysed. A quantitative comparative analysis, which follows a multi-criteria analysis, is performed for the proposed layouts. Then, a short discussion on a possible layout choice is made.

Another part of this dissertation is concerned with the *line balancing* of the assembly and packaging line. To this end, some preliminary work had to be done, prior to execution of the technique, including programming two distinct VBA applications that automate the line balancing process (see appendices B and C).

Data concerning the operations done to each product in this line had to be filtered and reorganized before being used. Line balancing is first used for obtaining a line per product, with fixed demand and available capacity. On a second phase, all products are put in those lines in order to see how performance changes, when only demand and the number of stations of the line are known. After an analysis of all scenarios, we discuss the quality of the resulting assembly and packaging lines.

Further information regarding line balancing is provided in section 4.3.

4.2 Layout Design

In what concerns the layout design component of this dissertation, the planning tool known as Muther's grid was adopted. This is a qualitative approach that is used by managers whenever there is a need to plan or rearrange the layout of their departments.

Based around a simple relationship diagram concept, in which preference is given to each section's location based on a rating system (based on levels represented by the letters A, E, I, O, U plus X), the need for proximity between two sections in a given workplace becomes easier to understand (see table 4.1).

A	Absolutely Necessary
E	Especially Important
I	Important
O	Okay
U	Unimportant
X	Undesirable

Table 4.1 – Relationship ratings and meaning

A grid is filled with these letters in order to classify how relevant it is for two sections to be adjacent to each other. If section 1 cannot be next to section 2 for safety reasons, for example, the most adequate classification would be X, as it is undesirable for these two sections to be next to one another. On the other end of the spectrum, if two sections depend on one another then it would be absolutely necessary or especially important for them to be closely located, corresponding to an A or E classification (Grimes 2011).

In order to assign these grades ("letters"), it is important to define adequate criteria that justify the reason for closeness or lack of. A code may then be attributed to each of these criteria, so it facilitates the explanation process, which is often done through a REL chart (a chart which considers not only the letters regarding the proximity score but also numbers, associated to some criteria, that explain the reason for that score) (Krajewski and Ritzman 1996).

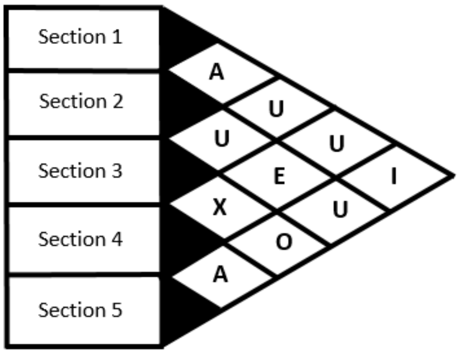

Figure 4.2 – Murther's grid example

Is also important to point out that different sections may have different total areas (typically presented in square meters) and this has to be taken into account as the physical environment presents a constraint on its own.

After determining the need for proximity between all sections in the facility, a set of alternatives for the layout was presented and analysed. This analysis was done considering the arrangement of the layout for the alternatives presented, having in mind the previously done proximity analysis, as well as the existent flows in the alternatives.

Then we have performed a comparative analysis considering specific criteria, to which weights were given according to their relevance in the context of this project. This comparative analysis consists of a *multi-criteria analysis* of the layout alternatives that, based on the sum of normalized values for the different criteria's results, "measures" each alternative's performance.

4.3 Line Balancing

Part of this dissertation focuses on line balancing. Line balancing consists of leveling the workload throughout a production line, by assigning work to a given number of stations, that should be as little as possible, in order to remove bottlenecks and excess capacity. The final goal is to increase production efficiency.

However the situations that justify its use vary, from the initial set up of a line, to the implementation of something new (such as a process or a product) or, as is the case in this work, it can be applied to change the hourly output rate.

Line balancing can be divided into different steps. The first step is to separate the whole process into work units that can be performed independently, and obtaining the time expected for completion for each of those units (also known as labor standard). Moreover the immediate predecessors, which are the work elements to be done before the following can take place, must be identified. With these steps completed, a precedence diagram can be properly elaborated (Krajewski and Ritzman 1996).

After the global view of the productive process is achieved through the design of the precedence diagram, the cycle time must be considered. Knowing what the required cycle time is, it is then possible to obtain the theoretical minimum number of workstations required, among which we can spread the work units previously identified (Graeml and Peinado 2007).

The time available per station is known and the process of allocating work units starts. This process is not done randomly, following a set of heuristic rules, with each work unit being selected and allocated individually and in a sequence. When doing so, there are two key rules that must never be broken:

- all the predecessors, of a given work unit, must have been allocated before the designated work unit can be allocated;
- a work unit that is being allocated to a given station can never exceed the remaining time, based on the previously calculated times, for each station (when no work unit can be allocated to a certain station, that station is considered full and the next station takes place).

Following a “popular” heuristic, the allocation could be done starting from the task that has more following tasks and, in case of a tie, priority should be given to the one with the highest duration. If both of these are tied, then the allocation can be done randomly among the ones that verify the above-mentioned criteria – this is how we have done in our work.

After all tasks are distributed among the stations, the idleness percentage can be calculated, which ideally should be as low as possible.

In this chapter, the general methodology followed in our work was presented. Two particular approaches used in this methodology were briefly described. In the next chapters, we present the application and of these approaches to our case, and analyze the obtained results.

5 Layout Redesign: Application to the Case Study

This chapter is devoted to the *layout design* part of this dissertation. First, an assessment and analysis of the current situation is done, followed by a proposal of layout alternatives that were created taking into account some specific characteristics (such as zero *hazard risk*, for example). Then, a comparative methodology leads to recommendations regarding the best and worst solutions out of the proposed set of alternatives.

5.1 Current Layout

The need to redesign the existent layout comes from an expansion of the current facilities, combined with a need felt by the company to improve their current production processes. Before proposing alternatives that aim to cover both of these requirements, it is necessary to assess the current situation. This assessment will serve as a starting point for the proposal of alternatives done in the following section.

Figure 5.1 shows the current layout as presented in chapter 3, which has some problems that need to be addressed.

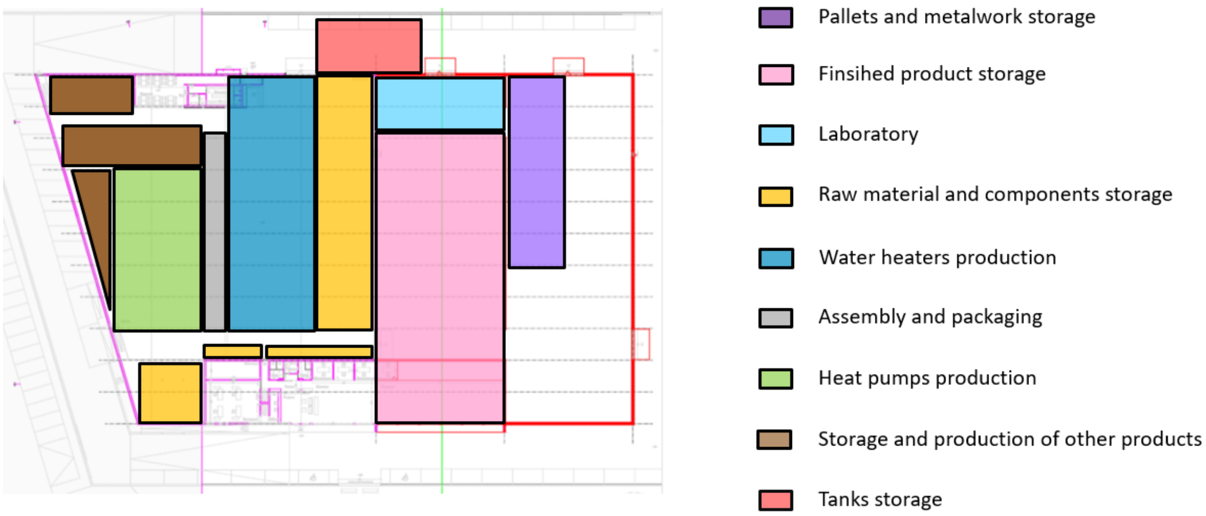

Figure 5.1 – Current layout

Prior to the beginning of this dissertation, INESC TEC built a detailed report based on surveys of the current facilities, where it was possible to identify the main problems that impacted the facility. These are the following:

- crossed movements;
- difficulty for products to reach the production line due to the current facility layout;
- obstructed pathways throughout the facility, which provide little room for proper circulation.

Having identified these problems, it is also crucial to understand and evaluate the need for proximity between different layout sections. To evaluate this need, a Muther's grid (see section 3.2) was applied.

For this evaluation, the criteria found in table 5.1 were defined. These criteria are the result of an analysis of the available data, in combination with meetings with the team responsible for surveying the facility. Following this procedure, the key aspects to the production process were identified and criteria were defined.

Code	Criteria
1	Production Sequence
2	Hazard Risk
3	Ability to Share Supervisors/Operators
4	Crossed Flows

Table 5.1 – Layout's sections proximity evaluation criteria

The *production sequence* criterion focuses on the fact that two sections correspond to a sequence in the production process, this meaning that sometime along the process, products or materials will have to be carried from one of the sections to the other for a product to be finished.

Although during the survey carried by INESC TEC there were not any substantial indications of sections between which proximity could pose a *hazard risk* to the facility and its workers, through further discussion with the INESC TEC team (that had the opportunity to visit the facility), the fact that welding was executed for the heat pumps raised some concerns. This concerns were related to the sparks generated by welding which, if performed too close to inflammable products, could potentially cause a fire. Despite not being very likely to occur, it introduces a relevant element for analysis and was therefore considered for the purpose of this study.

Some sections share supervisors and/or operators, which in a factory environment characterized by considerable facility dimensions means that, if not adequately placed, a shared supervisor or operator might have to cross the entire facility to ensure work is done properly. For this reason, the *ability to share supervisors/operators* was chosen as a criterion for evaluation.

In a production facility, *process flows* are key and avoiding to cross them is something to aim for. Whenever the interaction between two sections involves the transportation of either materials, components or even finished products, having them cross flows with another interaction within the facility may result in delayed operation execution and, for that reason, it is important to define such scenario as a criterion.

5.2 Information Collection

Once the criteria were defined, it was possible to assess the layout needs by generating a *proximity matrix*, more specifically a Muther's grid. As a reminder, the already mentioned evaluation scale considers grades represented by the vowels (ranging from 'A' to 'U'), where

'U' means that closeness between two sections is *unimportant* and 'A' means it is *absolutely necessary* for those two sections to be close. Furthermore the letter X is used when it is *undesirable* for two sections to be together.

The filling of the grid shown in figure 5.2 was the result of a process that started with a thorough analysis of the available documentation, which was the result from various visits to the facility, as well as interviews with ENERGIE's professionals. Considering the criteria defined by having a full understanding of the production process and existing layout sections, enabled us to assess the need for proximity between each pair of sections.

Furthermore, meetings with INESC TEC's team were carried out, to discuss ideas and interpretations of the different proximity needs.

