Optimizing Machine Utilization to increase Production Capacity

Francisco João Manata Dias

Dissertação de Mestrado

Orientador na FEUP: Prof. Carlos Bragança Oliveira

U.PORTO
FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Mestrado Integrado em Engenharia Mecânica

2017-06-09

"Good company in a journey makes the way seem shorter."

Izaak Walton

Resumo

No âmbito da dissertação para conclusão do Mestrado Integrado em Engenharia Mecânica da Faculdade de Engenharia da Universidade do Porto, foi proposta a realização de um projeto na empresa GROHE, uma fabricante de torneiras a nível internacional que se encontra representada em Portugal pela sua fábrica em Albergaria-a-Velha.

O projeto surge da necessidade da criação de uma ferramenta de cálculo de capacidade que, optimizando a alocação da produção de uma gama de produtos às máquinas de cada departamento do processo produtivo, consiga minimizar o tempo total de produção. Pretende-se como objectivo principal, perceber se, para realizar a procura desse mix de produtos, existe ou não capacidade na fábrica/departamento.

A necessidade desta ferramenta advém do facto de que a que vinha sendo utilizada não ser expedita e não apresentar resultados optimizados que fossem fiáveis e se aproximassem da realidade. A cada nova procura que surgisse, o chefe de operações (utilizador da ferramenta) demorava cerca de duas horas a atualizar o ficheiro para perceber se os departamentos tinham ou não capacidade para produzir o que fora estabelecido pelo planeamento. Isto deve-se ao facto da ferramenta necessitar de muitas iterações manuais que estavam a levar muito tempo a executar. Tudo isto para apresentar resultados que não eram optimizados. Era, então, necessário criar uma ferramenta o mais automática possível que realize essa otimização e que leve pouco tempo a atualizar.

Para realizar o que era pretendido, foram recolhidos os tempos de ciclo de produção de todos os produtos nas máquinas onde estes podem ser realizados, os tempos de setups das máquinas, os dados de qualidade da produção e todos os dados necessários para realizar o cálculo de capacidade para cada departamento. Foi criado um modelo de otimização em Programação Linear para ser implementado no Excel. Como o número de dados a ser processado é muito elevado, o Solver do Excel não era suficiente. Devido a isto, houve a necessidade de instalar um novo add-in de otimização que comportasse a quantidade de dados presente na base de dados. O software utilizado denomina-se OpenSolver. Para correr o otimizador de forma automática, foram criadas macros que foram associadas a botões na ferramenta.

Os resultados fornecidos pela ferramenta são:

- quantidade de produtos a produzir em cada máquina;
- percentagem de ocupação de cada máquina apenas em produção e comparação com o valor médio de 2016;
- percentagem de ocupação de cada máquina para concluir a produção.

Este conteúdo permitiu ao diretor de operações chegar a conclusões rapidamente com uma ferramenta que permitia ser atualizada em menos de metade do tempo da anterior. A ferramenta também se revelou bastante útil para os chefes dos departamentos que começaram a planear com a informação dada por esta.

A ferramenta começou a ser utilizada por todos os responsáveis dos departamentos tornando-se uma ferramenta standard que facilitou a interligação e comunicação entre os chefes de departamento e diretor de operações. Esta também serviu de suporte para os responsáveis de cada departamento demonstrarem ao departamento de planeamento que, mesmo otimizando o plano, não tinham capacidade para produzir o que era planeado quando esta situação se sucedia.

A ferramenta criada apresenta melhores resultados, com mais utilidades e em menos tempo do que a ferramenta anterior. Conclui-se que os objectivos para a ferramenta foram atingidos com sucesso.

Abstract

Within the scope of this dissertation, which concludes the Masters degree in Mechanical Engineering at the Faculty of Engineering of the University of Porto, a thesis project was proposed at the international faucet manufacturer GROHE, on its industrial site in Albergaria-a-Velha, Portugal.

This project is based on the need for a tool to perform capacity calculation that can minimize the total time of production time, optimizing the production allocation of a product mix to the machines of each department of the productive process. The main objective is to understand if, to match the demand of that product mix, there is (or isn't) capacity available in the factory/department.

The need for this tool comes from the fact that the previous one was not being prompt enough and was not presenting optimized results that could be reliable and close to the reality. For each new demand that came up, the operations manager – the main user of the tool – would need a couple of hours to update the file to understand if the departments had capacity to produce what was determined by the planning department. This is mostly due to the large number of manual iterations needed, which took a long time to perform. Additionally, the obtained results were not optimized. It was then, necessary to develop a new tool that was as automatic as possible, able to execute the optimization and quicker to update.

To achieve the intended objectives, data was collected on the production cycle times of every product of the machines where these could be produced. Data was also collected regarding the machines setup times, quality assessment and any other necessary data to perform the capacity calculation for each department. An optimization model was developed using Linear Programming and implemented in Excel. As the amount of data to be processed was high, Excel's Solver could not simulate the problem. There was the need to install a new optimization add-in that could bear the amount of data present in the data base. The software utilized is OpenSolver. To run the optimizer in an automatic manner, macros were created that were associated to buttons present in the tool. With this implementation, the results that can be obtained using the tool are:

- number of bodies to produce in each machine;
- percentage of occupation of each machine, considering only the production time and a comparison with the average value of the same indicator in 2016;
- percentage of occupation of each machine to conclude the production.

This allows the operations manager to quickly reach conclusions since the tool can be updated in half the time of the previous one. The new tool is also useful to the heads of the departments, who started to perform the production plan using the information provided.

The tool started to be utilized by all the heads of departments, becoming a standardized tool that facilitates the interconnection and communication between the heads of departments and the operations manager. This also served as a support tool for the departments responsible to demonstrate to the planning department that, even if the plan is optimized, the installed capacity is not sufficient to produce what was initially planned. Planning above the department's capacity was frequent in the company.

The developed tool provides better results, is faster and more useful than the previous one. It can thus be concluded that the objectives initially set for the project were successfully achieved.

Acknowledgements

I would like to thank my advisor in GROHE, engineer Joaquim Almeida for guiding and supporting me during the duration of this project. The help and support given were crutial for the accomplishment of the proposed aims and objectives. I would also like to thank the Heads of Departments engineers João Fonte, Victor Fernandes, Luís Rodrigues, Sérgio Machado and Celso Maia for the constant availability to help me whenever needed and for spending their own time testing the developed tool. Without them this project would not have had success.

I would like to thank my FEUP advisor, Prof. Carlos Bragança for always being available to guide and help me when it was necessary. His advices and guidance were essential for the execution of this project. My thanks also to Prof. Manuel Pina Marques of FEUP for helping me develop and implement the optimization model and for pointing me to the optimization software I used.

I would especially like to thank my parents, Vitor and Guida, for always supporting me and always putting my education as one of their lives' priorities. For this I am forever grateful. I would also like to thank my brother, sister, grandparents and the rest of my family for encouraging me during all my education process.

Thank you also to my GROHE office colleague, Paula Loureiro for the daily company and help provided. I also thank all the company employees who in any way helped with the execution of the project or cheered me up during the day, especially engineers João Rios and Tiago Martins and collaborators Catarina Costa and Porcina Oliveira. I would like to thank my internship colleagues José Miguel Costa and Luís Amaral for their friendship and companionship.

Finnaly I would like to thank all my friends in Porto and Aveiro for the moral support and the contagious joy.

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1 Introduction

This chapter describes the problem that was initially addressed and setup by the project and the importance of reaching good results for the company, GROHE. This company is also presented by describing the most important moments of its history.

In order to guide and organize the realization of the dissertation, the main aims and objectives are listed as well as the method that was planned to be used.

Finally, for better understanding of the dissertation, a brief reading guide is also provided.

1.1 Problem and motivation

The main topic of this dissertation is machine utilization optimization in order to increase effective capacity in a long-term perspective. The main goal is to develop and implement a numerical tool (preferably in Microsoft Excel) that can allocate which product will be produced in which machine, given the demand for the next month (or any other significant time frame), the machine cycle times, setup times and other relevant production data, with the objective of minimizing the total time.

From GROHE's side, the main goal is to reduce the number of shifts needed to accomplish the demand of each department. The company currently works almost every week from Monday to Saturday using four alternating shifts during the three 8-hour slots of the day. In a final and overarching perspective, the objective is to reduce working schedules to Monday to Friday with only three 8-hour shifts per day, significantly reducing labor costs.

The company is currently finding it difficult to plan its production in some of its departments. This is mostly because there isn't a standardized production planning tool for the whole plant and there is no tool that optimizes production time. This is the main reason behind the relevance of this project to GROHE.

As the project must aggregate all the departments of the production, it was set up in the Operations Department which is responsible for coordinating all the production departments.

1.2 GROHE

GROHE AG, is named after its founder and owner Friedrich Grohe, who initially bought Berkenhoff & Paschedag in 1936 and renamed the company in 1948 to Friedrich Grohe Armaturenfabrik. In the early stages of the company, the main focus was on manufacturing sanitary faucets. From 1990 to 2000 the company acquired two other faucet manufacturers, as well as the DAL group in 1994, leader of the flushing technology industry at the time.

Figure 1.1 - GROHE logo

In 1996 GROHE expanded by opening two new factories. One in Klaeng – Thailand – and another one in Albergaria-a-Velha – Portugal – where this project took place. Today, GROHE has five factories in total: three in Germany, one in Portugal and one in Thailand.

The company was recently (2014) acquired by LIXIL Group Corporation, a publicly listed company on the Tokyo Stock Exchange. LIXIL is a Japanese company known for being the global market leader in the sanitary wear industry and Japan's leading provider of housing and building materials.

Figure 1.2 - LIXIL logo

Presently, GROHE is the world's leading provider of sanitary fittings and is dedicated to providing innovative water products.

1.3 Objectives

The need for a better coordination of all the production departments, having more control over each one's productions and minimizing the production time, motivated the construction and development of a production time optimization tool and the realization of this project. The main aims and objectives of the project are the following:

- To understand the production process at GROHE Portugal. It is necessary to have a deep and detailed knowledge of the whole production process to be able to produce a tool that effectively helps the company and can be used;
- To gather and analyze as much data and information as possible. Production data such as machine cycle times, setup times, quality data and lot size, if it available, is strictly necessary to produce an accurate and complete tool;
- To implement the tool in Excel. The company's production is controlled using excel sheets. Consequently, in order to make things simpler for the user, it will be preferentially developed using Excel;
- To create an interface that is easy to work with and is designed to easily accept future changes and upgrades or improvements. New products are frequently included in the production. As such, it should be possible to add them to the tool as well as the corresponding machine cycle times. The program must also allow new machines to be added.

1.4 Structure of the Report

The present report has the following structure:

Chapter 1 – "Introduction" – This chapter introduces the report. The problem, company and objectives are described.

Chapter 2 – "GROHE Portugal" – In this chapter, the production of the company is described in detail. The material flows within the factory and between departments is also described here. Finally, the departments of the supporting structure are shown in the company organizational chart.

Chapter 3 – "Linear Programming Modelling" – This is the first chapter of the theoretical framework of this project. The method behind the development of a Linear Programming model is described in detail here, as is also the procedure of how to implement it in Excel's optimization add-in OpenSolver.

Chapter 4 – "Operations Management" – The most relevant definitions related to the thematic of Operations Management and to the tool develop methods are explained in the fourth chapter of this dissertation.

Chapter 5 – "Capacity and Machine Utilization Calculation – Initial State" – In this chapter, the tool that existed previously is introduced and its work method described.

Chapter 6 – "Optimizing Machine Utilization – Proposed Solution and Results" – This chapter is where the final results and tool are presented. The main differences between the previous tool and the one developed here is also outlined.

Chapter 7 – "Conclusions and Perspectives for Future Work" – This is the last chapter of the dissertation and where the main conclusions of the project are described. The prospective for future work regarding this subject is also pointed out here.

Appendix A – “Manual de Instruções do Programa de Cálculo de Utilização e Capacidade” – This appendix contains the instructions manual that explains how to use the tool. It is written in Portuguese for ease of use by the factory employees.

2 GROHE Portugal

A more detailed presentation of GROHE Portugal is given in this chapter, concerning not only the manufacturing process departments, but also the departments that support manufacturing and are within the company's structure.

The manufacturing process at GROHE Portugal is divided between five departments that stand in the following order in terms of the manufacturing process:

1. Foundry and Core making;
2. Machining;
3. Grinding and Polishing;
4. Electroplating;
5. Assembly.

Figure 2.1 - Manufacturing Process at GROHE.

The Maintenance Department supports all these departments and is responsible of maintaining the machines working in proper conditions and fixing them in case of failure.

GROHE recently added a new range of products with different colors. These colors are produced before the bodies reach the assembly in a department called PVD (Physical Vapor Deposition), which is recent in the factory. Due to this, the PVD department will not be discussed in this report.

The Operations Department leads and manages the manufacturing process and its department.

As each department of the manufacturing process has its own specificities, these will be discussed separately in the following sections.

2.1 Foundry and Core making

The department of Foundry and Core making, as its name describes, is composed of two different sections. It is responsible for the first part of the factory's manufacturing process. In the foundry section, metals that constitute the brass alloy are melted and mixed together in predetermined quantities. The mix is then submitted to a quality control analysis and, in case it passes all requirements, is cast using one of the following two possible casting procedures:

- Low Pressure Die Casting (Figure 2.2);
- Gravity Casting.

Figure 2.2 - Low pressure die casting machine

Ahead of casting the molten metal, it is necessary to make the sand cores that are inserted into the die. At GROHE, there is a specific section in the Foundry and Core making department that fabricates the cores.

The core making section manufactures the sand cores that are used to shape the internal holes and cavities of the faucet's body. A mixture of sand, resin, hardener and a conserving additive is used to obtain the sand cores. The mixture is put into core boxes that with the desired core shape. This is then heated in an oven at a temperature of approximately 220 ºC (Figure 2.3).

Heating the mixture makes the resin's catalyzer accelerate its solidification. Once out of the oven, the cores are burred and inserted in the dies to start the casting process.

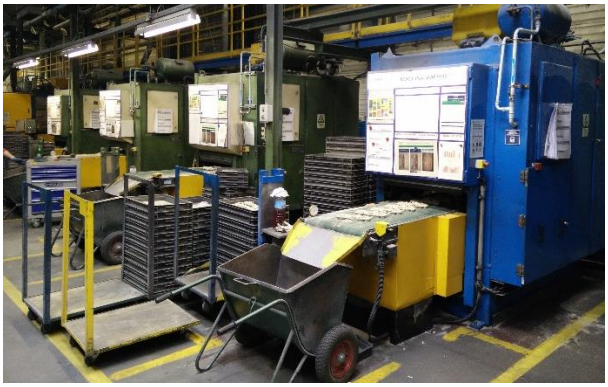


Figure 2.3 - Core making machines

Figure 2.4 - Bodies prepared to go to the Machining department

When the casting is complete, the bodies are taken to cutting machines where the operator cuts off the excess material that results from the casting procedures. The final process of the foundry department is to remove the remains of the sand cores that may still be inside the bodies. This is done with a blender. The bodies are then put into a rotating drum that makes them hit each other loosening the remaining sand from the cores.

Once all this process is complete, the pieces are ready to be sent to the Machining Department (Figure 2.4).

It should be noted that all the bodies that show defects or don't pass the quality control tests are considered scrap. Nonetheless, a significant part of this scrap is reutilized by melting it back into the liquid brass alloy and inserted into the casting process again.

2.2 Machining

Threaded holes with adequate tolerances cannot be done during the casting process. As such, the bodies need to be machined. This is done in the Machining Department using automated processes that are programmed with CNC (*Computer Numerical Control*). One of these programs running is presented in Figure 2.5.