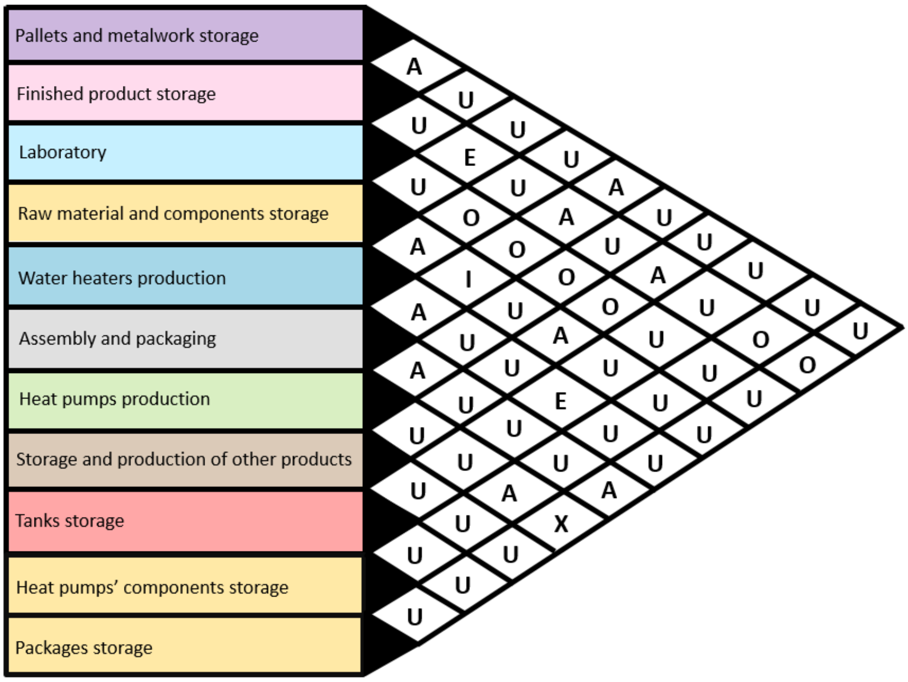

Figure 5.2 – Muther's grid applied to the case study

This Muther's grid is supported by a relationship chart which justifies the reasons for each closeness rating between sections (see Appendix D).

Before any of the layout designs was generated, the first step was to understand if there were any sections that should not be moved (from where they are now) or that could have a fixed position for some reason (fixed sections are represented in figure 5.3).

The 'Laboratory' is located, and was built, upon a mezzanine floor. This, combined with its purpose, which does not interfere directly with the production process on a daily basis, justifies why the 'Laboratory's position is considered fixed.

The 'Tank Storage' section is also going to have its position fixed, given that storage is conveniently located close to an entrance and the hydraulic test area.

The 'Finished Product Storage' section is not necessarily fixed for setup reasons, however there is one location that benefits the entire process and that is, close to an exit. Furthermore the purpose of the expansion was in fact to increase storage space, so to use the expansion area for that end is a natural option.

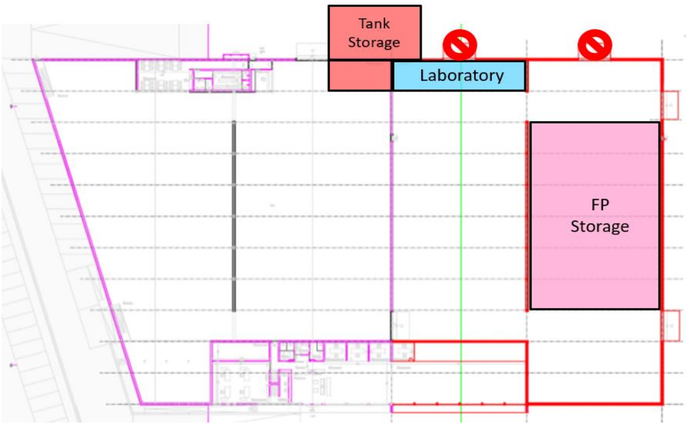

Figure 5.3 – Sections which are not to be moved from place

As referred, we have assessed the need for proximity between sections by a Muther's grid, supported by a REL chart (see appendix D), filled based on the defined criteria.

Despite the current layout being fairly well arranged in terms of section proximity, the proximity analysis should be kept in mind for the following sections, as it creates a constraint for layout redesign.

Making use of the information presented in this section of the document and in section 5.1, several layout alternatives are proposed in the following section.

5.3 Proposed Layout Alternatives

In this layout redesign part of the dissertation, four different layouts are presented as alternatives that could improve the way work is done within the facility. Each of these alternatives is the result of a different take on the existent building, with the aim of solving previously mentioned problems through the application of the described methodology.

From here on, the factory section previously designated as 'Storage and Production of Other Products' will be divided in two distinct sections: 'Others 1', which is the section for solar panel production; and 'Others 2' which is the section for the production of geothermic products.

Layout 1: Zero Hazard Risk

The first layout (figure 5.4) was created with the purpose of minimizing the *hazard risk* for the facility. To that end, the 'Heat Pumps Production' section had to be far away from the 'Packaging Storage' section.

At the same time, by managing to keep some sections close such as 'Water Heaters Production', 'Assembly & Packaging' and 'Heat Pumps Production', as well as the big storage sections, the sharing of operators and supervisors is enabled.

In the first iterations of this layout the 'Water Heaters Production' and the 'Assembly and Packaging' locations were swapped, with the intent of maximizing even further the distance between any form of packaging and the 'Heat Pumps Production' section. However this would cause unnecessary *crossed flows* for the heat pumps to be delivered to the assembly line.

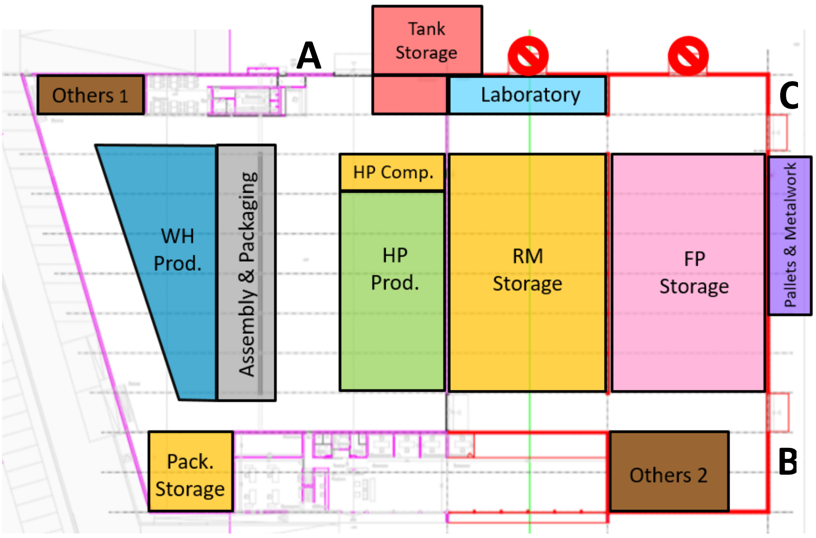

Figure 5.4 – Layout 1

As explained in the previous paragraph, despite a search for maximizing safety, the layout's flows (figure 5.5) could not be compromised. Heat pump's components are adjacent to the respective production section and for the most part, material is delivered to the respective productive unit, without crossing flows.

Given the chosen main entrance and exit points of the facility (entrance C and B, respectively), cross docking becomes possible. This is crucial, given that at times there are products that enter the facility without requiring any sort of transformation, conveniently directing those products towards the exit, thus minimizing movement.

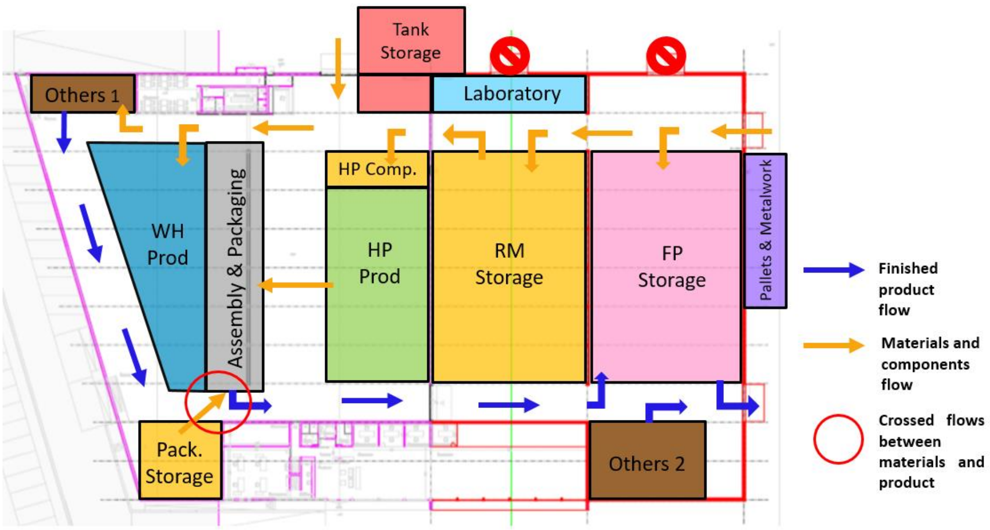

Figure 5.5 – Layout 1's flows

As seen in figure 5.5, there is some flow crossing between the packages that are going to the assembly line and the solar panels (identified as 'Others 1') going to the exit area. There is also not much available space to include product expedition area, near the exit.

Layout 2: One Entrance and One Exit

Layout 2 (figure 5.6) added another outlook, by keeping only one entrance and one exit. Initially the 'Raw Materials and Components Storage' section was located where the other products production sections ended up being (see figure 5.6). This was found to be less efficient given that a good percentage of material and components is to be stored there and, by having it further away from the entrance, it would result in increased movement.

One positive aspect of this layout is that it provides adequate space for reception of materials and, as opposed to the first layout, a substantial free area near the exit that could be used for product expedition.

Most of the advantages seen in the first layout are also valid in this alternative, with the added advantage of the 'Water Heaters Production' section being closer to the storage section that feeds materials and components to the former.

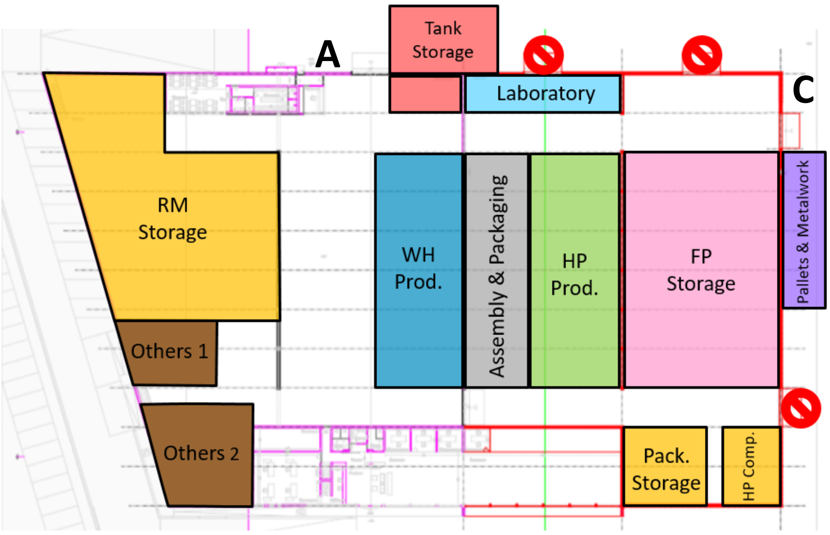

Figure 5.6 – Layout 2

However this proximity comes at a cost, by causing flow crossing with the transportation of finished products to storage. The product and material's flows (figure 5.7) are one of the biggest downsides of this alternative, as there are some areas of the layout where we can see *crossed flows* that could affect the efficiency of the productive process.

Another negative aspect of the layout is the fact that the two big storage sections are on opposite sides of the facility, making operators sharing very difficult to put into practice.

Looking at the *crossed flows* highlighted in figure 5.7, another layout considering two entrances as opposed to one, while maintaining the original entrance and exit flows, was analyzed.

As per figure 5.8, the *crossed flows* were reduced to two. The material entry from entrance A can now be executed with more room, avoiding the existing conflict. Furthermore, the added entrance eliminates the need to bring materials and components to the opposite side of the factory.

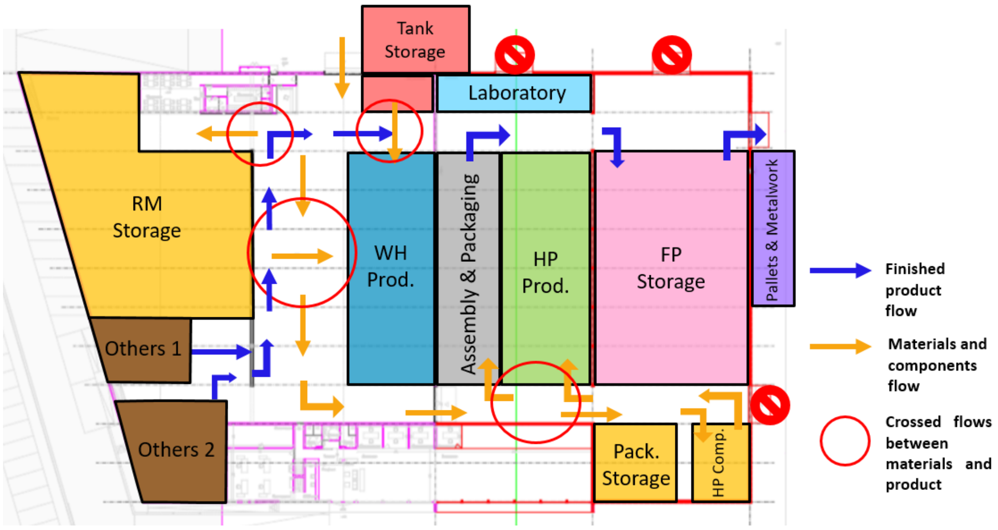

Figure 5.7 –Layout 2’s flows

For comparative analysis purposes, this scenario with two entrances was discarded, as it does not take into account the purpose of layout 2.

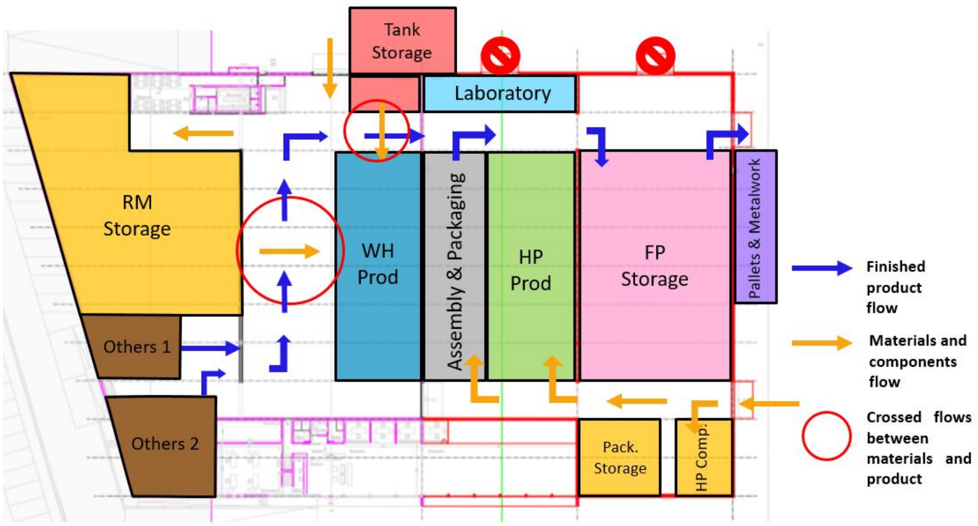

Figure 5.8 – Layout 2’s flows considering two entrances

The facility has a concrete wall located in the middle, which in this layout is located between the ‘Water Heaters Production’ and the ‘Assembly and Packaging’ sections. These sections are connected and make a U-turn at the end of the line. Normally this would be done within the limits of the areas defined for each section, but in this case given that there is a wall, there are only two options. One is to extend the line further down. However such alternative is not viable as it blocks the pathway that leads to the ‘Packaging Storage’ and ‘Heat Pumps Components’ Storage’ sections. The second alternative would be to demolish the wall, however this is something that could only be done after analyzing the walls structural composition. From the information gathered, the wall could be taken out, but in a rather expensive way. Despite this, an alternative to the original layout 2 is presented (figure 5.9).

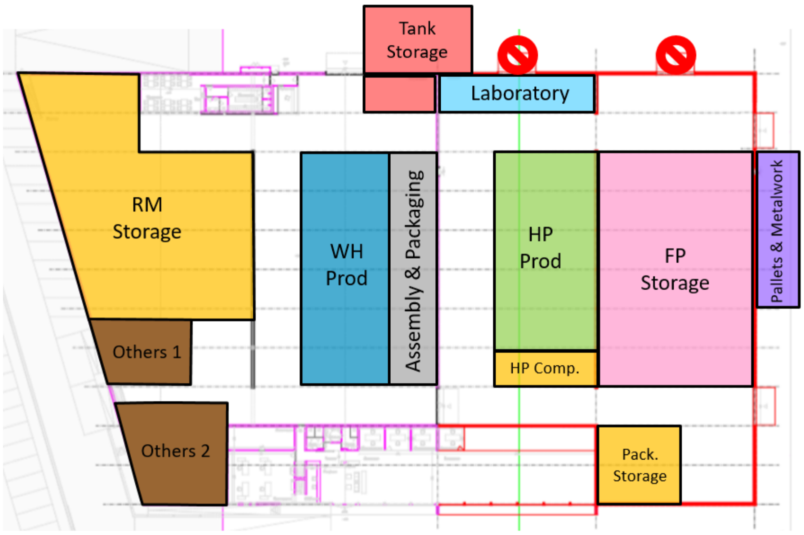

Figure 5.9 – Alternative to suggested layout 2 in case the central wall cannot be removed

The alternatives presented (figures 5.8 and 5.9) were created only to illustrate possibilities of solving existing problems concerning the initial layout and, therefore, will not be considered in the comparative analysis.

<u>Layout 3: Entrance B to Exit C Flow</u>

A different arrangement of the sections was done in layout 3 (figure 5.10), combining desired proximity between production sections to allow the *production sequence* to be promptly followed, storage spaces closely located to enable shared workforce. And, similarly to layout 2, this arrangement provides room for adequate material and component reception as well as product expedition, close to the entrance and exit respectively.

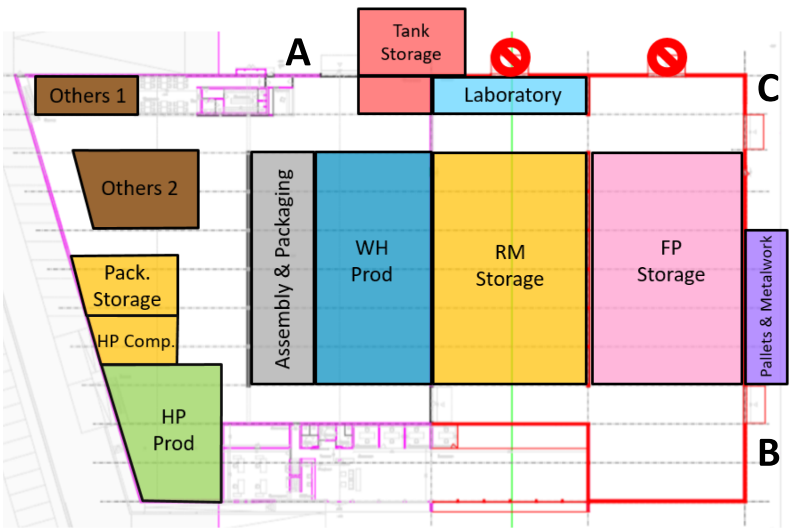

Figure 5.10 – Layout 3

Cross docking is also possible as this layout presents a similar flow to layout 1. The difference is the direction of the flow, which now goes from entrance B to exit C. Entrance A is still used for tank entry into the facility (in case of stainless steel tanks).

There are not many negative aspects in this layout, as it only has one crossed flow caused by tank transportation to the 'Water Heaters' Production' section that may occasionally cross with finished product going to the storage section.

Nevertheless, one of the biggest drawbacks of this alternative, is how distant the 'Others 1' (solar panels) and 'Others 2' (geothermic products) sections are from the 'Finished Product Storage', something that happened in the previous layouts, justified by the priority given to the main production line.

There is however one last layout alternative to be presented before doing the comparative analysis.

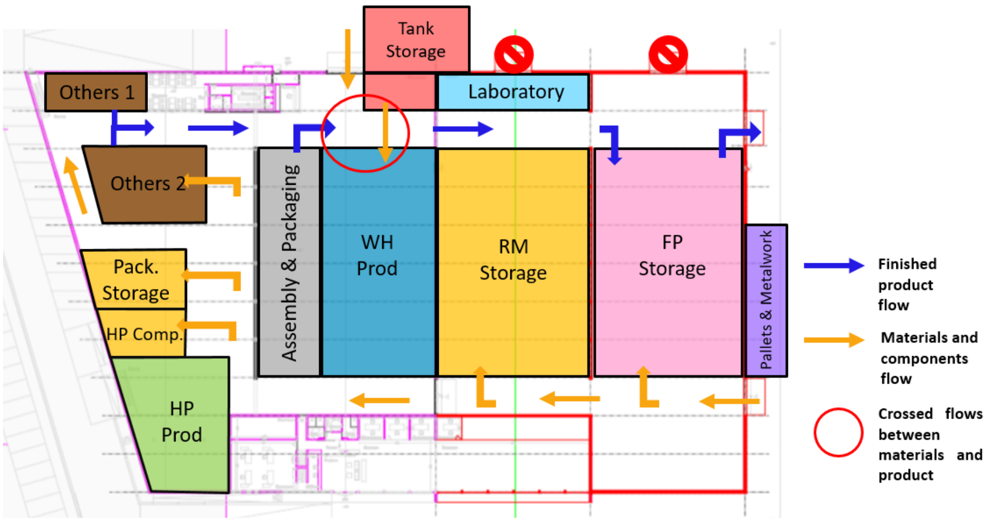

Figure 5.11 – Layout 3's flows

Layout 4: Zero Crossed Flows

The last layout (figure 5.12), focuses on eliminating *crossed flows*, ensuring a unidirectional flow line. Production involved sections proximity, possibility to share operators and supervisors across sections and the proximity between 'Heat Pumps Components Storage', as well as the 'Packaging Storage', and the 'Heat Pumps Production' and 'Assembly & Packaging' sections, respectively, are some of the advantages of this layout. Cross docking and both reception and expedition are viable in this alternative.

On the negative side there is the proximity between inflammable materials and the 'Heat Pump Production' section which, as previously discussed, increases concerns for safety reasons.

On the other hand, the purpose of layout 4 was achieved by managing to have a single direction flow (see figure 5.13). Although similar to the first layout, which shares the same entry and exit points, they differ due to the positioning of the heat pumps production related sections, as well as the products produced outside the main production line.

These four layout alternatives have clear positive and negative aspects that were here highlighted based on a qualitative approach.

In the following section, a quantitative approach is used, in a comparative way, to assess the performance of the different alternatives in different operational scenarios.