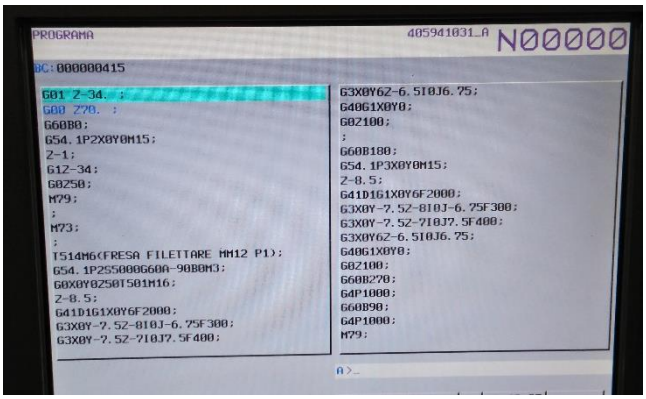


Figure 2.5 - CNC program running in a machine

After all the machining elements are executed in the faucet's bodies, the machined parts are washed and passed through several quality assurance tests. The operators do a visual inspection of the screw threads and holes prior to the body going through water tightness tests to ensure there are no leaks. Again, if the parts fail these tests, they are sent back to the Foundry Department as scrap and inserted back into the process from the beginning.

The machined bodies that pass the referred tests are pushed forward to the Grinding and Polishing Department (Figure 2.6).

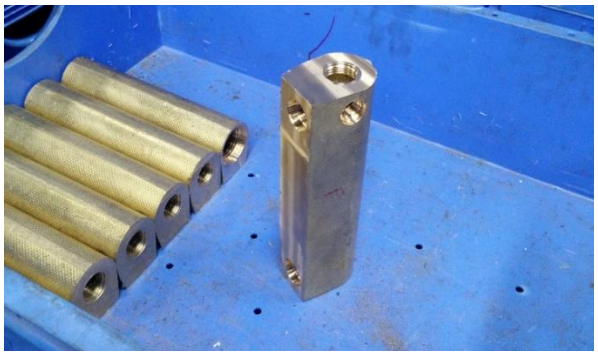


Figure 2.6 - Machined bodies prepared to go to the next department

Between departments, there are "Supermarkets" where the products are put when they are to advance in the process.

2.3 Grinding and Polishing

The surface roughness that comes naturally from the casting process is not acceptable. The Grinding and Polishing department is responsible for giving the bodies the expected external roughness, essential for the final client's approval.

As the name states, this department has two sections – grinding and polishing – both with manual and automatic processes.

The first operation in this department is usually performed by grinding robots (Figure 2.7) that execute the sanding of the accessible surfaces. As there are specific locations in some of the bodies that the robots cannot reach, the next step is done manually by operators with manual grinding machines. In specific situations, some parts may need to be ground completely manually. This might be due to not having yet developed the program to put them in the automatic robots or that these bodies have such irregular shapes that the only way to perform the sanding is manually.

Figure 2.7 - Grinding robot

Once the grinding operations are finished, the bodies go through one other quality inspection where operators search for surface defects. If defects are found and can be corrected, they are marked and the parts sent back to the manual grinding stage to be corrected. Otherwise, if the defects cannot be corrected, the bodies are considered scrap and are sent back for rework.

The surface is not completely treated until it is polished, which gives the bodies a shining effect and a smooth surface. Thus, after grinding, the bodies are sent to polishing machines for the last operation concerning the surface's roughness (Figure 2.8). This part of the process is carried out by two different types of polishing machines that execute most of the surfaces' polishing. If defects are found, operators correct them manually.

Figure 2.8 - Polishing machine

Before advancing to the following department, the bodies are washed and degreased.

These operations are critical for the Electroplating Department. The surface must be perfect so that the electroplating process has optimal adherence.

The bodies are then placed in suspensions and progress to the next department (Figure 2.9).

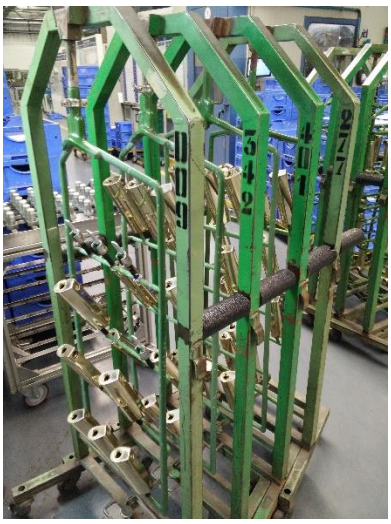


Figure 2.9 - Suspensions carrying the bodies to the next department

The department that follows is where the Electroplating process is executed.

2.4 Electroplating

As with the previous department (see section 2.3), the operations done in the electroplating stage are also related to surface treatment. Here the bodies receive their final treatment before assembly.

As said before, the bodies are sent to the Electroplating Department suspended. These suspensions are put on a lift that gets them up and through an automatic process, in an upper floor, which consists of a series of different chemical baths. The first bath washes and degreases the bodies to ensure maximal adherence to the chemical deposition. Afterwards, the nickel and chromium baths are applied. These treatments improve the corrosion resistance of the bodies giving them a longer life. It also gives the characteristic shinning and chrome color which is the body's final aspect. This automatic process takes around 1h 45min to be concluded.

Once this stage is finished, the suspensions are sent back down in a lift (Figure 2.10), similar to the one that took them up, and go through one other quality inspection. If defects such as inclusions are found, these cannot be fixed by putting the bodies through the galvanic process again. Thus, the nickel and chromium layers must be removed. This reverse process also takes place in the Electroplating Department. Afterwards, the recuperation process of the bodies continues in the Grinding and Polishing - Department, where they reintegrate the manufacturing process once again.

In case there are no defects found in the inspection, the shower and faucet's bodies proceed to the Assembly Department.

Figure 2.10 - Lift bringing down the bodies after the plating process

2.5 Assembly

The last stage to finish all the details on the bodies, is the addition of the printings. Elements such as the GROHE logo or red and blue arrows that indicate how to change the water's temperature are laser engraved by one of the three machines available in the Assembly Department (Figure 2.11). This procedure is done not only in the bodies but also in other components of the faucets or showers.

Figure 2.11 - Printed bodies

After being engraved, the different bodies and components proceed to the assembly lines according to their product stream. In these lines, the final faucets and showers are assembled, packaged and put in pallets ready for shipping (Figure 2.12).

The final quality control tests are performed in this stage. Pressure and sealing tests are executed to ensure the quality of the final product before it is packaged.

Figure 2.12 - Assembly line and its palletization

All the pallets are shipped directly to Germany, where the logistics center is located. From there, the products are distributed for the clients.

2.6 Supporting Structure

Naturally, in the organizational structure of GROHE Portugal, exist other departments to support the production. These departments, which provide all the resources and conditions necessary for the proper functioning of the company, are shown in the company's organizational chart in Figure 2.13.

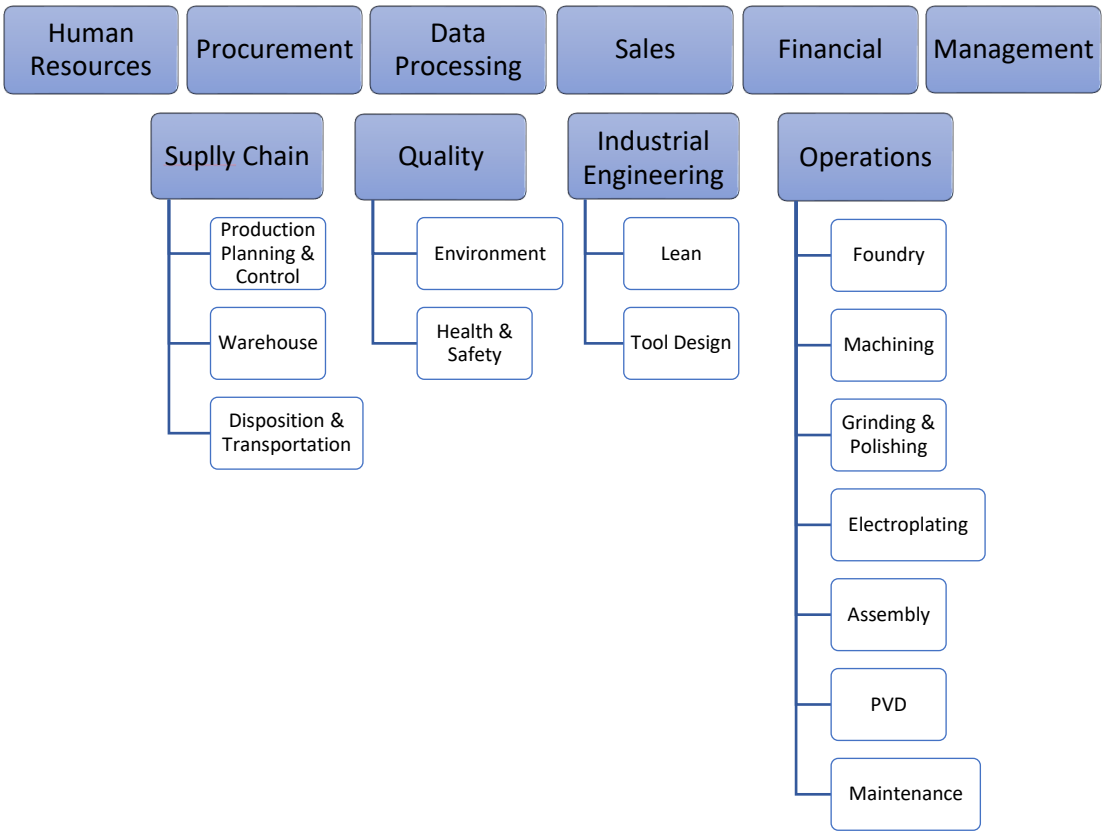


Figure 2.13 - Company's Organizational Chart.

Despite taking place in the Operations Department and consequently on its sub departments, for this project departments such as Quality or Data Processing will be important to gather the information needed to complete the tool and its calculations.

A good connection between the departments that support production is essential for a factory to achieve its production objectives.

3 Linear Programming Modelling

In this chapter, Operations Research (OR) method is presented and applied to solve a specific problem. One of the major steps of OR is to develop or formulate a model that can represent the essence of the problem to solve. The most frequently used type of model is the Linear Programming Model, which is described in this section in detail as it is used in this report. Computer simulation will be used to solve the mathematical model. The software used is an improved add-in of the Excel Solver called OpenSolver (OpenSolver Optimizer) which is programmed using Visual Basic for Applications (VBA). The process used to implement the model in the software using its interface and using VBA code is also explained in this chapter.

3.1 Operations Research and Its Approach

Operations Research (OR), as the name suggests, is the research done on operations. This means that a research is done and applied to problems related to how to conduct, coordinate and lead the operations or activities within a certain organization or factory. OR can be used in a number of different areas such as manufacturing, transportation, planning or health care (Hillier and Lieberman, 2001).

A typical OR study begins with defining and formulating the problem and collecting relevant data. Afterwards, a mathematical model to solve the problem is developed and implemented. This model translates the problem into mathematical relationships. Depending on how complex these relationships are and how they fit existing standard mathematical models, the model, if simple enough, can be analytically solved. In more complex cases, there is the possibility to simplify the model and use either a heuristic approach or computer simulation. Once the model is implemented, the solution is easy to obtain. However, the optimum solution must be studied in order to understand how it will be affected if the model's parameters change (this is also known as a sensitivity analysis). The next step is to check if the results make sense and if the solution is acceptable. One way to do this is to compare the output with historical data if it is available. The last step of this approach is to implement the solution and translate it into operating instructions (Taha, 2007).

From all the steps mentioned, the one which has a mathematical background is the development of the model. This step requires both knowledge and practice and will be explained in the following sections.

3.2 Constructing a Mathematical Model

A model can be defined as an idealized representation of a real problem. Models are used in multiple areas of science, engineering and business to help simplify the analysis of real life problems.

To solve an already defined problem using the OR approach, a mathematical model that represents it must be developed. This mathematical model is also an idealized representation of the real problem, translated into mathematical symbols and expressions. In a business problem, such as the one investigated in this report, the model is characterized by a system of equations and inequalities that describe the essence of the problem in hands (Hillier and Lieberman, 2001). A model consists of three parts:

- Defining the decision variables;
- Setting the constrains;
- Defining the objective function.

Decision variables are the quantifiable decisions that are going to be made and whose values are to be determined (for example, $x_1, x_2, \ldots, x_n$). By creating equations and inequalities that

represent the restrictions on the values of the decision variables, the constrains are set (for example, $x_1 + x_2 + \ldots + x_n \leq 300$). The appropriate measure of performance is expressed as a function of the decision variables and it is called the objective function (for example, production output: $PO = 6x_1 + 3x_2 + \ldots + 2x_n$). It is often wanted to optimize the objective function by either minimizing or maximizing it. The coefficients and constants that appear in the constrains and in the objective function are the parameters of the model (Hillier and Lieberman, 2001). These are obtained when discussing the problem and gathering the relevant data.

There are many different types of mathematical models, but one that is particularly important due to its frequent use and applicability is Linear Programming.

3.3 Linear Programming

A Linear Programming (LP) model is one of the possible mathematical models used in the OR approach. The best way to explain it is by exemplification using simple problems. Despite the simplicity of the following problem, which will only use two decision variables, it should be enough to understand LP's basic concepts and to establish the foundation for more complex models that are used to solve real life problems, such as the one discussed and analyzed in this report.

One of the most difficult parts of developing models is establishing logic operations between constraints and decision variables. To understand how these operations can be constructed and how they work, a series of examples will be presented in what follows.

3.3.1 Two Decision Variable Problem

The problem that follows was proposed by Taha (2007).

Problem:

"Reddy Mikks produces both interior and exterior paints from two raw materials, M1 and M2. The following table lists the basic data of the problem:

Table 3-1 - Reddy Mikks problem data

	Tons of raw material per ton of		**Maximum daily availability (tons)**
	Exterior paint	**Interior paint**	
Raw material, M1	6	4	24
Raw material, M2	1	2	6
Profit per ton ($1000)	5	4	

A market survey indicates that the daily demand for interior paint cannot exceed that for exterior paint by more than 1 ton. Also, the maximum daily demand for interior paint is 2 tons.

Reddy Mikks wants to determine the optimum product mix of interior and exterior paints that maximizes the total daily profit."

The first step is to specify the decision variables. This must be done carefully as it is essential when constructing a model. A proper definition of these variables makes the description of the objective function and the constraints much faster and straightforward. In the problem, it is necessary to determine the daily amounts of interior and exterior paints to be produced. The decision variables are, then:

- x_1 – Tons of exterior paint produced daily
- x_2 – Tons of interior paint produced daily

Next, to define the objective function it is important to understand if the objective is to maximize or minimize the function. In the case here described, the company wants to maximize daily profit. Thus, it is a maximization problem. As the profit per ton is given for both exterior and interior paints (5 and 4, respectively), the objective function comes:

$$\text{Maximize } P = 5x_1 + 4x_2 \tag{3.1}$$

where P is the profit.

The final step is to set the constraints. In this problem, there are 4 types of constraints:

- Availability of the raw materials M1 and M2;

It is known that, to produce a ton of the exterior paint, 6 tons of M1 are necessary and to produce one ton of the interior paint, the equivalent usage is 4 tons. It is also known that the maximum availability of M1 is 24 tons per day. Thus, the daily usage, in tons, of M1 to produce both paints must be lower than 24, that is:

$$6x_1 + 4x_2 \leq 24 \tag{3.2}$$

A similar analysis can be done for raw material M2, leading to:

$$x_1 + 2x_2 \leq 6 \tag{3.3}$$

- Market limit

Quoting the text in the problem: "(…) the daily demand for interior paint cannot exceed that for exterior paint by more than 1 ton". This means that the demand of interior paint less the demand of exterior paint must be lower than 1 ton, which can be written as:

$$x_2 - x_1 \leq 1 \tag{3.4}$$

- Demand limit

The maximum daily demand for interior paint is 2 tons, which means that:

$$x_2 \leq 2 \tag{3.5}$$

- Nonnegativity

Although nothing is said in the problem regarding this restriction, it is implicit that both decision variables cannot be negative. Thus:

$$x_1 \geq 0 \tag{3.6}$$

$$x_2 \geq 0 \tag{3.7}$$

The model is now complete. Any combination of values of the decision variables, that satisfy all the 6 constraints, is considered a feasible solution. For example, if $x_1 = 2$ tons per day and $x_2 = 2$ tons per day, all the constraints are satisfied so it is a feasible solution. If any of the constraints is not satisfied, the solution is considered infeasible. The objective, when solving the model, is to find the best feasible solution, reaching optimization (Taha, 2007).

There are several ways to achieve the best solution. Among these are the graphical method and the Simplex method. It is also possible to compute the model using an optimization software. As computer simulation is an essential part of the tool that was developed and is the only method used to solve the developed mathematical model (this will be explained later in Section 3.4).

3.3.2 Generic Format

In larger scale problems, to simplify the writing of the mathematical model, it is useful to build the model using generic expressions, whenever possible. For example, in the previous model, the objective function, the availability constraints and the nonnegativity constraints can be written in a generic manner:

Objective Function: maximize $P = \sum_{j=1}^{n} c_j\, x_j$

where x_j are the decision variables and c_j are the profit margins of producing the paint j.

Availability constraints: $\sum_{j=1}^{n} a_{ij}\, x_j \leq b_i\, , i = 1, 2, \ldots, m$

where a_{ij} are the tons of raw material i used to produce the paint j and b_i are the availabilities in tons of raw material i.

Nonnegativity constraints: $x_j \geq 0\, , j = 1, 2, \ldots, n$

When writing models on paper, the generic format should always be used to simplify the model's reading and implementation for solving (Taylor III, 2006).

3.3.3 Logic Operations using Linear and Integer Programming

In some problems, it is necessary to establish logic relations between constraints or decision variables. To perform this, LP may not be enough. Logic operations, such as disjunction, need binary decision variables. The binary decision variables are related to Integer Programming as these can only be equal to either 1 or 0. This section will review some logic relations and explain how to translate them into an optimization model.

Disjunction

The logic relation disjunction sets that, between two constraints, only one of them can be active. Mathematically, it can be stated as:

$$f(x) \leq 0 \ \vee \ g(x) \leq 0 \tag{3.8}$$

The following constraints can be used to translate this logic operation to a linear programming model:

$$\begin{cases} f(x) \leq \delta M \\ g(x) \leq (1-\delta) M \end{cases} \tag{3.9}$$

where δ is a binary variable and M is a "large" number which has to be greater than the possible values of both $f(x)$ and $g(x)$. If the system (3.9) is analyzed in detail, it is possible to evaluate if it sets the disjunction. If $\delta = 1$ the system (3.9) then becomes:

$$\begin{cases} f(x) \leq M \\ g(x) \leq 0 \end{cases} \tag{3.10}$$

Only the second constraint is imposed. The first one doesn't work as a constraint because regardless of the result of $f(x_i)$ the inequality is always true. The opposite happens if $\delta = 0$:

$$\begin{cases} f(x) \leq 0 \\ g(x) \leq M \end{cases} \tag{3.11}$$

Now, only the first constraint is active. $g(x)$ can assume any value.

If instead of constraints of less than ($\leq$), the problem implies "greater than" constraints ($\geq$), the logic used changes. For example, if the problem states that:

$$f(x) \geq 0 \ \vee \ g(x) \geq 0 \tag{3.12}$$

The constraints of the LP model become:

$$\begin{cases} f(x) \geq -\delta M \\ g(x) \geq (\delta - 1) M \end{cases} \tag{3.13}$$

To check the validity of the logic relation, set the value of δ to 0 or 1.

$$\delta = 0,$$

$$\begin{cases} f(x) \geq 0 \\ g(x) \geq -M \end{cases} \tag{3.14}$$

And,

$$\delta = 1,$$

$$\begin{cases} f(x) \geq -M \\ g(x) \geq 0 \end{cases} \tag{3.15}$$

$f(x) \geq -M$ is always true regardless of the value of $f(x)$. Consequently, it cannot be used as a constraint (Hooker and Osorio, 1999).

Implying conditions

(1) Implying conditions is also possible when modelling with LP. For example, it is necessary to imply that if a decision variable x_i is greater than 0, a binary variable δ_i must be equal to 1. Otherwise δ_i is equal to 0. This type of condition is useful, for example, for counting how many decision variables assume positive values. It translates to:

$$x_i > 0 \Rightarrow \delta_i = 1 \tag{3.16}$$

To input the condition (3.16) in the LP model, write the constraint:

$$x_i \leq \delta_i M \tag{3.17}$$

which sets that every time x_i is greater than 0, δ_i as to be equal to 1 making the inequality true.

(2) There are other types of conditions that can be imposed with LP modelling. For instance, the following condition needs to be translated into a LP model:

$$A > B \Rightarrow C \geq D \tag{3.18}$$

To impose the condition (3.18), both one auxiliary binary decision variable δ and a "large" number M are necessary. As before, this large number has to be greater than any of the values that the conditions may assume. To model the implying condition can be defined as:

$$A - B - \delta M \leq 0 \tag{3.19}$$

$$C - D - (1 - \delta)M \leq 0 \tag{3.20}$$

The combination of the two inequalities (3.19) and (3.20) defines the condition to imply. To verify this, it should be noted that to imply $a \Rightarrow b$ correctly, if a is true then b is also true and if b is false then a must also be false. On the one hand, if $A > B$ then to verify (3.19), $\delta = 1$. This makes the (3.20) $C \geq D$ which is what was meant to be proved. On the other hand, if $C < D$ then, to make (3.20) true, $\delta = 0$. Then (3.19) forcibly becomes $A \leq B$, which is again what was meant to be proved.

There are more conditions that may be implied using LP modelling. These use the same bases as the two demonstrated above and combine the use of binary variables and large numbers in a similar way (Winston, 2009).

3.4 Computer Simulation

To reach the solution of a large-scale problem with an already developed model, it is recommended to use a software that allows to simulate the problem. One of the software package available in the market to solve optimization problems is the Microsoft Excel Solver add-in. This software has, however, a limited number of decision variables. As the optimization problem studied in this report has a large number of constraints and decision variables – more than what the Excel Solver can cope with – the software used was OpenSolver instead.

OpenSolver is a free add-in for Excel that works and solves problems using linear, integer and nonlinear programming modeling with no limitations on the number of decision variables or constraints.

To demonstrate how to use OpenSolver, the model of the problem analyzed in section 3.3.1 will be used again. This problem will be implemented using both the graphics user interface (GUI) of the software and VBA.

3.4.1 Insert the model using the Interface

The GUI of OpenSolver is similar to the GUI of the Excel Solver. To open it, OpenSolver must already be installed. The OpenSolver options can be accessed through the Data option of the Excel quick access toolbar it will appear the OpenSolver options (Figure 3.1).

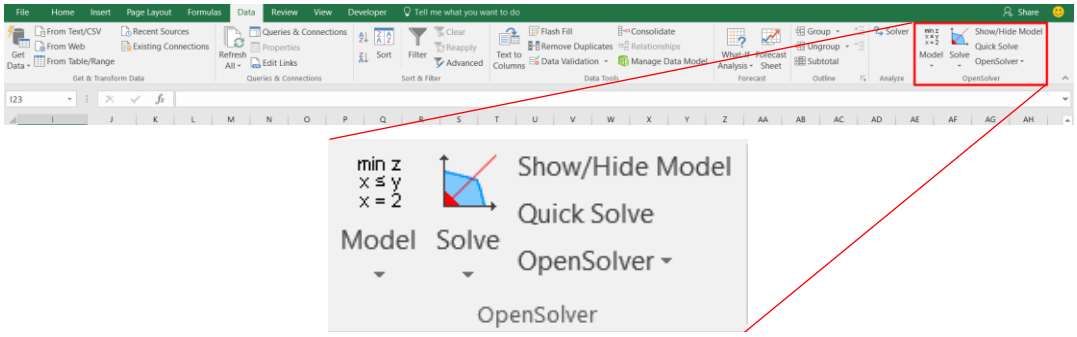


Figure 3.1 - OpenSolver options

To insert the model, choose the option “Model” and the interface will open, where it is possible to set the decision variables, the constrains and the option to either minimize or maximize. The GUI of OpenSolver is shown in Figure 3.2. It is intuitive and similar to the regular Solver’s GUI.

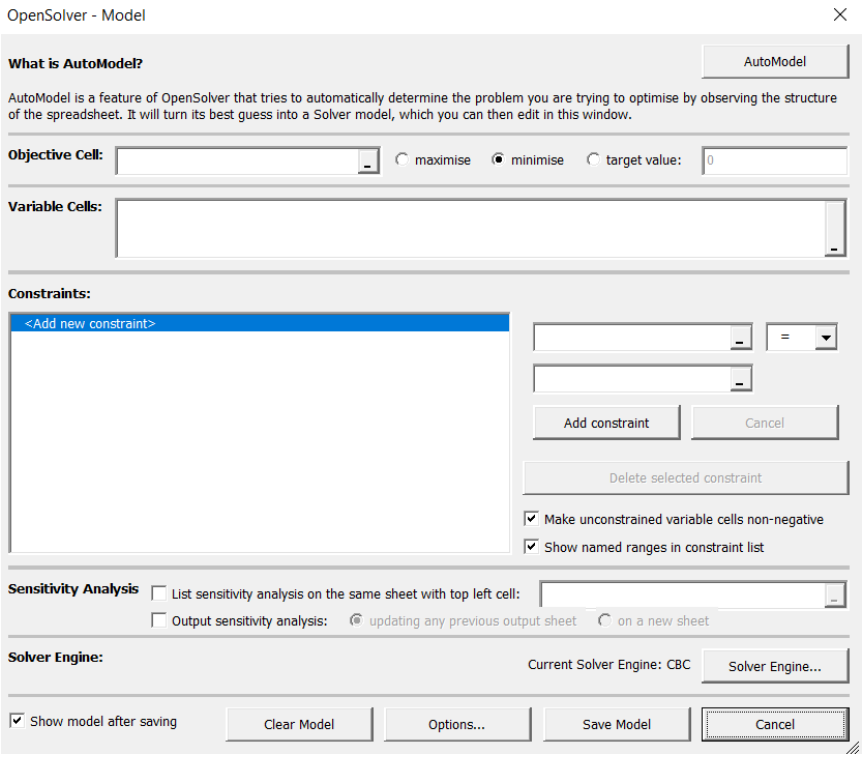


Figure 3.2 - OpenSolver interface

Before inserting the model, the problem must be adequately written in Excel. The first step is to define the problem's data in Excel in an easily readable way (Figure 3.3).

	A	B	C	D	E	F	G
1			x1	x2			
2			Tons of raw material per ton of				
3			Exterior Paint	Interior Paint	Total	limits	
4		M1	6	4	0	24	
5		M2	1	2	0	6	
6		Market limit	-1	1	0	1	
7		Demand limit	0	1	0	2	
8							
9		Profit per ton ($1000)	5	4	0		
10							
11			x1	x2			
12							
13							

Figure 3.3 - Problem data table in Excel

The decision variables are defined in cells C12 and D12. The range of cells from C4 to D7 are the parameters on the left side of the constraints. The column named "Total" has the functions of the left sides of the constraints and the objective function. The column named "limits" contains the limit values of each constraint. The Excel formulas of the column "Total" are listed in Table 3-2Table 3-2.

Table 3-2 - Functions translated to Excel formulas

	Function	Excel formula	Excel cell
M1	$6x_1 + 4x_2$	=SUMPRODUCT(C4:D4;$C$12:$D$12)	E4
M2	$x_1 + 2x_2$	=SUMPRODUCT(C5:D5;$C$12:$D$12)	E5
Market limit	$-x_1 + x_2$	=SUMPRODUCT(C6:D6;$C$12:$D$12)	E6
Demand limit	$0x_1 + 1x_2$	=SUMPRODUCT(C7:D7;$C$12:$D$12)	E7
Profit (objective)	$5x_1 + 4x_2$	=SUMPRODUCT(C9:D9;$C$12:$D$12)	E9

The SUMPRODUCT function is a simple way of adding multiplications. The first formula of Table 3-2 is equivalent to "=C4*$C$12+D4*$D$12" which is the exact mathematical expression of the function.

To insert the objective function and the decision variables it is necessary to write the cells in the corresponding fields. This can also be done by pressing the button "-" at the end of the field and choosing the cells directly from the Excel sheet.

To insert the constraints, write the cells in the fields (top field is left side and down field is the right side of the constraint), choose the relation between the both sides and press "Add constraint" (Figure 3.4).

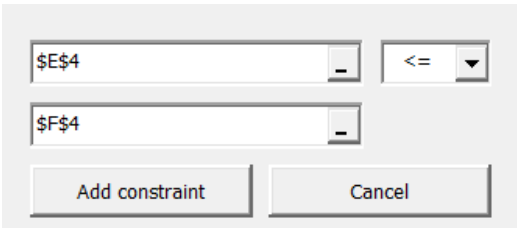


Figure 3.4 - Adding constraints (1)

As all the constraints have the same relation, they can be set up as shown in Figure 3.5.

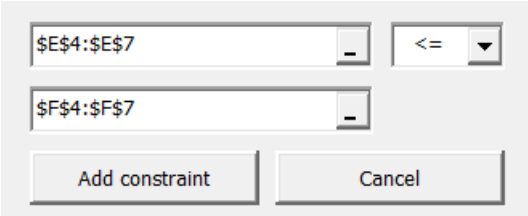


Figure 3.5 - Adding constraints (2)

To set up the nonnegativity constraints it is necessary to check the box “make unconstrained variable cells nonnegative” or write them as a normal constraint. Once all the constraints are inserted, the model is complete (see Figure 3.6) and the button “Save model” should be pressed. If the model is non-linear or there is the need to change the solving method, press the button “Solver Engine…” and choose another engine. The one selected in this example (CBC, see Figure 3.6) is used to solve linear problems.

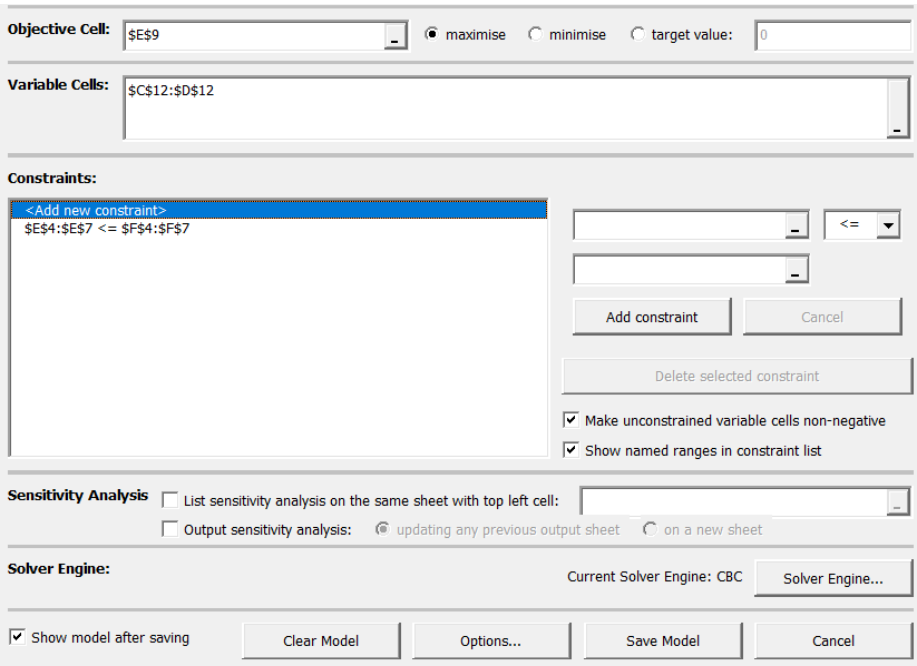
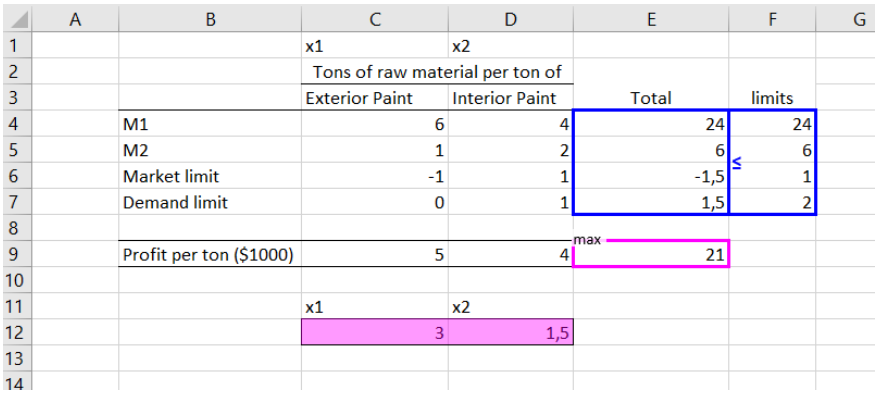


Figure 3.6 - Model inserted in the interface

Once the model is saved, its the representation will appear in the spreadsheet as boxes of different colours. To hide these boxes, press the “Show/Hide Model” button once in the OpenSolver area of the toolbox. To solve the problem, press “Solve” and the results should be shown automatically on the spreadsheet (Figure 3.7).