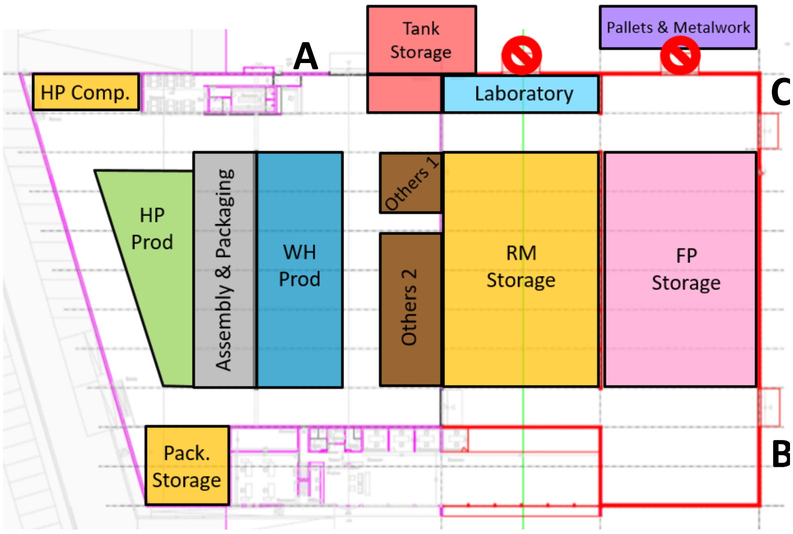

Figure 5.12 – Layout 4

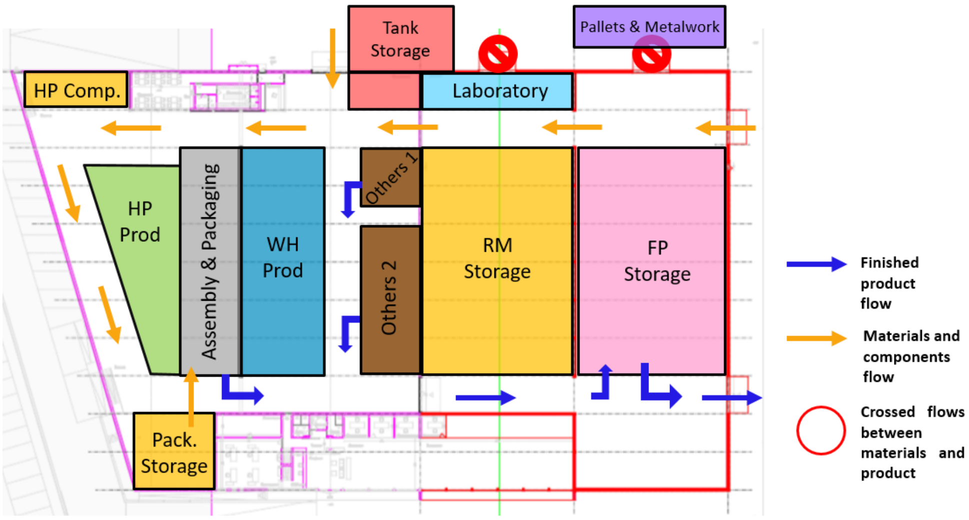

Figure 5.13 – Layout 4's flows

5.4 Comparative Assessment

Besides evaluating the proximity between sections and respective flows, there was also a need to quantify (with an acceptable degree of reliability) how well a layout alternative performed compared to the others. To this end, a comparative *multi-criteria analysis* was performed, considering the four alternative layouts described in the previous section. These layouts are compared in three distinct scenarios, and considering the multiple criteria introduced, as a way to support the choice of an alternative, in practice.

For this multi-criteria analysis, weights were given to the different criteria (see table 5.2) with a higher weight corresponding to a higher importance of that criterion. Furthermore, each criterion was measured with an appropriate unit.

Criteria were defined based on the information available from surveying, as well as meetings with INESC TEC's team. These criteria reflect what was deemed as important to address given the context of this project.

Criterion	Unit	Weight
Production Sequence	Metres	0,5
Hazard Risk	Qualitative	0,05
Ability to Share Supervisors/Operators	Metres	0,15
Crossed Flows	Number of Crossed Flows	0,3

Table 5.2 – Criteria, respective weights and units

The considered criteria are the following (along with the associated measurement attributes or units):

- *Production Sequence:* sum of the distance between all section pairs that represent a follow-up in terms of production sequence;
- *Hazard Risk*: what is the overall hazard risk of a layout;
- *Ability to Share Supervisors/Operators*: sum of the distance between all section pairs that can share supervisors/operators;
- *Crossed Flows*: number of total crossed flows in a layout.

By considering the above criteria we only take into account the key interactions that could have impact on the productive process, directly or indirectly.

Having understood all of the layouts and observing their respective flows, it was still necessary to have an objective way of comparing their performance according to the company's needs.

To this end, *weights* were assigned to the criteria, as seen in table 5.2. Furthermore, three distinct *scenarios* were created to better assess what could be impacting each layout's performance. The idea behind these scenarios is to consider different focus for the main production line and for the alternative production sections. The three scenarios considered are:

- *Scenario 1:* all relevant sections are considered;
- *Scenario 2:* section 'Others 2' (production of geothermic products) is excluded;
- *Scenario 3:* section 'Others 1' (production of solar panels) and 'Others 2' are excluded.

Having defined the criteria, and their weights and units, as well as the different scenarios under analysis, an individual analysis for each scenario was performed, followed by the comparative analysis (as described in what follows).

<u>Scenario 1 – All relevant sections considered</u>

This scenario represents the most realistic scenario of the three, as it includes all sections relevant for the productive process. Table 5.3 presents the results for each criterion per layout.

However, the results are expressed in different units, which does not enable a direct comparison between the different alternatives to be made. Therefore, a normalization of the values is required. Normalization is done considering that the best result corresponds to "1" and the worst corresponds to "0". Intermediate values are obtained through interpolation (with the exception of the qualitative criterion). Normalized results are presented in table 5.4.

Considering All Sections					
Criterion	Unit	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	Metres	369,10	337,29	345,79	250,11
Hazard Risk	Qualitative	Low	Medium	Medium	High
Ability to Share Supervisors/Operators	Metres	49,60	90,75	64,94	18,77
Crossed Flows	Number of Crossed Flows	1	4	1	0

Table 5.3 – Scenario 1 results

From table 5.4, we can see that layout 4 performs far better than the others. This is in large part due to its performance regarding the *production sequence*, where the sections that actively contribute for production to take place are, overall, much closer together than in the other layouts. Layout 4 also benefits from easily sharable supervisors/operators, much more so than the remaining layouts, with layout 1 being the second best alternative. It also has no *crossed flows*, as it was the main purpose for designing it. The only negative aspect in its performance is regarding the *risk of hazard*, which for layout 4 is high. However, as it does not represent a big concern (hence a 5% weight) it does not have a significant impact on the overall performance.

Regarding the *production sequence* criterion, layouts 2 and 3 have very similar results, however, as seen in the previous section, layout 2 sections arrangement raise doubts due to the existent wall in the middle of the facility, something that these results do not show.

Layout 3 does not perform well in regard to the *ability of sharing supervisors/operators*, in large part due to the distance between heat pumps and water heaters production sections. On the other hand, water heaters production is adjacent to the 'Assembly and Packaging' section, being that the latter is also closer to the heat pump production section, making the *sharing of supervisors/workers* easier than what the numbers seem to show.

Based on this analysis, layout 4 would be a highly recommended alternative, while layout 2 would be an alternative to avoid.

Scenario 2 will now focus on how the facility performance in terms of the production of their main production line products (as seen in chapter 3, some products include solar panels).

Considering All Sections					
Criterion	Weight	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	0,5	0	0,27	0,20	1
Hazard Risk	0,05	1	0,5	0,5	0
Ability to Share Supervisors/Operators	0,15	0,57	0	0,36	1
Crossed Flows	0,3	0,75	0	0,75	1
Totals	1	0,36	0,16	0,40	0,95

Table 5.4 – Scenario 1 normalized results

Scenario 2 – All relevant sections excluding 'Others 2'

In this scenario the production of geothermic products is excluded, which in practical terms means that the focus is shifted towards the main line of products that ENERGIE offers. Table 5.5 shows the results obtained.

Excluding 'Others 2'					
Criterion	Unit	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	Metres	342,54	269,11	273,69	213,59
Hazard Risk	Qualitative	Low	Medium	Medium	High
Ability to Share Supervisors/Operators	Metres	49,6	90,75	64,94	18,77
Crossed Flows	Number of Crossed Flows	1	4	1	0

Table 5.5 – Scenario 2 results

In the normalized results (table 5.6), we can observe that the only results that changed from the first scenario were those regarding the *production sequence* (all others are the same as before).

Excluding 'Others 2'					
Criterion	Weight	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	0,5	0	0,57	0,53	1
Hazard Risk	0,05	1	0,5	0,5	0
Ability to Share Supervisors/Operators	0,15	0,57	0	0,36	1
Crossed Flows	0,3	0,75	0	0,75	1
Totals	1	0,36	0,31	0,57	0,95

Table 5.6 – Scenario 2 normalized results

Once again, layout 4 proves to be the best choice, although the difference between layout 4 and layout 3 has been reduced by almost 20%. This happens due to an improvement in the results in the *production sequence* criterion, which means that the section responsible for the production of geothermic products negatively impacts the production performance of layout 3.

The same happens with layout 2, improving its overall performance. Despite this, layout 2 is still the least attractive alternative of the four.

Although not very realistic, the next scenario aims to see how well the main production performs, with different layout arrangements.

Scenario 3 – All relevant sections excluding 'Others 1' and 'Others 2'

In this final scenario (see table 5.7), as mentioned, the focus is on the main production line and on the production of products that do not require solar panels such as product 6 (MONOBLOC) as described in section 3.4.

In this scenario, besides the *production sequence* criterion, the *crossed flows* criterion's result for layout 2 suffers a change, as three of the four flow crossings resulted from finished product movement coming from both 'Others 1' and 'Others 2'. Table 5.8 presents the normalized results, and gives a clearer picture of what changes, regarding layout performance in this comparison.

Excluding 'Others 1' and 'Others 2'					
Criterion	Unit	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	Metres	197,72	160,78	129,61	176,08
Hazard Risk	Qualiative	Low	Medium	Medium	High
Ability to Share Supervisors/Operators	Metres	49,6	90,75	64,94	18,77
Crossed Flows	Number of Crossed Flows	1	1	1	0

Table 5.7 – Scenario 3 results

In this final scenario, one of the first things to note, regarding the *crossed flows* criterion, is that now layouts 1 to 3 have the same number of *crossed flows*, which makes them all the worst alternative, and layout 4, with no *crossed flows*, remains the best.

Another change has to do with the overall ranking of the alternatives, with layout 1 being theoretically the least attractive of the four, as opposed to layout 2. This highlights that the positioning of sections 'Others 1' (solar panels) and 'Others 2' (geothermic products) negatively impacts the overall performance in layout 2. This is even more true for layout 3.

Up until this scenario, layout 3 always performed slightly worse than layout 2, regarding the *production sequence* criterion. However, here we can see that the sections 'Others 1' and 'Others 2' clearly influenced this result, with layout 3 being the best alternative if those are not considered. This means that the production flows concerning the main line are better in layout 3 than in the remaining alternatives.

This is even more evident when the same comparison is made with layout 4 (that is now the third best option regarding *production sequence*). Similarly to what happens in layout 1, layout 4 has both of its large storage sections (raw materials and finished products) farther from the water heaters production section and the assembly and packaging section. This means that distances are going to be larger and, therefore, a lower result is to be expected.

In this scenario, layout 2 is dominated by layout 3, since for all criteria its results are equal or lower than the equivalent ones in layout 3. This means that layout 2 can be excluded from the analysis.