	A	B	C	D	E	F	G
1			x1	x2			
2			Tons of raw material per ton of				
3			Exterior Paint	Interior Paint	Total	limits	
4		M1	6	4	24	24	
5		M2	1	2	6	≤ 6	
6		Market limit	-1	1	-1,5	1	
7		Demand limit	0	1	1,5	2	
8					max		
9		Profit per ton ($1000)	5	4	21		
10							
11			x1	x2			
12			3	1,5			
13							
14							

Figure 3.7 - Results in the spreadsheet

In case of different solve options are necessary, press the button “Options…”at the bottom of the GUI. The Options window appears as shown in Figure 3.8 where it is possible to set the parameters that define the behavior of the solver.

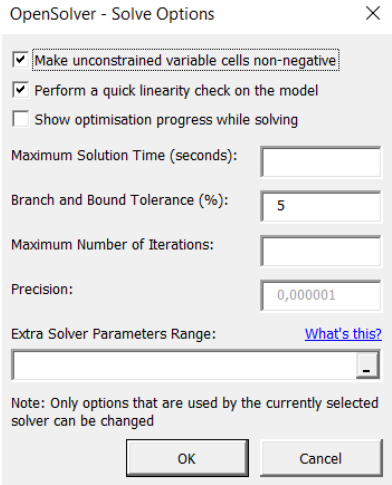


Figure 3.8 - Window of solve options

The steps to implement a problem have been presented using OpenSolver’s interface. However, when working with macros, it is useful to know how to set and actualize the model using VBA code.

3.4.2 Insert the model using VBA code

It is possible to use VBA code when there is the need to automatically set up and update the model on OpenSolver (OpenSolver API Reference). OpenSolver itself is programmed with VBA so its programmers, made it possible to set all the parameters and options using code.

Several OpenSolver functions can be setup and performed using VBA code. The ones that are shown here represent the most relevant for this report. Again, the Reddy Mikks problem will be used as an example, using the same Excel spread sheet as before.

Set Objective Function

To set the objective function in an OpenSolver model, the VBA functionthat should be used is SetObjectiveFunctionCell. The parameters of this function are listed in Table 3-3.

Table 3-3 - Set objective function with VBA function

Function/Sub	Public Sub SetObjectiveFunctionCell (ObjectiveFunctionCell As Range, Optional sheet As Worksheet)	
Name	**Type**	**Description**
ObjectiveFunctionCell	Range	The cell to set as the Objective Function
sheet	Worksheet	The worksheet containing the model (defaults to active worksheet)

Regarding the problem, the code that should be used is:

```
Call SetObjectiveFunctionCell (E9)
```

Set Decision Variables

To set the decision variables, the VBA function is SetDecisionVariables with the parameters listed in Table 3-4.

Table 3-4 - Set decision variables with VBA function

Function/Sub	Public Sub SetDecisionVariables (DecisionVariables As Range, Optional sheet As Worksheet)	
Name	**Type**	**Description**
DecisionVariables	Range	The range to set as the Decision Variables
sheet	Worksheet	The worksheet containing the model (defaults to active worksheet)

In the problem's case, the code is then:

```
Call SetDecisionVariables (C12:D12)
```

Add Constraints

To add a constrain in OpenSolver, the VBA function is AddConstraint and the parameters used for this function are listed in Table 3-5.

Table 3-5 - Add constraint with VBA function

Function/Sub	Public Sub AddConstraint(LHSRange As Range, Relation As RelationConsts, Optional RHSRange As Range, Optional RHSFormula As String, Optional sheet As Worksheet)	
Name	**Type**	**Description**
LHSRange	Range	The range to set as the constraint LHS
Relation	RelationConsts	The relation to set for the constraint. If Int/Bin, neither RHSRange nor RHSFormula should be set.
RHSRange	Range	Set if the constraint RHS is a cell/range
RHSFormula	String	Set if the constraint RHS is a string formula
sheet	Worksheet	The worksheet containing the model (defaults to active worksheet)

LHS and RHS represent the left and right hand sides of the constraint respectively.

The following 6 options can be used to set the relation parameter:

- EQ – equal to
- GE – greater or equal to
- LE – lower or equal to
- INT – integer

- BIN – binary
- AllDiff – All different

The code to set the constraints in the current example is:

```
Call AddConstraint (E4:E7, LE, F4:F7)
```

Update Constraints

If the range of the constraints changes, by adding or removing constraints, it is possible to update either (or both) the left and right hand sides of the constraints' range. For example, the last constraint is removed. When running the solver again it would be useful for it to automatically update the range of the constraints. Basically, this function deletes one constraint and inserts another one in the same position in case the constraint changes.

To update a constraint in an OpenSolver model, the VBA function is UpdateConstraint and the parameters are listed in Table 3-6.

Table 3-6 - Update constraint using VBA function

Function/Sub	Public Sub UpdateConstraint(Index As Long, LHSRange As Range, Relation As RelationConsts, Optional RHSRange As Range, Optional RHSFormula As String, Optional sheet As Worksheet

Name	**Type**	**Description**
Index	Long	The index of the constraint to delete
LHSRange	Range	The range to set as the constraint LHS
Relation	RelationConsts	The relation to set for the constraint. If Int/Bin, neither RHSRange nor RHSFormula should be set.
RHSRange	Range	Set if the constraint RHS is a cell/range
RHSFormula	String	Set if the constraint RHS is a string formula
sheet	Worksheet	The worksheet containing the model (defaults to active worksheet)

The code that updates the constraints in the current example is:

```
Call UpdateConstraint (1, Range (table (3, table.Columns.Count-1), table (table.Rows.Count, table.Columns.Count-1)), LE, Range (table (3, table.Columns.Count), table (table.Rows.Count, table.Columns.Count)))
```

It should be noted that the "table" in the code must be previously dimensioned as an Object by writing the following code:

```
Range("C4").Select
Set table = ActiveCell.CurrentRegion
```

The "table" is defined within its boundaries. Also note that the code "table.Columns.Count" stands for the last column of the "table" and "table.Rows.Count" stands for the last row of the "table".

With this code, it is possible to add and remove constraints of the same format, without the need to open the solver interface.

Run OpenSolver

To obtain the result of the simulation the add-in has to be run. The function to perform that action on VBA and its parameters are listed in Table 3-7:

Table 3-7 - Run OpenSolver using VBA function

Function/Sub	Public Function RunOpenSolver(Optional SolveRelaxation As Boolean = False, Optional MinimiseUserInteraction As Boolean = False, Optional LinearityOffset As Double=10.423, Optional sheet As Worksheet) As OpenSolverResult	
Name	**Type**	**Description**
SolveRelaxation	Boolean	If True, all integer and boolean constraints will be relaxed to allow continuous values for these variables. Defaults to False
MinimiseUserInteraction	Boolean	If True, all dialogs and messages will be suppressed. Use this when automating a lot of solves so that there are no interruptions. Defaults to False
LinearityOffset	Double	
sheet	Worksheet	The worksheet containing the model (defaults to active worksheet)

The code that runs the OpenSolver is:

```
Result = Call RunOpenSolver()
```

The result of the function can be one of the following:

- Pending = -4
- AbortedThruUserAction = -3
- ErrorOccurred = -2
- Unsolved = -1
- Optimal = 0
- Unbounded = 4
- Infeasible = 5
- NotLinear = 7
- LimitedSubOptimal = 10

An optimal solution is found when the function is equal to zero, so if the user interaction is minimized there should be one cell that contains the result so that the user can know the type of result obtained.

4 Operations Managements

As part of the Operations Department of the company, this project and the tool deal with some definitions and calculations that are directly related to Operations Management. Its definition and the definitions of the most important concepts related to this subject that may, in any way, appear or be relevant to the understanding of the project and tool, will be discussed in this chapter.

4.1 Definition

Operations Management, according to Kumar and Suresh (2009), is "(…) the process whereby resources, flowing within a defined system, are combined and transformed in a controlled manner to add value in accordance with policies communicated by management." The three keywords/key expressions of this definition are resources, system and transformed to add value. Thus, to understand the concept of Operations Management, it is important to also understand what is behind these ideas.

Resources, which can be human, material or capital are inputs to the manufacturing process. Human resources are the workforce of a company. All the employees of a company working towards the same objective are the most important assets within the company's resources. Material resources are the physical facilities and material owned by the company. Examples of material resources are the plant's equipment, inventories and supplies. Finally, capital is a store of value and can be presented in form of stock, bonds and/or taxes and contributions. A system is the arrangement of components designed to achieve objectives according to what was previously planned. A business system is a subsystem of a large social system and within the business system there are subsystems such as engineering, finance or operations. It is important that the hierarchical scale is recognized in Operations Management. An integrative approach between the business subsystems will more easily lead to the optimization and achievement of the system's goals. A schematic representation of an operations system is shown in Figure 4.1. The objective of combining the resources available in the system is to obtain final goods with higher value than the goods that entered the system. Value adding activities are done to transform the initial product into the final product. The more value adding activities, the highest the value of the final product (Kumar and Suresh, 2009).

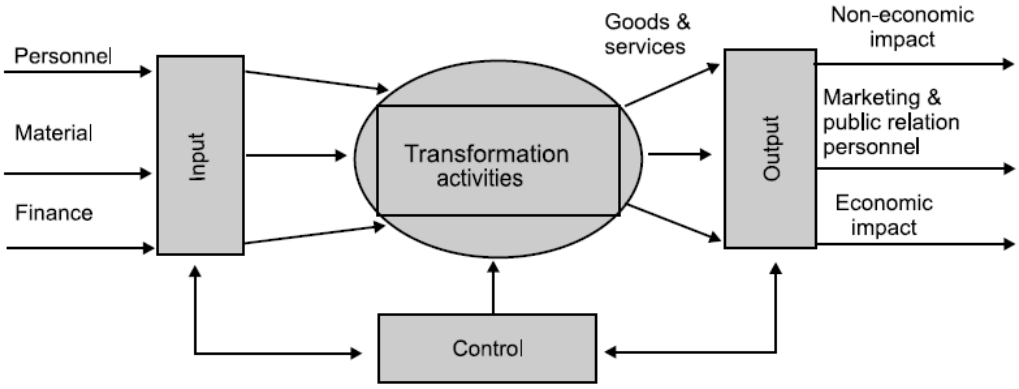


Figure 4.1 - Representation of an operations system in Kumar and Suresh, 2009, "Operations Management"

4.2 Objectives

One important objective of Operations Management is to process inputs into outputs under a production plan that effectively uses resources, capacity and knowledge available in the production facility. A sub-objective, directly related to this paper, is to maximize the utilization

of resources in an efficient way to try to achieve the factory's maximum capacity. Another major objective of operations managers is to deliver "the right thing at the right price at the right time" to achieve customer satisfaction. A good customer service is essential for any business to achieve growth and its financial goals (Kumar and Suresh, 2009).

4.3 Capacity and Capacity Calculation

As the title of the paper suggests, capacity and its measurement are essential parts of the project to develop. Thus, these definitions should be explained and this is done in this section.

According to Porter (2009) capacity can be described as "(…) the measure of an organization's ability to provide customers with services or goods in the amount requested at the time requested.". The services or goods to deliver can also come as demand.

In a factory environment, the capacity definition adapts to the throughput or number of units the facility can produce in a given period of time. Capacity decisions determine capital requirements and consequently a large portion of the factory's fixed costs (costs associated to human resources or machine maintenance). Besides, the factory's capacity determines if the demand will be satisfied. Projecting the right facility size that has the right capacity with high levels of utilization is critical. Factories that are too small, may not reach a good customer service and can even lose entire markets. Factories that are too large, may have equipment with under-optimal utilization ratios or that are simply not used, which will add cost to the production (Heizer and Render, 2011).

4.3.1 Design and Effective Capacity

Design capacity is the maximum theoretical output of a system in a specific period. To achieve the design capacity in a certain period, the production needs to be under ideal conditions during that time. As this never happens, the design capacity will never be reached. For the company to truthfully know if their capacity is sufficient for the demand, effective capacity is used.

Effective capacity is the capacity a firm can expect to achieve given the following factors:

- Product mix to process;
- Production planning and scheduling methods;
- Quality standards;
- Machine setups required and its duration variability;
- Unplanned machine stoppages or breakdowns;
- Machine unexpected maintenance.

In most situations, and having these factors into account, the effective capacity will be lower than the design capacity. Optimizing them and their inherent processes by continuous improvement will make the effective capacity come closer to the design capacity. For operations managers to know what the system's performance is, in terms of capacity, and if it is evolving in a positive way, the following two known measures are useful:

- Utilization – the percent of design capacity that is achieved.

$$Utilization\ (\%) = \frac{Actual\ Output}{Design\ Capacity} \times 100 \tag{4.1}$$

- Efficiency – the percent of effective capacity that is achieved.

$$Efficiency\ (\%) = \frac{Actual\ Output}{Effective\ Capacity} \times 100 \tag{4.2}$$

The key to improving these measures is, in many cases, found in correcting quality problems, in effective training, maintenance and scheduling (Heizer and Render, 2011).

4.3.2 Capacity Analysis/Calculation

It should be taken into consideration that facilities that present various work areas/machines/departments have their own capacities. Knowing this, capacity analysis is necessary as it determines the throughput capacity of each workstation in a system to eventually reach the capacity of the total system.

A key concept used in all capacity analysis is the role of constraint or bottleneck. A bottleneck is an operation that is the limiting factor or constraint. In a production system, the bottleneck has the lowest effective capacity of any operation of that system. This will limit the system's output to the bottleneck's output. It should be noted that all systems have their own bottleneck and it needs to be identified so that it can be managed. As an example, by analyzing Figure 4.2 it is possible to identify that the bottleneck is operation B, as it takes longer to produce one unit than the other operations of the system. The time necessary for a machine to produce one unit/part is the cycle time, which can also be described, in a more general way, as the time between finishing to consecutive units (Heizer and Render, 2011).

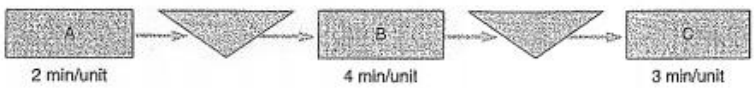


Figure 4.2 - Three Station Assembly Line in Heizer and Render, 2010, "Operations Management"

The same rule is applied when the system is a factory and the blocks are departments. The department with the lowest capacity is considered the bottleneck. The bottleneck, considering that the factory is the system, may change with demand and time period. This happens due to the variability of factors presented in Section 4.3.1.

The bottleneck is the crucial constraint of any system. As such, managers should pay special attention to it. Heizer and Render (2011) lists four ground rules to manage bottlenecks:

- "Release work orders to the system at the pace set by the bottleneck's capacity" – The concept of drum, buffer and rope are introduced to help with the scheduling of bottleneck and non-bottleneck operations. Briefly, the drum sets the pace of the production (provides the schedule) which is the bottleneck's pace. The buffer is the location where the inventory is accumulated before the bottleneck so that it is always operating at the drum's pace. The rope provides the communication necessary between operations, to pull units through the system;
- "Lost time at the bottleneck represents lost capacity for the whole system" – This means that the bottleneck must be kept busy;
- "Increasing the capacity of a non-bottleneck station is a mirage" – When the capacity of a non-bottleneck station is increased it as no impact on the system's capacity. If a non-bottleneck station works faster, it will only make WIP (work in process) inventory increase. This is not desirable as it has associated costs.
- "Increasing the capacity of the bottleneck increases capacity for the whole system" – This should be the focus of managers. Always try to improve the bottleneck's capacity.

Managing the bottleneck(s) is a necessary task because, as said before, it cannot be eliminated. All systems have at least one bottleneck and it is essential that it is identified for capacity analysis as it sets the capacity of the system. Improving the bottleneck's capacity will consequently improve the system's capacity.