As mentioned, layout 1 is the least attractive of the four. Layout 4 remains the best option overall. However layout 3 is close enough to make it also a very sound alternative, especially considering that the *production sequence* criterion is the most relevant one.

Excluding 'Others 1' and 'Others 2'					
Criterion	Weight	Layout 1	Layout 2	Layout 3	Layout 4
Production Sequence	0,5	0	0,54	1	0,32
Hazard Risk	0,05	1	0,5	0,5	0
Ability to Share Supervisors/Operators	0,15	0,57	0	0,36	1
Crossed Flows	0,3	0	0	0	1
Totals	1	0,14	0,30	0,58	0,61

Table 5.8 – Scenario 3 normalized results

5.5 Final Remarks

After conducting an analysis for all three scenarios, there are some observations to be made, supporting the choice of a layout alternative.

Overall, layout 4 could be indicated as the "best" alternative, as it was the one that performed best on all three scenarios. However, if the *hazard risk* is a concerning factor, this alternative could be replaced by one of the others. Furthermore, if the company were to change their product line or demand changes, to products that do not require solar panels and exclude geothermic products, then layout 4 is not a sure option.

To that end, layout 3 could be the best option. All around layout 3 is a good alternative, given that its main production line performance seems to be quite sound. Its results are partially affected by the *ability to share supervisors/operators*, although in this case numbers are deceiving because distances are measured in pairs, which excludes the fact that the assembly and packaging line is between the 'Water Heaters Production' section and the 'Heat Pumps Production' section, making this sharing much more feasible. If *hazard risk* is a big concern, or focus is to be directed to the main production line (as opposed to including the production sections for other products), then layout 3 is a better alternative than layout 4.

Layout 1, although very good at reducing the *hazard risk*, and having good results regarding the *ability to share supervisors/operators*, is not a very attractive alternative overall. First, because *hazard risk* is not something that ranks very high among the current priorities for this project. Second, layout 1 could be seen as a worse version of layout 4 in terms of production and layout flows, despite their similarities in terms of sections' arrangement and flow direction. The ability to share workforce is not good enough in comparison to the one offered by layout 4, to justify recommending layout 1.

Layout 2 would be the least recommendable alternative out of the four. Despite performing better than layout 1 in the last scenario, such result is still deceiving. The reason for this is that layout 2 biggest flaw is covered by removing the production of solar panels and geothermic products, which is *crossed flows*.

Crossed flows in this layout could cause a loss in performance that would compromise this layout's results regarding the *production sequence* criterion. Besides this, it is important to mention that for this layout to be feasible the wall that separates the 'Water Heaters Production' and the 'Assembly and Packaging' section would have to be taken out, representing an additional capital expenditure that no other layout has to incur in. For all these reasons, layout 2 should be avoided.

6 Line Balancing: Application to the Case Study

6.1 Introduction

In this part of the dissertation, we analyse the assembly and packaging line, knowing that three different products go through it.

To that end and assuming, in accordance to the survey done by INESC TEC, that the time it takes the same product model, with different capacities, to reach the end of the process is the same, three distinct products and associated lines are to be studied. Products 2, 4 and 6 are the ones under study (as per table 3.1).

To this end, two different general use software *applications* were developed using the programming language VBA, in Excel. The first application *(application 1)* determines what is the minimum amount of stations needed for a certain product to be assembled and packed, knowing that both the demand and available capacity are fixed. If the theoretical minimum number of workstations is not achievable, the application informs the user and provides the needed number of stations to successfully assemble and pack the product, with the known cycle time. Furthermore, it distributes all the operations by the correct order among those stations. It also provides information regarding the idleness and efficiency percentages.

The second application *(application 2)* acts as a complement to the first, by allowing the user to know what is the minimum cycle time and available capacity needed to ensure that the operations fit within a given line. Essentially, it does the same as the first one, but in this case the cycle time used is the minimum necessary (although always above the minimum cycle time for the process) to make it possible for a product to be assembled in a specific line, that has a certain number of stations previously defined by the user. Again, the user is able to see the order by which the operations must be assigned to each station, as well as the information regarding idleness and efficiency percentages.

The interfaces for each *application* can be found in appendices B and C.

Both applications distribute the operations per station, starting with the one which has the highest number of successors, while ensuring that all predecessors are already allocated to a station and there is enough capacity in the station to accommodate that operation. In case of a tie in the number of successors, the operation with the highest duration has priority.

For each of the three selected products (see section 3.3), our application (*application 1*) generates a different configuration of the line, for its assembly and packaging, considering the known demand and available capacity. For these lines, we have adopted the following terminology: for product 2, the application generates line A; for product 4, line B; and for product 6, line C.

Afterwards each of the lines generated will have their performance tested for each of the products, through the use of *application 2*.

6.2 Line A

Product 2, as mentioned in chapter 3, is a 500 litres ECO model. This product has to follow a total of 13 operations, in order for the process to be completed. The names, durations, successors and predecessors of these operations are presented in appendix A.

All the data related with product 2, including the production line generated for this specific product, operations distribution per station and performance percentages are displayed in table 6.1.

Product 2					
Available Capacity			480 minutes		
Demand			30 units		
Minimum Cycle Time			9,32 minutes		
Product 2 – Line creation					
Takt-Time (minutes)	**Theoretical Minimum Number of Working Stations**	**Was the Theoretical Minimum Number of Working Stations possible?**	**Real Minimum Number of Working Stations**	**Idleness (%)**	**Efficiency (%)**
16	3	Yes	3	32,22	67,78
Distribution of tasks among stations					
Station 1		**Station 2**		**Station 3**	
OP1; OP2; OP3		OP4; OP5; OP6; OP7; OP8; OP9		OP10; OP11; OP12; OP13	

Table 6.1 – Product 2 and performance of line A, with fixed cycle time

As it can be seen, product 2 requires a line that has a minimum of 3 stations. However the *takt-time* is almost the double of the minimum *cycle time* for this product assembly and packaging procedure, which combined with a considerable idleness percentage of 32,22%, raises the question: can we improve this distribution and increase efficiency? Using *application 2*, an analysis of the performance of all three products, including product 2 was made.

Line A (3 Stations)						
	Minimum Cycle Time	**Theoretical Cycle Time (minutes)**	**Minimum Cycle Time Needed (minutes)**	**Available Capacity (minutes)**	**Idleness (%)**	**Efficiency (%)**
Product 2	9,32	10,84	12,32	370	11,97	88,03
Product 4	13,28	21,84	23,35	701	6,49	93,51
Product 6	10,60	18,54	20,64	619	10,19	89,81

Distribution of tasks among stations			
	Station 1	**Station 2**	**Station 3**
Product 2	OP1; OP2; OP3	OP4; OP5; OP6; OP7	OP8; OP9; OP10; OP11; OP12; OP13
Product 4	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12	OP13; OP14; OP15; OP16; OP17; OP18; OP19; OP20	OP21; OP22; OP23; OP24; OP25; OP26; OP27; OP28; OP29; OP30; OP31; OP32; OP33
Product 6	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9	OP10; OP11; OP12; OP13; OP14; OP15; OP16; OP17; OP18	OP19; OP20; OP21; OP22; OP23; OP24; OP25; OP26

Table 6.2 – Performance of all three products in line A

As seen in table 6.2, product 2 can have its cycle time reduced to 12,32 minutes, which enables an increase in efficiency of 20,25%. However it is important to point out that this does not account for any problems that may occur during the process, as it represents the lowest possible cycle time considering the operations durations, predecessors and successors.

On the other hand the available capacity required is 110 minutes below the existing available capacity shown in table 6.1, which provides some room to adjust the workload, if necessary.

On the opposite end, products 4 and 6 are not able to see their process take place in a 3 station line, without increasing the available capacity, as they require 221 and 139 minutes more than the existing available capacity, respectively. An increase in available capacity could be achieved by putting workers on overtime or by expanding the workforce, for example. Just based on numbers, in that case, the results in terms of efficiency would in fact be very satisfactory, although such a significant increase does not seem realistic or achievable. On the other hand, numbers also tell that the stations could be overstaffed, given the discrepancy between the minimum cycle time of each product and the actual cycle time needed to make 3 stations capable of completing the process.

For these reasons, it would not be recommended to insert products 4 and 6 in line A.

6.3 Line B

An ECO TOP model of 300 litres capacity (product 4) was the next product subject to analysis (see the associated information in appendix A). The procedure for product 4 is the one that has the highest number of operations (33, in total).

Product 4					
Available Capacity			480 minutes		
Demand			30 units		
Minimum Cycle Time			13,28 minutes		
Product 4 – Line Creation					
Takt-Time (minutes)	**Theoretical Minimum Number of Working Stations**	**Was the Theoretical Minimum Number of Working Stations possible?**	**Real Minimum Number of Working Stations**	**Idleness (%)**	**Efficiency (%)**
16	5	No	6	38,11	61,89
Distribution of tasks among Stations					
Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8	OP9; OP10; OP11; OP12	OP13; OP14	OP15; OP16; OP17; OP18; OP19; OP20; OP21; OP22	OP23; OP24; OP25; OP26; OP27; OP28; OP29; OP30	OP31; OP32; OP33

Table 6.3 – Product 4 and performance of line B, with fixed cycle time

In this case, the theoretical minimum number of workstations was not achievable. That happens because the process operations have different durations, and the theoretical minimum considers that all operations have the same duration and equally splits them among the existing stations. It could also have to do with precedencies, but since in these different processes all operations only depend on the one immediately before, it makes no difference.

6 is therefore the minimum number of stations with a *takt-time* of 16 minutes, which for product 4 translates into an efficiency of 61,89%. As opposed to what was observed with the previous product, there is not a big gap between the minimum cycle time and the actual cycle time, which could mean that resources are being better used.

Line B (6 Stations)						
	Minimum Cycle Time (minutes)	Theoretical Cycle Time (minutes)	Minimum Cycle Time Needed (minutes)	Available Capacity (minutes)	Idleness (%)	Efficiency (%)
Product 2	9,32	5,42	9,32	279	41,80	58,20
Product 4	13,28	10,92	13,28	399	17,80	82,20
Product 6	10,60	9,27	12,01	360	22,78	77,22
Distribution of tasks among stations						
	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**	**Station 6**
Product 2	OP1	OP2; OP3; OP4	OP5; OP6; OP7; OP8; OP9	OP10; OP11; OP12; OP13	-	-
Product 4	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8	OP9; OP10; OP11; OP12	OP13	OP14; OP15; OP16; OP17; OP18; OP19; OP20; OP21; OP22	OP23; OP24; OP25	OP26; OP27; OP28; OP29; OP30; OP31; OP32; OP33
Product 6	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8	OP9; OP10	OP11; OP12	OP13	OP14; OP15; OP16; OP17; OP18; OP19; OP20	OP21; OP22; OP23; OP24; OP25; OP26

Table 6.4 – Performance of all three products in line B

In table 6.4 we can see that product 4 has seen a significant increase in efficiency (20,31%), with an adjustment of 2,72 minutes to the cycle time. Theoretically, it would be possible to reduce the cycle time to 10,92 minutes, however the minimum cycle time for the process is at 13,28 minutes, which coincides with the minimum cycle time required to allocate all operations to the different stations. The distribution of operations among stations also suffered alterations from the third station onwards.

As expected, all products are able to be assembled and packed using this line without exceeding the available capacity of 480 minutes. This was expected since product 4 has the highest number of operations as well as the highest sum of durations, followed by product 6 and then product 2.

Idleness percentages are higher in this line, especially for product 2, which does not require the use of all stations, leaving two of them stopped, this explaining a percentage of almost 42%. However, if we only consider the stations that have operations assigned, the idleness drops to 12,70% which is significantly better and shows that the stations which are being used are, in fact, efficient.

6.4 Line C

The last product under analysis is product 6 (a MONOBLOC model, with 300 litres of capacity). The process for this product consists of 26 operations in total (which can be found in appendix A). This product differs, in terms of structure, from the other two products, as mentioned in chapter 3.3.

In table 6.5, we can see that the last operation is to be executed separately in station 6, even though it only amounts to a duration of 1,28 minutes (see appendix A). This is an indicator that with a lower cycle time, it is possible to better distribute operations and increase the resource usage for this product's process. With a fixed *takt-time* of 16 minutes, the idleness is at 38,09%.

Similarly to product 4, product 6 is not able to meet the theoretical minimum number of workstations. Instead, the line for this product consists of 5 stations.

Product 6					
Available Capacity	480 minutes				
Demand	30 units				
Minimum Cycle Time	10,60 minutes				
Product 6 – Line Creation					
Takt-Time (minutes)	**Theoretical Minimum Number of Working Stations**	**Was the Theoretical Minimum Number of Working Stations possible?**	**Real Minimum Number of Working Stations**	**Idleness (%)**	**Efficiency (%)**
16	4	No	5	38,09	61,91

Distribution of tasks among Stations				
Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**
OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8	OP9; OP10; OP11; OP12	OP13; OP14; OP15; OP16; OP17	OP18; OP19; OP20; OP21; OP22; OP23; OP24; OP25	OP26

Table 6.5 – Product 6 and performance of line C, with fixed cycle time

When looking at table 6.6, a different allocation of product 6 operations among line C has been made – operation 26 is no longer isolated in the last station, due to a reduction of the cycle time of almost 4 minutes. This reduction translates into a reduction of the idleness in more than 30%.

Product 2, while not performing so poorly, is obviously distant from the efficiency displayed with a 3 station line. In any case, it is interesting to observe that even though its operations do not manage to fill all stations, even if the cycle time is down to the minimum, the efficiency percentage obtained is roughly 2% higher than the one registered for a 3 station line, using all of the available capacity (see table 6.1). This shows that resource usage is fundamental when improving process efficiency, regardless of the number of stations in a line.

As expected, product 4 process is not successfully executed in this line without increasing the available capacity. The increase is, however, of 24 minutes, much less than the ones verified in line A, and only 4,22% less efficient than in line B, despite that line being made specifically for product 4.

Line C (5 Stations)						
	Minimum Cycle Time (minutes)	**Theoretical Cycle Time (minutes)**	**Minimum Cycle Time Needed (minutes)**	**Available Capacity (minutes)**	**Idleness (%)**	**Efficiency (%)**
Product 2	9,32	6,51	9,32	279	30,16	69,84
Product 4	13,28	13,10	16,80	504	22,02	77,98
Product 6	10,60	11,12	12,06	362	7,75	92,25

Distribution of tasks among stations					
	Station 1	**Station 2**	**Station 3**	**Station 4**	**Station 5**
Product 2	OP1	OP2; OP3; OP4	OP5; OP6; OP7; OP8; OP9	OP10; OP11; OP12; OP13	-
Product 4	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9	OP10; OP11; OP12; OP13	OP14; OP15; OP16; OP17; OP18; OP19; OP20; OP21; OP22	OP23; OP24; OP25; OP26; OP27; OP28; OP29; OP30	OP31; OP32; OP33
Product 6	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8	OP9; OP10; OP11	OP12; OP13	OP14; OP15; OP16; OP17; OP18; OP19; OP20	OP21; OP22; OP23; OP24; OP25; OP26

Table 6.6 – Performance of all three products in line C

6.5 Final Remarks

After analysing all these different lines, it is possible to conclude that line A (generated for product 2), consisting of only 3 stations, is not a viable option to implement as it far exceeds the existing available capacity. Given the small number of stations, those stations could easily get overstaffed and even though, theoretically, numbers suggest that products 4 and 6 would benefit from great efficiency if cycle time conditions were met, the reality would likely be different as productivity, due to poor work conditions, would have an impact on those numbers.

With the existing conditions, the only viable option would be line B which has 6 stations. However product 2 process performs poorly, with less than 60% efficiency.

Based on the numbers collected there are two alternatives to line B.

The first one would be to increase the available capacity so that line C would be viable. The reason for this is that, as discussed, the increase would not be that significant and increases in efficiency of 11,64% and 15,03% would be possible for products 2 and 6 respectively (when compared to line B). This while product 4 would suffer a minimal efficiency loss at 4,22%, as previously observed.

The second alternative would be to have two distinct lines, one exclusively made for product 2, and 6 stations line for both products 4 and 6. Product 2 would benefit from a 30% increase in efficiency (when compared to a 6 stations line), reaching an efficiency potential of roughly 88%, while products 4 and 6 would be able to have efficiencies close to 80%. The downside of such solution would be the capital expenditure of installing two different lines and operating them.

For a decision to be made, further analysis and surveying would have to be done This would lead decision-makers to understand whether or not it would be advantageous for the company to adopt a given production line in the long term. Furthermore, an in-depth study to understand if the lines would fit within the adopted layout design would have to be made, as the existing layout and the layouts proposed in this dissertation do only account for a single assembly and packaging line.

7 Conclusion and Future Research

This dissertation aimed to put into practice a set of well documented tools, integrated in a clear methodological approach, to analyse and improve the performance of an industrial company that produces equipment for DHW and climatization.

This dissertation has two main components.

The first component is related to the design of the *facility layout*, which started with an analysis of the current situation and the identification of key proximity relationships, through the use of a Muther's grid. Afterwards, a series of layout alternatives were presented, with each of these alternatives being analysed in terms of their product and material's flows. Then, an overall comparative evaluation of the designs through a multi criteria approach was done. From this approach, one of the alternatives is recommended.

The second main component of the work aims at understanding how different *assembly and packaging processes*, for different products, would influence the type of line required for execution, providing alternatives for implementation.

The solutions provided, in terms of *layout design*, are the result of combining different types of analyses, both of a qualitative and a quantitative nature. On the other hand, the solutions provided for *line balancing* are strictly quantitative, although remarks about what could happen beyond the numbers are made, to put calculations into context.

At the end of this work, a project meeting was held, where the methodology was discussed and comments regarding the results obtained were made. Globally, the outcomes of this dissertation were considered interesting and with a potential for replication.

From this meeting it is important to highlight the comments regarding the importance of adopting a "standard work" approach, as it can positively influence the line's configuration.

Furthermore we have also discussed the importance of knowing the idle time per station, as an indicator to assess how balanced the line is. It was also noted that it would be interesting to study the impact that the size of the production series had on the performance of the lines.

All in all, in this kind of work, despite the analysis that were performed and the alternatives that were generated (derived from information retrieved through field surveying, meetings and interviews), the final decision rests with the business owners. What is considered a good solution is highly dependent on what are the business needs at a specific point in time, which considering the fast-paced world we live in, means that those needs could change frequently.

Future work on these problems could be supported by simulation techniques that would enable a combined analysis of flows, line balancing and overall performance. This would bring the added advantage of realism and, consequently, an increased accuracy, which facilitates the interpretation of the results.

Given the pandemic times we live in, more than ever layout design assumes an important role in all kinds of business that have to readjust their long established procedures for various reasons. Businesses have to be alert regarding the economy state and how it keeps evolving, understanding what products/services will have higher demand. This creates uncertainty, which can be addressed with tools for layout and production planning and design, in line with the work presented in this dissertation.

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APPENDIX A: Assembly and Packaging Operations for Different Products

Product 2 – ECO 500L

Operation ID	Name	Successors	Duration (mins)	Predecessors
OP1	Execution of electrical connections	OP2 to OP13	9,32	-
OP2	Flange assembly	OP3 to OP13	0,60	OP1
OP3	System and respective accessories preparation. Application to heat pumps	OP4 to OP13	0,45	OP1 and OP2
OP4	Vacuum execution	OP5 to OP13	8,25	OP1 to OP3
OP5	Gas charge	OP6 to OP13	0,87	OP1 to OP4
OP6	Removal of the system previously applied to the heat pumps	OP7 to OP13	0,57	OP1 to OP5
OP7	Electrical test	OP8 to OP13	2,63	OP1 to OP6
OP8	Finishes including painting of the finished product	OP9 to OP13	1,52	OP1 to OP7
OP9	Tagging (includes measurements)	OP10 to OP13	0,20	OP1 to OP8
OP10	Water heater transfer to pallet	OP11 to OP13	4,30	OP1 to OP9
OP11	Card boxes application	OP12 and OP13	2,65	OP1 to OP10
OP12	Tagging for expedition	OP13	0,13	OP1 to OP11
OP13	Packages strapping	-	1,05	OP1 to OP12