5 Calculating Capacity and Machine Utilization – Initial State

The tool previously used by the Operations Department will be presented in this chapter, to evaluate if each department has enough capacity to match the demand for a specific production time period. The reasons why the project to develop a new tool was created is also explained in the present chapter. Some of the language that the company uses to express and evaluate data will be explained as it was kept in the developed tool. The existing tool is implemented in Microsoft Excel.

5.1 Existing tool

The objective of the tool is to evaluate if the departments have enough capacity for a specific demand. To achieve this, the percentage of time used for each machine to produce the product mix demanded is calculated and must be lower than 100%. The company calls this percentage of time utilized by each machine "Utilization". To calculate machine utilizations, the data used as input is the following:

- Body reference and stream – there is a code to represents each body digitally;
- Bodies produced per shift per type of machine – the number of bodies each machine can produce in the duration of a shit. The value represents the production of a single product during the shift. The shifts last 8 hours but only 7.5 hours are considered (0.5 hours for meal break);
- Demand – the required output of the factory;
- % of scrap+rework – percentage of bodies rejected as scrap or that have to be reinserted in the process after corrections (rework). This value changes with product and department;
- Productivity – percentage of time that the machines are effectively producing;
- Available shifts per type of machine – number of shifts available for production for each machine or type of machine.

These are the data inputs for the calculations. Whenever there is a new demand because the period changed, the cycle time of a machine to produce a body changes, there are quality improvements or productivity changes, the input values should be updated. Keeping the database updated provides results that are closer to reality.

Auxiliary calculations need to be done to calculate machine utilization. These are listed and explained next:

- Quantity to produce – the quantity to be produced of each product is not equal to its demand. As the bodies go through the production process, they must pass quality tests. In case this doesn't happen, the bodies are rejected. The quantity of bodies that don't pass quality inspections is given by the % of scrap+rework. Therefore, the quantity to produce is calculated as:

$$Quantity\ to\ produce = Demand * (1 + \%(scrap + rework)) \tag{5.1}$$

- Necessary shifts to complete the production – the machine where each product is produced is chosen. The quantity of bodies produced per shift by the machine is known. However, it has to be taken into account that there are always machine stoppages for maintenance, change of tools, breakdowns, etc. This is represented by the productivity input. The shifts necessary to complete production are:

$$Necessary\ shifts = \frac{Quantity\ to\ produce}{Bodies\ produced\ per\ shift * Productivity} \tag{5.2}$$

- Machine Utilization (%) – this is the result wanted. It is the sum of the necessary shifts for all the products that are done in the same machine and the shifts available for production in that machine:

$$Machine\ Utilization\ (\%) = \frac{\sum Necessary\ shifts}{Available\ shifts} \times 100 \qquad (5.3)$$

The aspect of the tool is presented in Figure 5.1 and Figure 5.2. The tool is similar for all the departments.

	A	B	C	D	E	F	G	H	I	J	K
1									% Productivity	80%	
2				20,00	days						
3				jan/16							
4	STREAM	Body	Body_Cube	Demand	Quantity to produce	Necessary shifts	Machine	Bodies/shift	% scrap after machining	% Productivity	Option
5	TH	64593340	64593	14 300	14 892	143,19	BULA 1_2_5	130	4,1%	80%	MEPSA , BULA_5
6	CA	400792138	400792	7 848	8 038	33,49	BULA 1_2_5	300	2,4%	80%	MEPSA
7	CA	401166138	401166	784	828	3,45	BULA 1_2_5	300	5,6%	80%	MEPSA
8	CA	404645038	404645	0	0	0,00	BULA 1_2_5	225	58,3%	80%	MEPSA
9	LB	7222038	07222	0	0	0,00	BULA 3_4	200	2,8%	80%	
10	TH	64593340	64593	10 500	10 935	105,14	BULA 3_4	130	4,1%	80%	

Figure 5.1 - Excel tool used initially (input data table)

	Available shifts	Necessary shifts	% Utilization
Mepsa	780	774,44	99,3%
BULA_1_2_5	180	180,14	100,1%
BULA_3_4	120	116,51	97,1%
Copiativas	90	83,70	93,0%
KUKA_1	60	58,26	97,1%
KUKA_2_3	120	119,57	99,6%
Manual	180	63,30	35,2%
Total Robots	1350	1333	98,7%

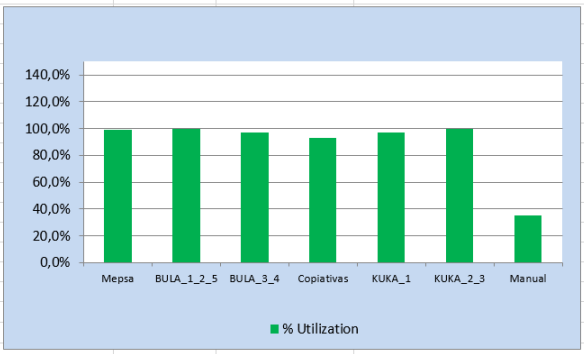


Figure 5.2 - Excel tool used initially (results)

The first column of Figure 5.1 indicates the stream. The existing streams are:

- TH – Thermostatic
- LB – Basin/Bidet
- BR – Blue and Red
- BC – Bath/Showers
- CZBX – Kitchen (Low)
- CZAL – Kitchen (High)
- CO – Costa
- CA – Classic
- AT – Atlanta
- VE – Concealed Valves
- UN – Others

The operations manager work is to allocate the production of bodies to the machines. This can be complicated when the number of references is high and when machines have different capacities/cycle times to produce the same body.

The column with the heading "Body_Cube" serves as a reference to get the values of scrap and rework from the quality cube where all the information regarding the Quality Department is.

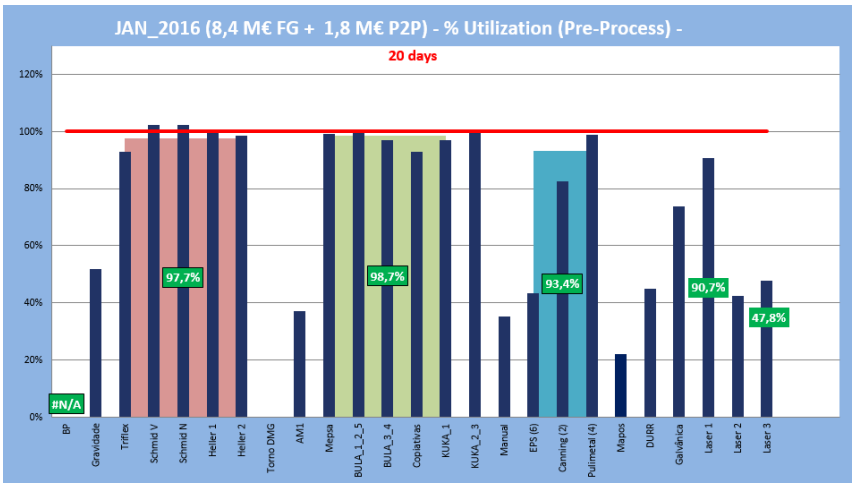


Figure 5.3 - Resume of machine utilizations

To sum up all the utilization results from the worksheets of all departments, there is a worksheet called “RESUME”. The data is presented in a graphic format (Figure 5.3).

5.2 Improvements to implement

The tool that was used was taking too long to work with. The problem was that if the operations manager, who created and worked with the tool, choose to produce the bodies in the machines with the highest capacity for each body, they would have machines with utilizations that surpass the 100% limit. As such, this becomes an iterative process. Every time this happened, it was necessary to change the machine in which some products where produced and check again the final utilization. Even with their huge experience in doing this, the calculation for all the departments was taking several hours to be finished and the results most probably would not be optimized.

The tool also had the problem that the production of a body could not be done by two different machines or type of machines. As an example, if the production of the body 64953340 shown in Figure 5.1 is required or wanted to be done half in BULA_5 and the other half in one of the MEPSAs, the tool does not allow that as it is only possible to choose one of them in the “Machine” column. This makes the tool not flexible increasing the problem identified in the paragraph above.

Another problem of the existing tool is that it does not allow to know/calculate the utilization of an individual machine because the utilizations are calculated for groups of machines of the same type. This may lead to errors because there are products that are not produced in all the machines of the same type. This may also cause an excess of utilization in specific machines without the knowledge of the user. For instance, in Figure 5.4 there is an excerpt of the machining department’s worksheet in which it is possible to see that some bodies produced in one of the four Triflexs cannot be produced in all the four. This is due to the machines not having the program to perform the operations for that product or simply because the machines of the same type can have little differences that do not allow all the machines to execute the exact same machine operations. Lack of standardization between machines of the same type happens in more than the Machining Department. As an example, the MEPSA machines in the Grinding Department, despite having the theoretical possibility of performing the same operations and grind the same products, as they are all equal, do not do it because the programs are not available in all the machines. Some MEPSA machines have programs for products that others don’t. In conclusion, the calculations of the machine utilization should be done separately to avoid the errors described above.

STREAM	Body	Body_Cube	Demand	Quantity to produce	Necessary shifts	Machine	Bodies/shift	% Scrap	% Productivity	Option
BC	11897038	11897	0	0	0,00	Triflex	750	2,8%	90%	TR1, TR2 e TR4
BC	64131038	64131	224	240	0,44	Triflex	600	7,2%	90%	TR1, TR2 e TR4 (700)
BC	64132138	64132	484	542	1,00	Triflex	600	12,0%	90%	TR1, TR2, TR3 e TR4
CA	64378038	64378	193	204	0,65	Triflex	350	5,4%	90%	TR2
CZBX	64390038	64390	773	953	1,93	Triflex	550	23,3%	90%	TR1, TR2,TR3 e TR4
BC	64418038	64418	266	283	0,66	Triflex	480	6,5%	90%	TR2 e TR4 (500)

Figure 5.4 - Previous tool, Machining worksheet

This tool does not take into account the number of setups per machine and the time they take to be completed. This is a mandatory improvement to the tool as the setups, in some departments, can take up to 2 hours. Setups have an implicit influence on the departments capacity because they occupy machine time. These, instead of producing, are stopped to perform a setup, decreasing the time available for production. The introduction of setups to the tool will approximate it to reality.

Besides the improvements that were previously explained and that have a direct influence on the capacity analysis and how close it is to reality, there are also improvements that are related to the applicability of the new tool.

The tool here presented is missing some of the values to correctly calculate the utilization of the Laser Print machines. It only includes printed bodies and the Laser Printers also print components such as levers and caps. Therefore, the calculated utilizations are not correct and the inputs for all the components should be added.

There is also the need to create a worksheet that calculates the utilizations for the assembly lines of the Assembly Department, as these calculations are not in the file with the previous tool.

One of Excel's major issues is working with files constructed by other people or constructing a file that has to be shared. As the organization of one person can be completely different from another, sharing documents can sometimes be problematic. This Excel sheet was easy to read but there was no guidance or intuitive manner of understanding how it worked and how to change its input values. That is because the tool was not being shared. However, the new one will be, as it is meant to be used by the heads of all production departments and so it must be as user friendly as possible.

These are all the possible improvements identified to create the new tool. The most important improvement – and the justification for this project – is the creation of a semi-automatic method of optimizing what the operations manager has been doing manually. Distributing the production by the machines in an optimized way will, in theory, save time and increase the effective capacity of each department and of the factory in general.

The new developed tool is presented in the following chapter.

6 Optimizing Machine Utilization – Proposed Solution and Results

The created solution and its results will be presented in the current chapter. Firstly, it will be explained, by steps, how the tool was developed. Following this, the outputs that are possible to obtain by utilizing the tool are shown and described. Finally, the applicability of the tool and the results it achieved are presented.

Here it will not be explained how to work with the tool. To do that, an Instructions Manual was written. This manual is presented in Appendix A and is written in Portuguese because the people who are going to read it and work with the tool more frequently, at least for now, are the heads of the production departments in the Albergaria plant, in Portugal.

6.1 New tool development

The main objective of the project was to develop a new capacity calculation tool. This tool has to be able to optimize machine utilization. This is done by distributing the production by the machines by minimizing the number of shifts. Doing this will give the managers the information they need to be able to evaluate if the departments have (or don't have) the capacity to match the demand for that particular period.

The steps taken to produce the program are listed below and will be analyzed individually further ahead.

- Collecting the list of references of the bodies that are produced;
- Collecting the cycle times for every machine/process of each department;
- Collecting the setups times;
- Collecting quality data;
- Modelling the problem using LIP (Linear and Integer Programming);
- Implementing the model in Microsoft Excel;
- Developing the program in VBA to make the tool adjustable to changes.

List of Products' References

At GROHE, each produced body has its own reference so they can be identified by the informatics system as a number. As the bodies advance in the manufacturing process and department, their reference changes so that it is possible to track them during the whole process. Moreover, there are some bodies that start with the same reference and, in the middle of the process, due to going through different operations, originate different products which consequently have different references. In addition to this, each final body as its own reference in the quality cube (the quality cube is where the information regarding the scrap and rework rates are) which is usually the first 5 or 6 digits counting from the left of the final body reference. Due to all these factors, it was necessary to create a tree table of references that had all the information of the body's references throughout the process (Figure 6.1).

Body	Stream	Eletroplating	Machining	Foundry	Ref Cube
400755038	CZBX	400755038	400755031	400755029	400755
400756138	CZBX	400756138	400756131	400756129	400756
400792138	CA	400792238	400792231	400792229	400792
400833038	LB	400833038	400833031	400833029	400833
400865038	LB	400865038	400865031	400865029	400865
400909240	TH	400909238	400909031	400909029	400909
401166138	CA	401166038	401166031	400792229	401166
401268038	BC	401268038	401268031	401268029	401268
401283038	BC	401283038	401283031	401283029	401283
401289038	BC	401289038	401289031	401289029	401289
401460038	CZBX	401460038	401460031	400756129	401460
401774038	CZBX	401774038	401774031	401774029	401774

Figure 6.1 - Excerpt of the reference tree table.

As can be easily verified in Figure 6.1, the only thing that usually changes in the references when moving forward in the process are the last 3 digits. When the bodies are cast their reference ends in “29”. After going through the machining operation their reference will end in “31”. When the bodies have been grinded and polished and gone through the plating process, the references end in “38”. Finally, if the bodies have to go to the laser printer, their reference will end in “40”. In conclusion, all the final bodies’ references should end in “38” or “40”. The only exception to this rule are the concealed valves that are just casted and machined, ending in “31”. The third digit from the right often changes with corrections of the product. It starts with 0 and increases when corrections are applied.

An example of products that have the same reference after being cast and change afterwards are 400756138 and 401460038. Their process changes in the Machining department. This table is very important because of these cases. With this in mind, it is now possible to aggregate the production of two or more products with different final references but with the same reference in a certain production department.

Collecting Cycle Times

In the previous tool, the calculations of the time spent in production were done using the number of bodies produced in a shift. The production cycle times were used to perform the same calculations in the new tool. In addition to being a more accurate measure, cycle times were essential to the development of the optimization model. As an example, the table with the cycle times of the Machining Department is presented in Figure 6.2.

Body	Machined Body	Stream	Triflex1	Triflex2	Triflex3	Triflex4	Schmid1	Schmid2	Schmid3	Schmid4	Heller1	Heller2	DVK	Minimill
406176040	406176031	LB					124	124						
406179040	406179031	LB			82	82								
406187140	406187131	LB	69	69	69	69			45	45	138			44
406194038	406194031	BC				116								
406208140	406013131	TH	97		97	97	71	71						
406209140	406012131	TH					81	81				122		
406218140	406218131	TH					81	81				131		
406219140	406013131	TH	97		97	97	71	71						
406233140	406012131	TH					81	81				122		
406234140	406012131	TH					81	81				122		
406296040	402905131	TH			51	47								
406335040	400909031	TH			79	77								
406348040	406348031	LB					124	124						
406416140	406416131	TH					79	79						
406756038	406756031	CZBX	75	75	75	75								
406777038	0	LB		45		45								
406778340	406778331	LB	69	69	69	69			45	45				44
407058040	407058031	TH	52		52	52						103		
407061040	407061031	TH	80											
407345040	407345031	LB	96	96		92			121	121				30

Figure 6.2 - Part of the table with cycle times per product per machine of the Machining Department.

A table similar to the one in Figure 6.2 was created for every department that needed optimization. To identify if the department needed the optimization tool, it was verified if, to produce the same product, there was more than one option/machine with different cycle times. If the cycle times were equal, regardless of the machine, the optimization was not necessary. The departments/sub-departments where it was concluded that optimization of the allocation of the production was necessary were:

- Foundry;
- Machining;
- Grinding;
- Polishing;
- Laser Print.

The Electroplating, Core making and Assembly departments did not need the tool as their capacity occupation calculation was direct. In the Electroplating Department, there is only one production line which has the same production cycle time, no matter the product. The 6 machines that produce the cores for casting, are all equal and have the same cycle time. The

same happens with the 5 operators that cut the cores. It is considered that they all can cut the same number of cores in the same time. In the Assembly Department, there is no differentiation between the assembly lines of the same stream. Consequently, the calculation of the capacity is trivial. The worksheets of these departments will be presented further ahead in Section 6.2.

Collecting Setup Times

A setup occurs every time a production of a certain product in a machine stops and another product has to be initiated in the same machine. It is possible to deduce that the duration of the setups depends on the machine, the product that was being produced and the product that is going to be produced next. The ideal manner to include the setups in the calculation of machine utilization would be to have a matrix for each machine with the average setup time for every possibility of products that were produced before (in the rows) and that were to produce next (in the columns). There are about 200 final products at GROHE, which leads to a matrix with approximately 40000 inputs (200*200). The result would be 50 (number of machines of all the departments approximately) matrixes with 40000 cells each. Besides the huge amount of inputs, there was also no available data to fill these matrixes so it was in fact impossible to move on with the ideal mode of adding the setups to the calculation.

The alternative was to use the average setup time of each machine regardless of the products that were leaving and going to production. This measure, although introducing some error, makes the calculations and the model much simpler. To calculate the average setup time of each machine, it was given the following data per machine:

- Percentage of total time spent in setups in 2016;
- Total time available for production in 2016;
- Number of setups done in 2016.

It was estimated that the values for one year should be enough to get a good approximation. The average then becomes:

$$Avereage\ setup\ time = \\ = \frac{Percentage\ of\ time\ in\ setups * time\ available\ for\ production}{Number\ of\ setups} \tag{6.1}$$

Collecting Quality Data

Quality data is divided in two aspects: scrap and rework. The bodies considered as scrap have an incorrigible defect that was detected in the quality tests. These bodies are melted and start the process again in the Foundry Department. Bodies in which defects were detected but can be corrected, are put through rework. Measures to recover these bodies are taken so they can return to the manufacturing process as further ahead in the production line as possible.

Quality has a big influence in capacity occupation. Having high quality standards like GROHE, implies that only very good quality parts advance in the process. This can sometimes lead to large percentages of scrap and rework, which will decrease the capacity to manufacture the final product. Daily efforts are done to fight quality issues of the process to reduce the quantity of bodies that are considered scrap or have to go through rework.

To perform the capacity calculation for each department separately, it is necessary to know that the values of scrap and rework many not be the same for all the departments. The scrap and rework data will be presented as percentages and are available for each product. These values represent the percentage of extra production that will have to be done so that, at the end of the process, the demand quantity of finished goods is achieved.

The values were taken from the quality cube where all the information regarding quality is kept. The cube is basically a data base and it can only be accessed from inside the company's

informatics system. The scrap and rework percentage values are presented as "Scrap/Rework Rate vs Assembled parts". The input to the cube that changes depending the department for which the data is wanted is where the defects are detected. In some departments, there is no need to include the rework percentages as they do not have rework possibility. Table 6-1 sums up the quality values that are used in each department.

Table 6-1 - Quality input data for each department.

Department	*Scrap and/or Rework*	*Detected Departments*
Foundry	Scrap	Foundry; Machining; Grinding/Polishing; Eletroplating; Assembly
Machining	Scrap	Machining; Grinding/Polishing; Eletroplating; Assembly
Grinding	Scrap	Grinding/Polishing; Eletroplating; Assembly
Polishing	Scrap and Rework	Eletroplating; Assembly
Electroplating	Scrap and Rework	Eletroplating; Assembly
Assembly/Laser Print	Scrap and Rework	Assembly

The cube has data since it started to be measured in 2008. However, the used data are more recent because actions to correct quality problems have since been implemented. Using data that old would probably increase the percentages of both scrap and rework, hiding the improvements that have been achieved in this area. To avoid this, only the values from 2016 and 2017 were used.

As an example, the pivot table for the Electroplating and Polishing Departments is shown in Figure 6.3.

Row Labels	Scrap Rate vs Assembled Pieces	Rework Rate vs Assembled Pieces
⊞ 00168	3,06%	33,19%
⊞ 01132	0,73%	
⊞ 01575	12,70%	40,12%
⊞ 02229		
⊞ 03472	0,45%	2,83%
⊞ 04676	1,45%	19,56%
⊞ 04677	6,62%	31,81%
⊞ 05725		
⊞ 05726		31,16%

Figure 6.3 - Quality data pivot table for Electroplating and Polishing Departments.

The references of the bodies without the department termination are listed on the first row of the table in Figure 6.3. As said before, when presenting the list of references, a quality reference without the termination is associated to each body, so that it becomes possible to associate the scrap and rework values to the respective body.

Modelling the problem

The problem to be solved is the following:

Know how much of each product should be produced in each machine in order to achieve the demand for the period and to minimize the total time. The total time is the sum of production duration, setup times and time spent due to other reasons such as possible machine breakdowns or preventive maintenance. For each machine, this should not surpass the time available to produce in the same period which has to be established by the number of shifts.

The model developed to solve it was:

Coefficients:

t_{ij}– Cycle time to produce body *i* in machine *j*

s_j – Average setup time for machine *j*

C – Time available for production

P_i – Quantity of body *i* to be produced

w_j – Percentage of time spent in activities other than production or setups in machine *j*

Decision Variables:

x_{ij} – Integer, number of bodies *i* produced in machine *j*

γ_{ij} – Binary, =1 if the body is produced in machine *j*

Constraints:

Time availability: $\frac{\sum_i(x_{ij}*t_{ij})+s_j\sum_i(\gamma_{ij})}{1-w_j} \leq C$, $\forall_j$

Demand Satisfaction: $\sum_j x_{ij} \geq P_i$, $\forall_i$

Setup Counting: $x_{ij} \leq \gamma_{ij} * M$, $\forall_j, \forall_i$

M is a very big number. It must be greater than any value x_{ij} may assume.

Nonnegativity: $x_{ij} \geq 0$, $\forall_j, \forall_i$

Objective Function:

Minimizing total time: min $\sum_j(\frac{\sum_i(x_{ij}*t_{ij})+s_j\sum_i(\gamma_{ij})}{1-w_j})$

Note that the percentage of time given by w_j is in relation to the time spent in production and setups, not a percentage of the available time to produce.

Implementing the model in Microsoft Excel

Computer simulation was used to solve the modelled problem. The data was transferred in a convenient manner to Microsoft Excel and to perform the optimization, the model was implemented in the OpenSolver add-in. A worksheet was attributed to each department. To introduce how the model was implemented in Excel, the implementation of the Machining Department be used as example.

To perform the optimization, four new tables had to be created. The first table contains the information regarding all the cycle times. Despite already existing a table with this information, another one had to be created in order to perform the optimization. This new table has three

steps incorporated. The first one is to aggregate the demand of the final products that have the same reference in that department. This was done with the help of a pivot table. The second is to attribute infinite cycle times to the cells that were empty in the first table that had the cycle times (Figure 6.2). This is a technique used so that the production is never allocated to machines that are not able to produce that body. As it is impossible to set a cell to be equal to infinite, it is substituted by a large number. The third is to transform the demand into the quantity to produce by adding the quality percentages. The table with the result of these steps of the Machining Department is shown in Figure 6.4.

AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR	AS
Machined Body	**Triflex1**	**Triflex2**	**Triflex3**	**Triflex4**	**Schmid1**	**Schmid2**	**Schmid3**	**Schmid4**	**Heller1**	**Heller2**	**DVK**	**Minimill**	**Demand**	**%Scrap&Rew**	**Quantity to produce**
11897031	36	35	38,1	36	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	10%	0
64131031	37,7	38	38	37,68	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	5%	0
64132131	43	40,6	43,7	44,5	1E+08	1E+08	40	40	1E+08	1E+08	1E+08	1E+08	0	12%	0
64378031	73	75,2	74,6	74,6	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	9%	0
64390031	47,45	49	48	48	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	400	20%	481
64418031	54	55,5	53,5	53,2	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	600	9%	655
64545031	43,5	48,1	45	43,4	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	10%	0
64583231	43	1E+08	41	42	1E+08	1E+08	1E+08	1E+08	1E+08	92,03	1E+08	1E+08	0	4%	0
64590231	41	1E+08	36,1	36,5	1E+08	1E+08	1E+08	1E+08	1E+08	104,6	1E+08	1E+08	0	5%	0
64593231	57	1E+08	55,7	55,8	100,5	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	6000	5%	6283
64637131	53	1E+08	55	55	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	450	15%	518
64677031	38,5	37	38	39	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	12%	0
64773031	48,2	54,5	1E+08	49	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	16%	0
65507231	74,5	1E+08	74,5	74,5	65	65	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1500	7%	1609
65602131	40	37	37	40,8	48,6	48,6	29,65	29,65	73,75	1E+08	1E+08	1E+08	0	4%	0
65604131	1E+08	37	37	1E+08	1E+08	1E+08	30	30	71,25	1E+08	1E+08	1E+08	0	6%	0
65605131	41	38	39,5	40	48,6	48,6	30	30	76,25	1E+08	1E+08	1E+08	0	7%	0
65867131	32	31	32	1E+08	1E+08	1E+08	30	30	1E+08	1E+08	1E+08	1E+08	1000	10%	1099
65868031	1E+08	25,5	1E+08	28,5	1E+08	1E+08	25	25	1E+08	1E+08	1E+08	1E+08	0	7%	0
65869131	52	1E+08	53	52	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	100	16%	116
65872131	57	1E+08	57	58	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	0	28%	0
65873131	1E+08	36	1E+08	1E+08	1E+08	1E+08	29,5	29,5	1E+08	1E+08	1E+08	1E+08	0	7%	0
65876031	1E+08	56	56	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1E+08	1100	7%	1173

Figure 6.4 - Table with the cycle times to use in optimization tool

The second table is where the decision variables x_{ij} are inserted. After running the optimization tool, the production allocated to each machine will appear in this table. Part of the mentioned table of the worksheet that contains the calculations for the Machining Department is shown in Figure 6.5.

AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ
Machined Body	**Triflex1**	**Triflex2**	**Triflex3**	**Triflex4**	**Schmid1**	**Schmid2**	**Schmid3**	**Schmid4**	**Heller1**	**Heller2**	**DVK**	**Minimill**	**Produced Quantity**
11897031	0	0	0	0	0	0	0	0	0	0	0	0	0
64131031	0	0	0	0	0	0	0	0	0	0	0	0	0
64132131	0	0	0	0	0	0	0	0	0	0	0	0	0
64378031	0	0	0	0	0	0	0	0	0	0	0	0	0
64390031	481	0	0	0	0	0	0	0	0	0	0	0	481
64418031	450	0	0	205	0	0	0	0	0	0	0	0	655
64545031	0	0	0	0	0	0	0	0	0	0	0	0	0
64583231	0	0	0	0	0	0	0	0	0	0	0	0	0
64590231	0	0	0	0	0	0	0	0	0	0	0	0	0
64593231	0	0	3427	2856	0	0	0	0	0	0	0	0	6283
64637131	518	0	0	0	0	0	0	0	0	0	0	0	518
64677031	0	0	0	0	0	0	0	0	0	0	0	0	0
64773031	0	0	0	0	0	0	0	0	0	0	0	0	0
65507231	0	0	0	0	0	1609	0	0	0	0	0	0	1609
65602131	0	0	0	0	0	0	0	0	0	0	0	0	0
65604131	0	0	0	0	0	0	0	0	0	0	0	0	0
65605131	0	0	0	0	0	0	0	0	0	0	0	0	0
65867131	0	0	0	0	0	0	0	1099	0	0	0	0	1099
65868031	0	0	0	0	0	0	0	0	0	0	0	0	0
65869131	116	0	0	0	0	0	0	0	0	0	0	0	116
65872131	0	0	0	0	0	0	0	0	0	0	0	0	0
65873131	0	0	0	0	0	0	0	0	0	0	0	0	0
65876031	0	1173	0	0	0	0	0	0	0	0	0	0	1173

Figure 6.5 - Table with the produced quantities of each product in each machine

The third table (Figure 6.6) has the counting of the setups. In it are represented the binary decision variables. To know how many setups are done per machine, the binary decision variables along the machine's column are added together.

EI	EJ	EK	EL	EM	EN	EO	EP	EQ	ER	ES	ET	EU
Corpo Maquinado	Triflex1	Triflex2	Triflex3	Triflex4	Schmid1	Schmid2	Schmid3	Schmid4	Heller1	Heller2	DVK	Minimill
11897031	0	0	0	0	0	0	0	0	0	0	0	0
64131031	0	0	0	0	0	0	0	0	0	0	0	0
64132131	0	0	0	0	0	0	0	0	0	0	0	0
64378031	0	0	0	0	0	0	0	0	0	0	0	0
64390031	1	0	0	0	0	0	0	0	0	0	0	0
64418031	1	0	0	1	0	0	0	0	0	0	0	0
64545031	0	0	0	0	0	0	0	0	0	0	0	0
64583231	0	0	0	0	0	0	0	0	0	0	0	0
64590231	0	0	0	0	0	0	0	0	0	0	0	0
64593231	0	0	1	1	0	0	0	0	0	0	0	0
64637131	1	0	0	0	0	0	0	0	0	0	0	0
64677031	0	0	0	0	0	0	0	0	0	0	0	0
64773031	0	0	0	0	0	0	0	0	0	0	0	0
65507231	0	0	0	0	0	1	0	0	0	0	0	0
65602131	0	0	0	0	0	0	0	0	0	0	0	0
65604131	0	0	0	0	0	0	0	0	0	0	0	0
65605131	0	0	0	0	0	0	0	0	0	0	0	0
65867131	0	0	0	0	0	0	0	1	0	0	0	0
65868031	0	0	0	0	0	0	0	0	0	0	0	0
65869131	1	0	0	0	0	0	0	0	0	0	0	0

Figure 6.6 - Table with setup counting

The fourth table (Figure 6.7) is an auxiliary table that contains the result of $\gamma_{ij} * M$. This table does not give any value adding information to the user but has to be present to allow the implementation of the model in the optimizing software.

EX	EY	EZ	FA	FB	FC	FD	FE	FF	FG	FH	FI	FJ
Corpo Maquinado	Triflex1	Triflex2	Triflex3	Triflex4	Schmid1	Schmid2	Schmid3	Schmid4	Heller1	Heller2	DVK	Minimill
11897031	0	0	0	0	0	0	0	0	0	0	0	0
64131031	0	0	0	0	0	0	0	0	0	0	0	0
64132131	0	0	0	0	0	0	0	0	0	0	0	0
64378031	0	0	0	0	0	0	0	0	0	0	0	0
64390031	1E+08	0	0	0	0	0	0	0	0	0	0	0
64418031	1E+08	0	0	1E+08	0	0	0	0	0	0	0	0
64545031	0	0	0	0	0	0	0	0	0	0	0	0
64583231	0	0	0	0	0	0	0	0	0	0	0	0
64590231	0	0	0	0	0	0	0	0	0	0	0	0
64593231	0	0	1E+08	1E+08	0	0	0	0	0	0	0	0
64637131	1E+08	0	0	0	0	0	0	0	0	0	0	0
64677031	0	0	0	0	0	0	0	0	0	0	0	0
64773031	0	0	0	0	0	0	0	0	0	0	0	0
65507231	0	0	0	0	0	1E+08	0	0	0	0	0	0
65602131	0	0	0	0	0	0	0	0	0	0	0	0
65604131	0	0	0	0	0	0	0	0	0	0	0	0
65605131	0	0	0	0	0	0	0	0	0	0	0	0
65867131	0	0	0	0	0	0	0	1E+08	0	0	0	0
65868031	0	0	0	0	0	0	0	0	0	0	0	0
65869131	1E+08	0	0	0	0	0	0	0	0	0	0	0
65872131	0	0	0	0	0	0	0	0	0	0	0	0
65873131	0	0	0	0	0	0	0	0	0	0	0	0
65876031	0	1E+08	0	0	0	0	0	0	0	0	0	0

Figure 6.7 - Model's auxiliary table

Both tables in Figure 6.6 and Figure 6.7, such as the table containing the production information (Figure 6.5), are only filled after running the solver, as they represent part of the solution. However, the model needs to be inserted in the software so that the tables can show the solution. To do this, the calculations and coefficients that are present in both sides of the constraints and in the objective function must be represented in cells of the worksheet. All this information is present in short in Table 6-2. For each constraint side, there is the Excel's formula, and its location and explanation, if necessary. The location of the expressions and coefficients is not the same for all the departments as these do not have the same number of machines and consequently do not occupy the same space in the worksheet. It should be noted that the example is related to the Machining Department. The same information that is presented for the sides of the constraints is also presented in Table 6-2 for the objective function.