Product 4 – ECO TOP 300L

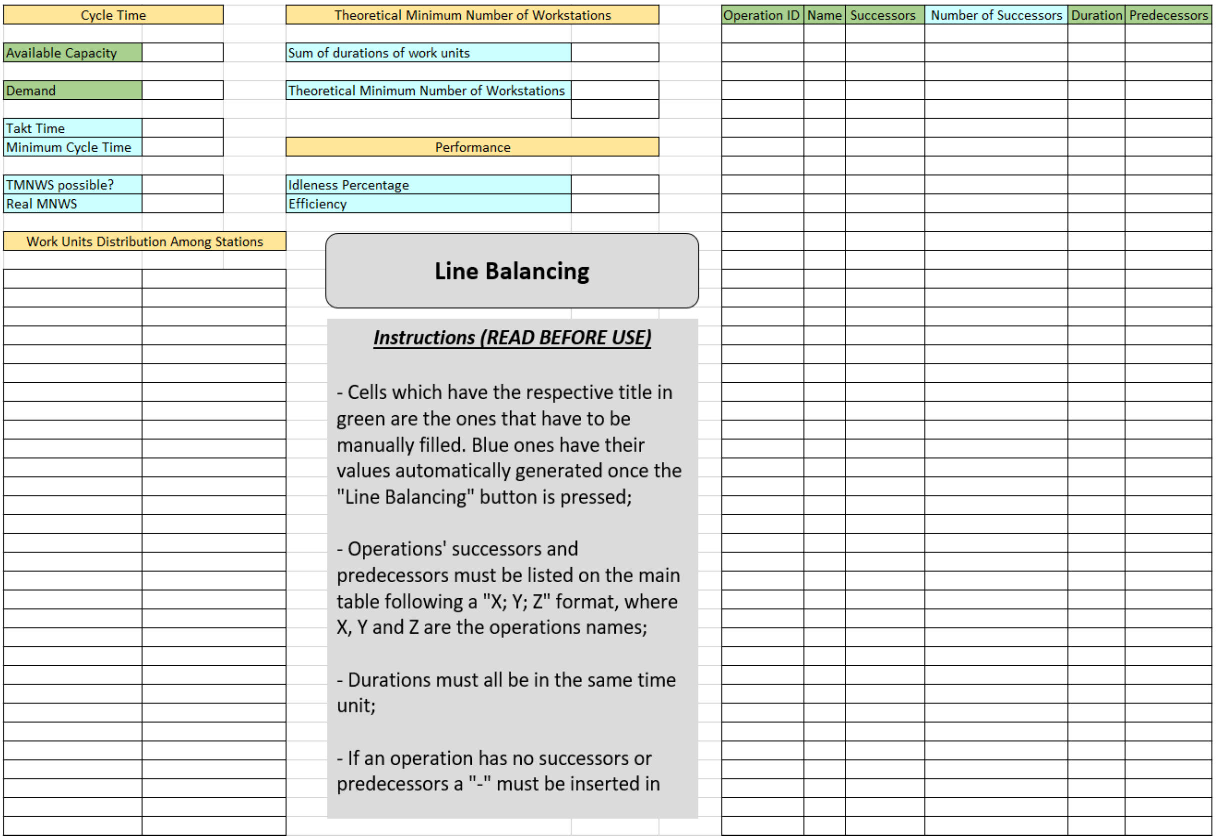
Operation ID	Name	Successors	Duration (mins)	Predecessors
OP1	Heat pump's batch transportation to the assembly line	OP2 to OP33	0,43	-
OP2	Insertion of the heat pumps on the top of the water heaters	OP3 to OP33	0,27	OP1
OP3	Screwing of the heat pumps	OP4 to OP33	3,06	OP1 and OP2
OP4	Tube fitting	OP5 to OP33	1,03	OP1 to OP3
OP5	Nitrogen injection	OP6 to OP33	0,00	OP1 to OP4
OP6	Visual inspection to find leaks	OP7 to OP33	2,02	OP1 to OP5
OP7	Covers application	OP8 to OP33	1,00	OP1 to OP6
OP8	Cable crossing to the central part of the water heater	OP9 to OP33	0,58	OP1 to OP7
OP9	Execution of electrical connections	OP10 to OP33	8,41	OP1 to OP8
OP10	Flange preparation (insulation application)	OP11 to OP33	0,55	OP1 to OP9
OP11	Flange assembly	OP12 to OP33	1,18	OP1 to OP10
OP12	System and respective accessories preparation. Application to heat pumps	OP13 to OP33	0,93	OP1 to OP11
OP13	Vacuum execution	OP14 to OP33	13,28	OP1 to OP12
OP14	Gas charge	OP15 to OP33	1,60	OP1 to OP13
OP15	Removal of the system previously applied to the heat pumps	OP16 to OP33	1,52	OP1 to OP14
OP16	Transportation to electrical testing of the top part	OP17 to OP33	0,48	OP1 to OP15
OP17	Preparation for the attachment of the top part to the water heaters and finishes procedures	OP18 to OP33	2,83	OP1 to OP16
OP18	Display insulation	OP19 to OP33	1,27	OP1 to OP17
OP19	Screwing of top part to the water heaters	OP20 to OP33	0,56	OP1 to OP18
OP20	Display installation	OP21 to OP33	1,17	OP1 to OP19
OP21	Electrical test	OP22 to OP33	2,37	OP1 to OP20
OP22	Back lid application	OP23 to OP33	0,94	OP1 to OP21
OP23	Finishes including painting of the finished product	OP24 to OP33	9,95	OP1 to OP22
OP24	Tagging (includes measurements)	OP25 to OP33	0,47	OP1 to OP23
OP25	Stickers application	OP26 to OP33	2,29	OP1 to OP24
OP26	Water heater transfer to pallet	OP27 to OP33	0,87	OP1 to OP25
OP27	Card boxes transportation and preparation	OP28 to OP33	0,32	OP1 to OP26
OP28	Styrofoam transportation	OP29 to OP33	0,71	OP1 to OP27
OP29	Accessories preparation	OP30 to OP33	0,15	OP1 to OP28
OP30	Styrofoam application	OP31 to OP33	1,03	OP1 to OP29
OP31	Card boxes application	OP32 and OP33	3,18	OP1 to OP30
OP32	Tagging for expedition	OP33	0,32	OP1 to OP31
OP33	Packages strapping	-	0,75	OP1 to OP32

Product 6 – MONOBLOC 300L

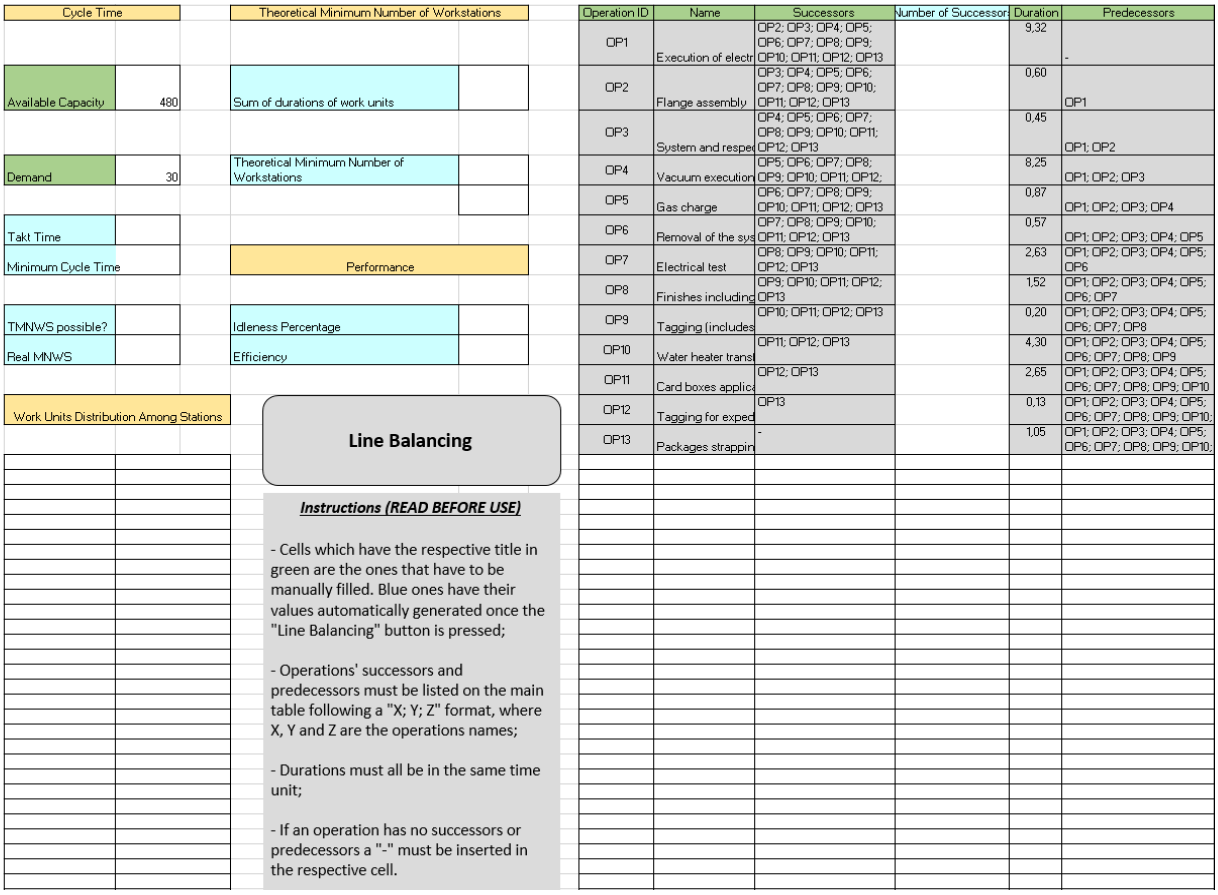
Operation ID	Name	Successors	Duration (mins)	Predecessors
OP1	Heat pump's batch transportation to the assembly line	OP2 to OP26	0,67	-
OP2	Insertion of the heat pumps on the top of the water heaters	OP3 to OP26	0,37	OP1
OP3	Screwing of the heat pumps	OP4 to OP26	4,53	OP1 and OP2
OP4	Tube fitting	OP5 to OP26	1,47	OP1 to OP3
OP5	Nitrogen injection	OP6 to OP26	0,62	OP1 to OP4
OP6	Visual inspection to find leaks	OP7 to OP26	1,38	OP1 to OP5
OP7	Covers application	OP8 to OP26	1,05	OP1 to OP6
OP8	Cable crossing to the central part of the water heater	OP9 to OP26	0,39	OP1 to OP7
OP9	Execution of electrical connections	OP10 to OP26	10,17	OP1 to OP8
OP10	Flange preparation (insulation application)	OP11 to OP26	0,96	OP1 to OP9
OP11	Flange assembly	OP12 to OP26	0,93	OP1 to OP10
OP12	System and respective accessories preparation. Application to heat pumps	OP13 to OP26	0,78	OP1 to OP11
OP13	Vacuum execution	OP14 to OP26	10,60	OP1 to OP12
OP14	Gas charge	OP15 to OP26	1,53	OP1 to OP13
OP15	Removal of the system previously applied to the heat pumps	OP16 to OP26	1,45	OP1 to OP14
OP16	Preparation for the attachment of the top part to the water heaters and finishes procedures	OP17 to OP26	0,80	OP1 to OP15
OP17	Screwing of top part to the water heaters	OP18 to OP26	1,30	OP1 to OP16
OP18	Display installation	OP19 to OP26	0,58	OP1 to OP17
OP19	Electrical test	OP20 to OP26	2,58	OP1 to OP18
OP20	Finishes including painting of the finished product	OP21 to OP26	3,76	OP1 to OP19
OP21	Tagging (includes measurements)	OP22 to OP26	1,20	OP1 to OP20
OP22	Water heater transfer to pallet	OP23 to OP26	2,93	OP1 to OP21
OP23	Styrofoam application	OP24 to OP26	1,25	OP1 to OP22
OP24	Card boxes application	OP25 and OP26	2,78	OP1 to OP23
OP25	Tagging for expedition	OP26	0,25	OP1 to OP24
OP26	Packages strapping	-	1,28	OP1 to OP25

APPENDIX B: VBA Application 1

Interface 1 – Initial interface



__Interface 2 – Cells filled by user__



Cycle Time	
Available Capacity	480
Demand	30
Takt Time	
Minimum Cycle Time	
TMNWS possible?	
Real MNWS	

Theoretical Minimum Number of Workstations	
Sum of durations of work units	
Theoretical Minimum Number of Workstations	

Performance	
Idleness Percentage	
Efficiency	

Work Units Distribution Among Stations	

Line Balancing

Instructions (READ BEFORE USE)

- Cells which have the respective title in green are the ones that have to be manually filled. Blue ones have their values automatically generated once the "Line Balancing" button is pressed;

- Operations' successors and predecessors must be listed on the main table following a "X; Y; Z" format, where X, Y and Z are the operations names;

- Durations must all be in the same time unit;

- If an operation has no successors or predecessors a "-" must be inserted in the respective cell.