Table 6-2 - Constraint and Objective Function Excel information

Name of the constraint/O.F.	*Side*	*Expression/Coefficient*	*Location in Excel*	*Excel Formula*	*Formula Explanation*
Time availability	L	$\frac{\sum_i(x_{ij} * t_{ij}) + s_j \sum_i(\gamma_{ij})}{1 - w_j}$	CS21:DD21	=(SUMPRODUCT(AE3:AE132; AX3:AX132)+CS51)/ (1-DP9)	The formula is inserted in cell CS21. It is replicated for the rest of the cells until DD21 for all the machines of the department. The Excel's Sumproduct function performs the first sumatory. In cell CS51 are calculations regarding the setups of the machine in cause (second parcel of the sum of the numerator). Represents the total time spent per machine.
Time availability	R	C	CS7:DD7	=CS6*$Z$7	The formula is inserted in cell CS7. It is replicated for the rest of the cells until DD7 for all the machines of the department. CS6 contains the number of shifts available for production on that machine. Z7 is fixed and contains the seconds per shift.
Demand Satisfaction	L	$\sum_j x_{ij}$	BJ3:BJ132	=SUM(AX3:BH3)	The formula is inserted in cell BJ3 and replicated for the rest of the location cells for all the products. Represents the quantity of a product produced by all the machines.
Demand Satisfaction	R	P_i	AS3:AS132	=AQ3*(1+AR3)	The formula is inserted in cell AS3 and replicated for the rest of the products. AQ3 contains the demand for the product and AR3 the percentages of scrap plus rework
Setup Counting and Nonnegativity	L	x_{ij}	AX3:BI132		
Setup Counting	R	$\gamma_{ij} * M$	EI3:FJ132	=EJ4*$EG$2	The formula is replicated for the all the cells of the location. EG2 is fixed and contains the big number.
O.F.: Minimizing Total Time	-	$\sum_j (\frac{\sum_i(x_{ij} * t_{ij}) + s_j \sum_i(\gamma_{ij})}{1 - w_j})$	DF21	=SUM(CS21:DD21)	Represents the sum of the time spent by all the machines.

The input data is transferred into Excel and the model is ready to be inserted in OpenSolver. Using the information of the table that contains the location of the constraints sides calculations or coefficients, it is possible to insert the model in the software using the Add-in's GUI (Figure 6.8).

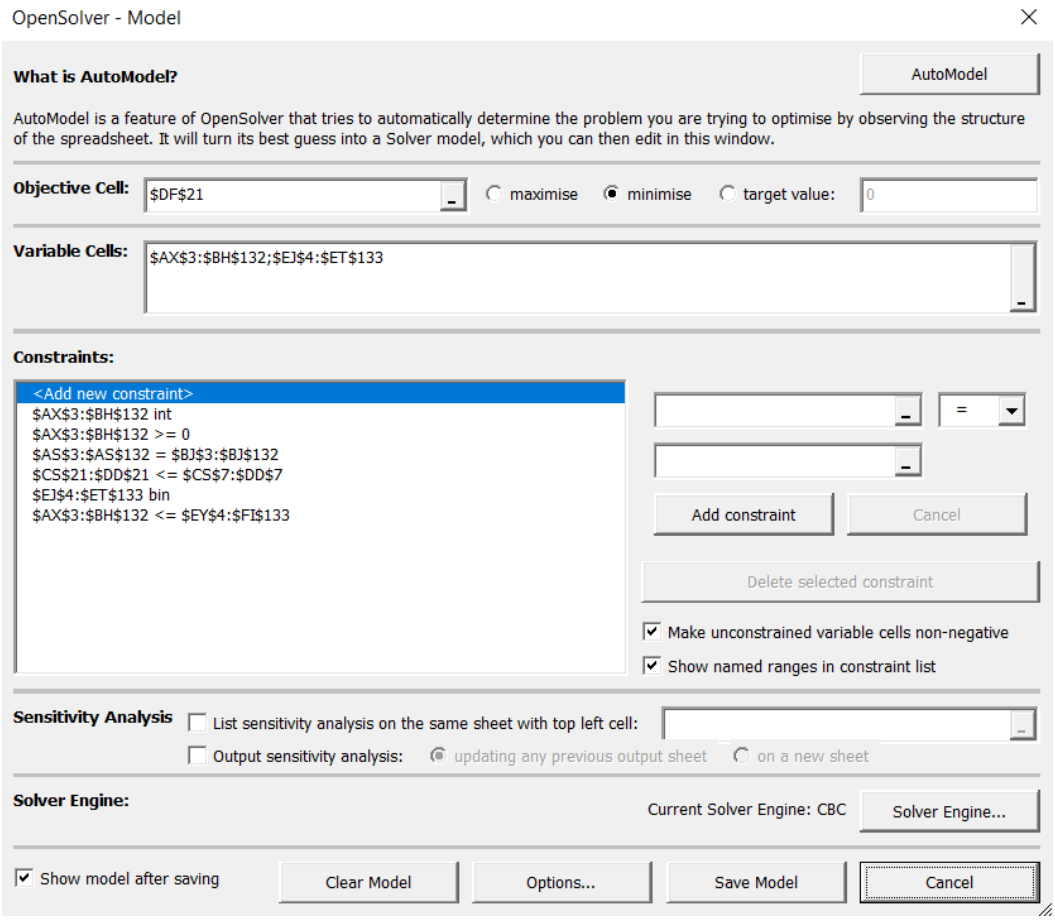


Figure 6.8 - Inserting the model on OpenSolver using its graphics user interface (GUI).

Besides defining the constraints defined in the model, it is also necessary to include two more constraints to set the decision variables x_{ij} and γ_{ij} as integer and binary respectively.

The model is now implemented. The only thing that still needs to be done is to define the maximum number of shifts that are available for production for each machine, set the demand for the period that is going to be calculated and choose the w_j coefficient for all the machines. This last input value is often close to 10% because one of the global objectives of the operations is to have a 90% production utilization of the machines. To obtain the solution, run the optimizing software. The results will appear on the worksheet in the designated cells.

To analyze the results in a more efficient and faster way, two graphics were created. The first represents the percentage of production time per machine in relation to the total time used by that machine. This percentage is compared to the equivalent value from 2016. The objective of this chart is to understand if the machines are having higher production utilizations with the optimization than in the past. The second chart represents, in percentage, the time spent by each machine over the time available for production for that machine. This graphic is useful to understand if the machines are being over or underutilized.

These two graphics combined with the information from the table that contains the decision variables x_{ij}, give the user enough information to take practical conclusions on how to optimize the machine utilization in order to achieve the highest possible effective capacity.

Program in VBA

As the tool was being experimented and used more frequently, it emerged that it was necessary to make the tool easier to use. One of the common errors that came up frequently was the solver reaching the end of the optimizing process and returning a message stating that there is no feasible solution to the problem. After looking into this issue, it was discovered that in most occasions this message was returned, the problem was that the time available for production was not enough to produce the desired quantity.

The implemented solution for this problem was to automatically increase the shifts available for production when the result was “no feasible solution found”. To automatically perform this, a small program was written in VBA. The program runs OpenSolver and increases the shifts available for production until a feasible solution is found or until the limit of shifts is reached. This limit is defined within the code. A button was created to initiate the macro containing the code (Calculate button on Figure 6.9). The code used to perform this task is the following:

```
Sub Calculate()
Dim i, j, k As Integer
Dim l As Long
k = Range("DI4").Value
l = 5
While l <> 0 And k <= 60
      Range("DJ4") = k
      l = RunOpenSolver(False, True)
      Range("DK5") = l
      k = k + 1
Wend
End Sub
```

A feasible solution is only reached when the result of the function RunOpenSolver is 0. The number of shifts for the program to perform the first iteration is inserted in cell DI4. After running and having found a feasible solution, the minimum number of shifts necessary to finish the designated production is written in cell DJ4. To verify if the solution was, in fact, feasible, the RunOpenSolver function result is displayed in cell DK5 (Figure 6.9). If the program cannot find a feasible solution within the established limit (in the case of the code presented the limit is set to 60 shifts) it will stop the iterations and present a solution that is not valid.

From the moment the program was created, it was no longer necessary to change the model in the interface.

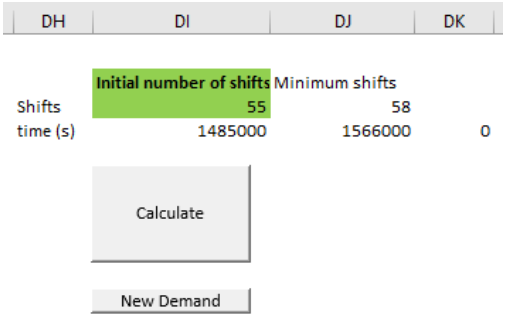


Figure 6.9 – Initial number of shifts, minimum shifts of result and buttons to run the macros

Besides this problem, and knowing that the tool contained a large data base, it was noticed that this data base was constantly suffering alterations either due updates of cycle times either for reasons such as reference alterations or due to new bodies being inserted in the production process. To avoid misleading results when the data base is updated, code to update the decision

variables and the constraints was included. All the constraints but the fourth are updated as this one does not change with any of the alterations of the data-base.

Updating the data base can also be done automatically using an “Input” file. As this update is not relevant for the report, only to ensure the good functioning of the tool by the user, its explanation is only presented in the instructions manual, in Appendix A.

When there is a new demand to insert in the tool and before running the macro “Calculate()”, it is necessary to update the constraints and refresh the pivot table that originated the table present in Figure 6.4. A macro was also created to do this automatically, called “New_Demand()”, which button is shown in Figure 6.9.

With the introduction of the macros, the tool is ready to be used.

6.2 Tool Applications and Results

The tool was initially developed to help the operations manager perform a faster, more accurate and optimized calculations of machine utilization to know if the departments had the capacity to produce the demand set by the Planning Department for a medium/long term. The results were satisfying as it was much quicker to run the program for all the departments and make the necessary adjustments. In addition to taking less time to calculate if the effective capacity could match the demand, the results produced by the new tool, as they are now optimized, were more reliable. The previous results were not optimized and, even if they were, it was impossible for the user to know it.

Looking at the results given by the tool, to the Operations Manager, the most important are knowing if the factory has the capacity to reach the demand and with how much machine utilization. This data gives them enough information to know if the production has slack and can produce more than planned, if the production is in its limit or there is the need to produce on Saturdays in case the demand is too high. This information is mainly given by the plot containing the total time over the time available for production for each machine and by the minimum number of shifts necessary to reach the demand. The mentioned plot is shown in Figure 6.10 for the Machining Department in the month of February, occupying a minimum of 66 shifts.

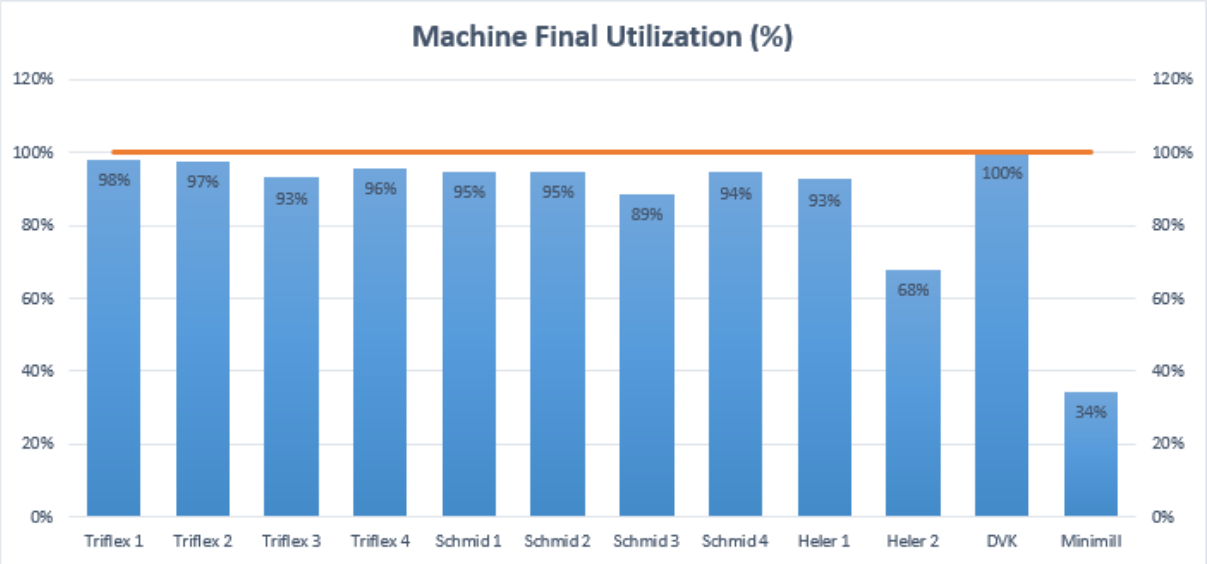


Figure 6.10 - Graphic of machine final utilization in percentage

As an example, analyzing the chart, the main conclusions that can be achieved with the minimum number of shifts are that, knowing that February 2017 has only 20 week days (results in 60 shifts as each day has 3 different shifts), 2 more days or 6 more shifts are necessary in the

Machining Department to produce the necessary quantities. It is also possible to conclude that the Heler 2 machine is being underutilized. Consequently, if the capacity of the Foundry Department allows it and if it serves the best interests of the production and company, it is possible to produce extra bodies. In conclusion, the tool becomes an appliance of decision making for the Operations Manager.

A problem identified with the tool was that, for a medium/long term, the counting of the setups was not the most accurate. As the departments have to achieve the weekly demand that the Production Planning Department plans, counting the setups must be done short term (week) and not for the medium/long terms (months). When the tool was being used to measure the capacity of a month, the number of setups originated by the program was low when compared to reality. The difference of not counting correctly the setups is less than 3%. It was concluded that it does not influence the final results enough to not consider them as valid.

The issue described above led to a new application of the tool. Instead of using the developed tool just for the medium/long term and only by the Operations Manager, it could be used by the heads of each production department, on a weekly basis, to calculate machine utilizations, evaluate if there is capacity to match the demand and to help them execute the production plan for the week. It was hard for the heads of some departments to perform the plan of production so that the minimum time possible was spent. The tool allows the user to change the period of time for which the capacity is calculated by changing the shifts for the first iteration and the shifts available for production. The last thing to do is to set the demand for the week instead of introducing it for the month. The results given are in the same format as before (two charts and one table). In this case, for the heads of the departments, the table containing the decision variables x_{ij} could be essential to help them with the execution of the production plan. In fact, the plan to minimize the production time is easily deducted from the table. Take as an example the excerpt of that table, which resulted from running the program for week 20 (May 15 to May 20) of the Machining Department in Figure 6.11.