Operation ID	Name	Successors	Number of Successors	Duration	Predecessors
OP1	Execution of electr	OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		9,32	-
OP2	Flange assembly	OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,60	OP1
OP3	System and respe	OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,45	OP1; OP2
OP4	Vacuum execution	OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12;		8,25	OP1; OP2; OP3
OP5	Gas charge	OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,87	OP1; OP2; OP3; OP4
OP6	Removal of the sys	OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,57	OP1; OP2; OP3; OP4; OP5
OP7	Electrical test	OP8; OP9; OP10; OP11; OP12; OP13		2,63	OP1; OP2; OP3; OP4; OP5; OP6
OP8	Finishes including	OP9; OP10; OP11; OP12; OP13		1,52	OP1; OP2; OP3; OP4; OP5; OP6; OP7
OP9	Tagging (includes	OP10; OP11; OP12; OP13		0,20	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8
OP10	Water heater trans	OP11; OP12; OP13		4,30	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9
OP11	Card boxes applic	OP12; OP13		2,65	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10
OP12	Tagging for exped	OP13		0,13	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10;
OP13	Packages strappin	-		1,05	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10;

Interface 3 – After running the application

Cycle Time	
Available Capacity	480
Demand	30
Takt Time	16,00
Minimum Cycle Tim	9,32
TMNWS possible?	Yes
Real MNWS	3

Theoretical Minimum Number of Workstations	
Sum of durations of work units	33
Theoretical Minimum Number of Workstations	3
	2,0625

Performance	
Idleness Percentage	32,22%
Efficiency	67,78%

Work Units Distribution Among Stations	
Station 1	OP1; OP2; OP3
Station 2	OP4; OP5; OP6; OP7; OP8; OP9
Station 3	OP10; OP11; OP12; OP13

Line Balancing

Instructions (READ BEFORE USE)

- Cells which have the respective title in green are the ones that have to be manually filled. Blue ones have their values automatically generated once the "Line Balancing" button is pressed;

- Operations' successors and predecessors must be listed on the main table following a "X; Y; Z" format, where X, Y and Z are the operations names;

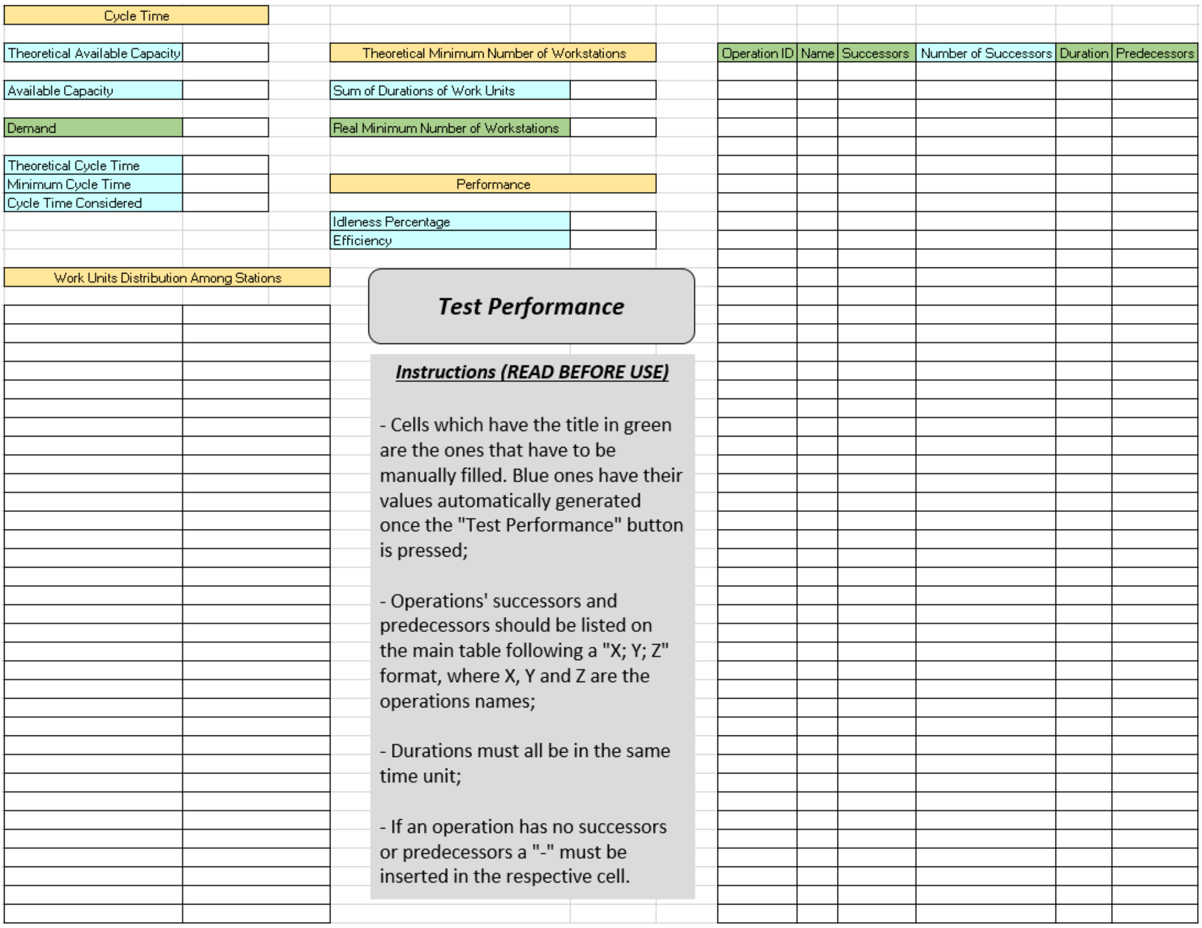
- Durations must all be in the same time unit;

- If an operation has no successors or predecessors a "-" must be inserted in the respective cell.

Operation ID	Name	Successors	Number of Successors	Duration	Predecessors
OP1	Execution of electr	OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	12	9,32	-
OP2	Flange assembly	OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	11	0,60	OP1
OP3	System and respe	OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	10	0,45	OP1; OP2
OP4	Vacuum execution	OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12;	9	8,25	OP1; OP2; OP3
OP5	Gas charge	OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	8	0,87	OP1; OP2; OP3; OP4
OP6	Removal of the sys	OP7; OP8; OP9; OP10; OP11; OP12; OP13	7	0,57	OP1; OP2; OP3; OP4; OP5
OP7	Electrical test	OP8; OP9; OP10; OP11; OP12; OP13	6	2,63	OP1; OP2; OP3; OP4; OP5; OP6
OP8	Finishes including	OP9; OP10; OP11; OP12; OP13	5	1,52	OP1; OP2; OP3; OP4; OP5; OP6; OP7
OP9	Tagging (includes	OP10; OP11; OP12; OP13	4	0,20	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8
OP10	Water heater transl	OP11; OP12; OP13	3	4,30	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9
OP11	Card boxes applica	OP12; OP13	2	2,65	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10
OP12	Tagging for exped	OP13	1	0,13	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10;
OP13	Packages strappin	-	0	1,05	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10;

APPENDIX C: VBA Application 2

Interface 1 – Initial interface



Interface 2 – Cells filled by user

Cycle Time	
Theoretical Available Capacity	
Available Capacity	
Demand	30
Theoretical Cycle Time	
Minimum Cycle Time	
Cycle Time Considered	

Theoretical Minimum Number of Workstations	
Sum of Durations of Work Units	
Real Minimum Number of Workstations	5

Performance	
Idleness Percentage	
Efficiency	

Work Units Distribution Among Stations	

Test Performance

Operation ID	Name	Successors	Number of Successors	Duration	Predecessors
OP1	Execution of electrical co	OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		9,32	-
OP2	Flange assembly	OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,60	OP1
OP3	System and respective a	OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,45	OP1; OP2
OP4	Vacuum execution	OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		8,25	OP1; OP2; OP3
OP5	Gas charge	OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,87	OP1; OP2; OP3; OP4
OP6	Removal of the system pr	OP7; OP8; OP9; OP10; OP11; OP12; OP13		0,57	OP1; OP2; OP3; OP4; OP5
OP7	Electrical test	OP8; OP9; OP10; OP11; OP12; OP13		2,63	OP1; OP2; OP3; OP4; OP5; OP6
OP8	Finishes including paintir	OP9; OP10; OP11; OP12; OP13		1,52	OP1; OP2; OP3; OP4; OP5; OP6; OP7
OP9	Tagging (includes measu	OP10; OP11; OP12; OP13		0,20	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8
OP10	Water heater transfer to p	OP11; OP12; OP13		4,30	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9
OP11	Card boxes application	OP12; OP13		2,65	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10
OP12	Tagging for expedition	OP13		0,13	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11
OP13	Packages strapping	-		1,05	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP12

Instructions (READ BEFORE USE)

- Cells which have the title in green are the ones that have to be manually filled. Blue ones have their values automatically generated once the "Test Performance" button is pressed;

- Operations' successors and predecessors should be listed on the main table following a "X; Y; Z" format, where X, Y and Z are the operations names;

- Durations must all be in the same time unit;

- If an operation has no successors or predecessors a "-" must be inserted in the respective cell.

Interface 3 – After running the application

Cycle Time	
Theoretical Available Capacity	195
Available Capacity	279
Demand	30
Theoretical Cycle Time	6,51
Minimum Cycle Time	9,32
Cycle Time Considered	9,32

Theoretical Minimum Number of Workstations	
Sum of Durations of Work Units	32,533333
Real Minimum Number of Workstations	5

Performance	
Idleness Percentage	30,16%
Efficiency	69,84%

Work Units Distribution Among Stations	
Station 1	OP1
Station 2	OP2; OP3; OP4
Station 3	OP5; OP6; OP7; OP8; OP9
Station 4	OP10; OP11; OP12; OP13
Station 5	

Test Performance

Instructions (READ BEFORE USE)

- Cells which have the title in green are the ones that have to be manually filled. Blue ones have their values automatically generated once the "Test Performance" button is pressed;

- Operations' successors and predecessors should be listed on the main table following a "X; Y; Z" format, where X, Y and Z are the operations names;

- Durations must all be in the same time unit;

- If an operation has no successors or predecessors a "-" must be inserted in the respective cell.

Operation ID	Name	Successors	Number of Successors	Duration	Predecessors
OP1	Execution of electrical co	OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	12	9,32	-
OP2	Flange assembly	OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	11	0,60	OP1
OP3	System and respective a	OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	10	0,45	OP1; OP2
OP4	Vacuum execution	OP5; OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	9	8,25	OP1; OP2; OP3
OP5	Gas charge	OP6; OP7; OP8; OP9; OP10; OP11; OP12; OP13	8	0,87	OP1; OP2; OP3; OP4
OP6	Removal of the system pr	OP7; OP8; OP9; OP10; OP11; OP12; OP13	7	0,57	OP1; OP2; OP3; OP4; OP5
OP7	Electrical test	OP8; OP9; OP10; OP11; OP12; OP13	6	2,63	OP1; OP2; OP3; OP4; OP5; OP6
OP8	Finishes including paintin	OP9; OP10; OP11; OP12; OP13	5	1,52	OP1; OP2; OP3; OP4; OP5; OP6; OP7
OP9	Tagging (includes measu	OP10; OP11; OP12; OP13	4	0,20	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8
OP10	Water heater transfer to p	OP11; OP12; OP13	3	4,30	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9
OP11	Card boxes application	OP12; OP13	2	2,65	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10
OP12	Tagging for expedition	OP13	1	0,13	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP11
OP13	Packages strapping	-	0	1,05	OP1; OP2; OP3; OP4; OP5; OP6; OP7; OP8; OP9; OP10; OP12

APPENDIX D: REL Matrix

	Pallets & Metalwork Storage	Finished Product Storage	Lab	Raw Material & Components Storage	Water Heaters Production	Assembly & Packaging	Heat Pumps Production	Storage & Assembly Of Other Products	Tank Storage	Heat Pumps Components Storage	Packaging Storage
Pallets & Metalwork Storage		A	U	U	U	A	U	U	U	U	U
		(1, 4)	-	-	-	(1, 4)	-	-	-	-	-
Finished Product Storage			U	E	U	A	U	A	U	O	O
			-	(3)	-	(1, 4)	-	(1, 4)	-	-	-
Laboratory				U	O	O	O	O	U	U	U
				-	-	-	-	-	-	-	-
Raw Material & Components Storage					A	I	U	A	U	U	U
					(1, 4)	-	-	(1, 4)	-	-	-
Water Heaters Production						A	U	U	E	U	U
						(1, 3, 4)	-	-	(1, 4)	-	-
Assembly & Packaging							A	U	U	U	A
							(1, 3, 4)	-	-	-	(1, 4)
Heat Pumps Production								U	U	A	X
								-	-	(1, 4)	(2)
Storage & Assembly Of Other Products									U	U	U
									-	-	-
Tank Storage										U	U
										-	-
HP Components Storage											U
											-
Packaging Storage											