AW	AX	AY	AZ	BA	BB	BC	BD	BE	BF	BG	BH	BI	BJ
Machined Body	**Triflex1**	**Triflex2**	**Triflex3**	**Triflex4**	**Schmid1**	**Schmid2**	**Schmid3**	**Schmid4**	**Heller1**	**Heller2**	**DVK**	**Minimill**	**Produced Quantity**
405750031	0	0	0	0	0	0	0	0	0	0	0	0	0
405822031	0	0	0	0	0	0	1229	0	0	0	0	0	1229
405913131	0	0	1753	0	0	0	0	0	0	0	0	0	1753
405940031	0	0	0	0	0	0	0	0	0	2702	0	0	2702
405941031	0	0	0	0	316	1138	0	0	0	0	8105	0	9559
406012131	0	354	0	0	0	0	0	0	57	0	0	0	411
406013131	0	0	0	0	5328	0	0	0	0	0	0	0	5328
406014131	0	0	0	0	0	799	0	0	0	0	0	0	799
406068131	0	0	0	0	0	0	0	0	0	0	0	0	0
406069131	0	0	0	0	0	0	0	532	0	0	0	0	532
406111031	0	0	0	0	0	0	0	0	0	0	0	0	0
406130031	0	0	0	0	0	0	0	0	0	0	0	0	0
406131131	692	0	0	0	0	0	0	0	0	0	0	0	692
406144031	0	0	0	0	0	0	0	0	0	0	0	0	0
406161131	0	0	0	0	0	0	0	0	0	0	0	0	0
406176031	0	0	0	0	0	743	0	0	0	0	0	0	743

Figure 6.11 - Excerpt of the table containing the production per machine of the Machining Department.

To plan the production, it is just needed to calculate the time each quantity takes to be produced and add the time of a setup at the end of each production. Doing this successively will end up giving the production plan.

So, by using the tool, the heads of the production departments can write the plan almost immediately. Naturally, this plan will, in most cases, suffer further modifications when the productions of all the departments are aligned. Nevertheless, this plan has flexibility without affecting the total time. This is only possible by changing the order of the production in the same machine without permuting the quantity that is to produce. In addition to allowing the construction of the production plan, from the tool, it is also possible to take similar conclusions to the ones the Operations Manager is taking but for a week period.

The tool can also be used to evaluate the performance of the departments. If after a week of production, the plan and the effective production are compared, the heads of the departments can easily reach a conclusion on how their department is working.

The final utilization of every machine of all departments is presented in a graphic that is contained in a worksheet called resume. The graphic is shown in Appendix B. It also presents the average utilization for each department and the shifts available for production that were considered in the calculations.

The Machining Department was identified as the bottleneck of the production. Naturally, the bottleneck in the factory will always depend on the product mix to produce but this department was being considered the bottleneck in most occasions. One of the reasons that was previously identified for that to happen was the manual construction of the plan. Having this in mind, the priority was to install the tool in the computer of the head of the Machining Department so that he could start using it.

What was done to measure the possible improvements and the time savings that the new tool allows, was to compare machining production plans done previously with a new plan for the same produced quantities but using the tool. As exemplification, this practice will be shown for week 22 of the year (29th of May to the 3rd of June). The initial production plan of the Machining Department is presented in Appendix C. The produced quantity with that plan was inserted in the program as the demand and the program was run.

The results showed that this production was possible to be performed in 17 shifts instead of the 18 shifts, with the machine utilizations represented in Figure 6.12.

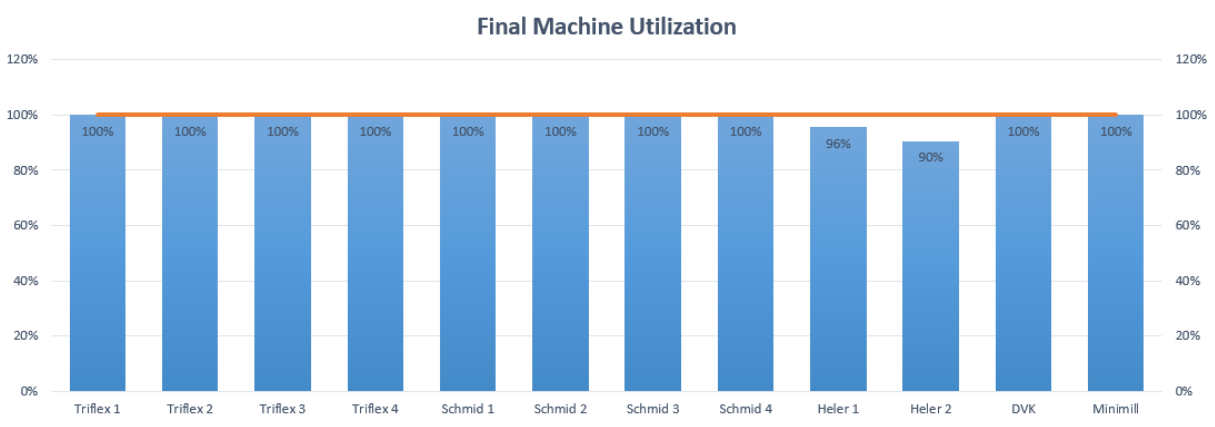


Figure 6.12 - Machine utilization for week 22

Using the table containing the amount of each product to produce in each machine, a new production plan was developed. This plan is represented in Appendix D. It is important to emphasize that the utilizations do not correspond in perfection to the production plan because the plan considers only complete hours and it was always considered the worst-case scenario (for example, the setups of the Triflexs take in average 80 minutes but are considered as lasting 120 minutes).

As it is possible to conclude, by optimizing the plan in this case, it was possible to reduce by one the number of shifts utilized for the production. A reduction of almost 6% to the total time that can start being used for other purposes such as preventive maintenance or for doing the next week's setups in case they are necessary.

To point out that the optimization was implemented for the Foundry, Machining, Grinding, Polishing and Laser Print departments/processes. For the tool to cover all departments, worksheets were created for the remaining departments where the capacity was calculated to verify if the demand could be satisfied. The departments/processes for which these worksheets were created are:

- Core making;
- Electroplating;
- Assembly.

For these departments, there is no need of optimization as there is no difference between the machines/lines' productive capacity (core making and assembly) or there is only one production line (electroplating). The capacity calculations for these departments/processes will be presented next.

Core Making

In the core making process the core has to go through two processes: the first done by one of the 6 machines which consists of giving shape to the cores, and the second, done by 5 operators, consists of trimming the cores coming out of the machines. Knowing the cycle times to produce the cores of each product to be casted and being these equal, regardless the machine/operator, cycle times are multiplied by the number of cores to produce and divided by the time of one shift to obtain the necessary shifts of production for that product. Adding this value for all the products will give the result of the second column of the table (Figure 6.13) taken from the core making worksheet. To calculate the total %Utilization (last column of the same table), are added the shifts spent in production and the shifts spent in setups and then divided by the percentage of time without unpredicted stoppages. Finally divide the number of shifts by the available shifts of all the machines.

	Available shifts per machine	Necessary shifts (production)	Shifts/setup	Number of setups	%time without stopage	Necessary shifts	Machines	Available shifts	%Utilization
Core making machines	15	71,42840233	0,083333333	32	90%	82,32785444	6	90	91%
Core making men	15	78,99944793			90%	87,77716437	5	75	117%

Figure 6.13 - Calculation of capacity utilization in the core making process

Electroplating

In the Electroplating Department, there is only one production line. It is used suspensions to carry the products through the line. The number of products that each suspension carries depends on the product. For each product is attributed a specific type of suspension. The total time for a set of 4 suspensions to go through all the line's processes is 1h45min. However, every 3 minutes these sets finish the process. Consequently, the cycle time is 3 minutes. To calculate the utilization of the line the quantity to produce is divided by the capacity of each product corresponding suspension to obtain the number of suspensions needed (Figure 6.14).

Body	Stream	Suspension	Bodies/susp	Alternative susp	Bodies/susp	Demand	%Scrap&Rew	Quantity to produce	Necessary Suspensions
64378031	CA	869.A.0004	25			0	9%	0	0
64390031	CZBX	869.A.0075	8			400	41%	564	71
64418031	BC	869.A.0076	6			600	27%	761	127
64545031	BC	869.A.0048	12			0	30%	0	0
64583231	TH	869.A.0063	10			0	14%	0	0
64590231	TH	869.A.0050	6			0	31%	0	0
64593231	TH	869.A.0080	10			6000	14%	6840	684
64637131	CA	869.A.0071	10			450	15%	517	52
64677031	BC	869.A.0048	12			0	37%	0	0
64773031	BC	869.A.0042	10			0	40%	0	0
65507231	TH	869.A.0092	10			1500	28%	1928	193

Figure 6.14 - Calculation of the necessary suspensions per body

The suspensions needed are added for all the products, divided by 4 suspensions to know the number of cycles and then multiplied by 3 (minutes) to know the total time used in the production. The line does not need setups as the electroplating treatment is equal regardless the product. The total time for production is divided by a percentage of suspension utilization (as not all the suspensions carry their full capacity). This value is divided by the time available for production to obtain the utilized capacity of the line. As there is only one electroplating production line, the capacity should have a margin of approximately 20% added to its full capacity to prevent from unexpected process breakdowns.

Assembly

In this department, the capacity calculation is done for each stream. The capacity calculation in the Assembly Department is similar to the one executed for the core making process. For each finished good the cycle time is presented as well as the quantity to be produced. Multiplying one by the other the production time is obtained. Divide this value by the time of a shift to get the quantity of shifts on production. These calculations are present in Figure 6.15.

FG	Originating Body	Ref cube	Stream	Cycle Time	Demand	Scrap&Rev	antity to prod	Production time	Production Shifts
32669000	65795231		CZBX	87,9204	0	10%	0	0	0
32670000	408017040	408017	LB	91,872	1488	2%	1519	139553,568	5,168650667
32670DC0	404310DC3		LB	114,288	100	10%	110	12571,68	0,465617778
32671000	408236040	408236	LB	98,436	0	2%	0	0	0
32701001	401289038	401289	BC	85,44	0	17%	0	0	0
32708000	64418038	64418	BC	116,8164	200	6%	212	24765,0768	0,917225067
32723000	408301040	408301	LB	93,42	0	2%	0	0	0
32750000	65795231		CZBX	67,368	972	10%	1069	72016,392	2,667273778
32752000	401062338		CZAL	67,104	2784	10%	3062	205472,448	7,610090667
32786000	401062338		CZAL	88,128	396	10%	435	38335,68	1,41984
32787000	2855131		CZBX	126,84	216	10%	237	30061,08	1,113373333
3280400E	#N/A		LB	58,5	0	10%	0	0	0
32830000	408301040	408301	LB	79,464	4000	2%	4087	324769,368	12,02849511
32836000	400065038	400065	BC	85,3788	108	9%	117	9989,3196	0,3699748

Figure 6.15 - Calculation of the necessary production shifts per finished good

The production shifts are added together for the same stream and the setups are counted, transformed into shifts occupied and added to the production shifts. This value is divided by the time without unpredicted stoppages to give the final value of the utilized shifts. Dividing the total shifts by the shifts available for production it is obtained the line's capacity utilization for each stream. The calculations referred are resumed in Figure 6.16.

Stream	Quantity of lines	Available shifts	Necessary shifts	Setups	Setup time	Total setup time	Shifts on setups	unpredicted stoppag	%Utilizatior
BR	3	204	120,3293867	40	5480,884489	219235,3796	8,119828873	10%	70%
CTH	4	272	236,525454	13	3026,737509	39347,58761	1,45731806	10%	97%
CA	2	136	49,13049267	22	4581,39755	100790,7461	3,732990596	10%	43%
AT	1	68	19,76397667	7	4371,84	30602,88	1,13344	10%	34%
CO	1	68	18,811812	8	3899,489362	31195,91489	1,155404255	10%	33%
CZBX	5	340	268,2255427	74	2947,017616	218079,3036	8,077011243	10%	90%
CZAL	2	136	82,28196729	13	2746,248175	35701,22628	1,32226764	10%	68%
CM	2	136	99,96770667	42	3231,29244	135714,2825	5,026454907	10%	86%
TH	8	544	426,0633973	53	2951,59294	156434,4258	5,793867623	10%	88%
BC	3	204	84,9507012	34	4001,364965	136046,4088	5,038755881	10%	49%
LB	5	340	285,0932044	68	2791,218304	189802,8447	7,029734989	10%	95%
PM	1	68	5,105172	5	0	0	0	10%	8%
BI	1	68	0,3542	1	0	0	0	10%	1%
UN	1	68	6,24316	3	6329,67033	18989,01099	0,703296703	10%	11%
VE02	1	68	11,93156533	4	3988,085106	15952,34043	0,590827423	10%	20%
INV	1	68	26,994	2	0	0	0	10%	44%

Figure 6.16 - Calculation of assembly lines' utilization

One of the identified problems of the tool is that all the productions are considered as "one shot" productions. Meaning that every time a certain product starts to be produced, the quantity to produce of this product is done completely at once (one setup per product). This assumption can sometimes be incorrect, mainly in the Assembly Department where setups due to missing components are recurrent, increasing the number of setups per product.

The inclusion of the sheets to calculate the capacity of the departments that do not need optimization in its capacity calculation finalize the tool.

7 Conclusions and Perspectives for Future Work

The present dissertation comes from the necessity of arranging a more expedit, accurate and optimized manner for the calculation of the capacity of GROHE Albergaria plant's departments by the operations manager. The existing Excel tool was taking too much time to update when there was a new demand for the following month. The tool previously used was manual and needed a considerable amount of steps before achieving satisfying results. Even so, the effective capacity calculated in the final result could almost always be increased as it was not obtained through optimization. This meant that only by chance would the final result be the best possible. The objective was to create a tool that could quickly calculate the effective capacity of each department when the machine production plan was optimized.

The conclusions that were reached throughout the time the project was being developed as well as some of the results obtained, are present in this chapter. The ideas and perspectives for future work regarding the tool and factory will also be presented.

7.1 Conclusions

It is possible to conclude that the main objective of this project was achieved. The new tool was developed and implemented having in mind the deffects of the existent one. The main improvements of the new tool are:

- Reducing the time used to calculate if the effective capacity could satisfy the demand. When the previous tool was being used, performing this calculation for all the departments could take a couple of hours which were reduced to less than an hour with the new tool;
- Allowing the machine utilizations to be calculated individually for each machine;
- Calculating the setups time;
- Optimizing machine utilization by constructing a linear programming model. The solution of this model distributes the production by the existing machines minimizing the total time spent by all the machines;
- Calculating the capacity of the Assembly Department;
- Automatizing the tool. Creating macros that run by pressing buttons and automatically perform the calculations, making the tool easy to use for everyone.

Besides achieving the primary objective, the proposed tool was found to be very useful not only for the operations manager but also for the heads of the Foundry, Machining, Grinding and Polishing and Assembly departments. It also concluded that using the tool to plan the production saved them time and optimized the production plan, minimizing the total time spent producing. This appliance was particularly helpful for the Machining Department because it was being identified as the bottleneck of the plant's production in most part of the situations, regardless of the product mix. It was prooved that by applying optimization to the plan it was possible to reduce the production by one shift (almost 6% of the total time).

Moreover, the tool started to be used by the heads of the referred departments as a support when arguing that the department did not have capacity for a specific demand set by the Production Planning Department. In this case, even when the production time is optimized, the shifts necessary for production are higher than the available shifts. Before the tool was made available, there was no way for them to support this. As such they could not prove to the Planning Department that the demand was higher than its capacity.

The tool also allows users to evaluate their department's performance after a week of production, by comparing actual production to expectations.

Having the tool being used by the operations manager and the heads of the production departments meant that the tool was now a standard. This is an advantage for all as the calculations are done in an equal manner between the departments and they all understand

exactly how it works so when its results are presented, everyone knows how they were obtained and can discuss or make suggestions for improvement.

In conclusion, the developed tool is more complete and accurate, faster and easier to use when compared to the previous one. It is also more useful than just for measuring if the capacity matches the demand, which is an extra to what was asked at the beginning of the project. The results were considered more than satisfatory by the company.

7.2 Perspectives for Future work

The tool was only being tested for three weeks by the supposed users. This means that a large part of the improvements will appear later when the users are more familiarized with how the tool works and what it can and cannot do.

The improvements that are possible to point out now are:

- Create a macro to perform the addiction of new machines;
- Reconstruct the LP model in order to include the correct counting of the setups for the long term.
- Include the calculations of PVD's capacity and chamber utilization.

For future work, and following this project, it is considered that a tool like the one developed would be useful to the Production Planning Department. It was realized that this department did the planning for the departments without knowing their capacity and if the department was able to achieve those production goals or not. This meant that planning had to be discussed on a weekly basis with the leaders of the departments and then redone taking into account the specfic capacities. Having a tool that gives this information and is addapted to the Production Planning Department's objectives will reduce the constant production alignments that are currently being done.

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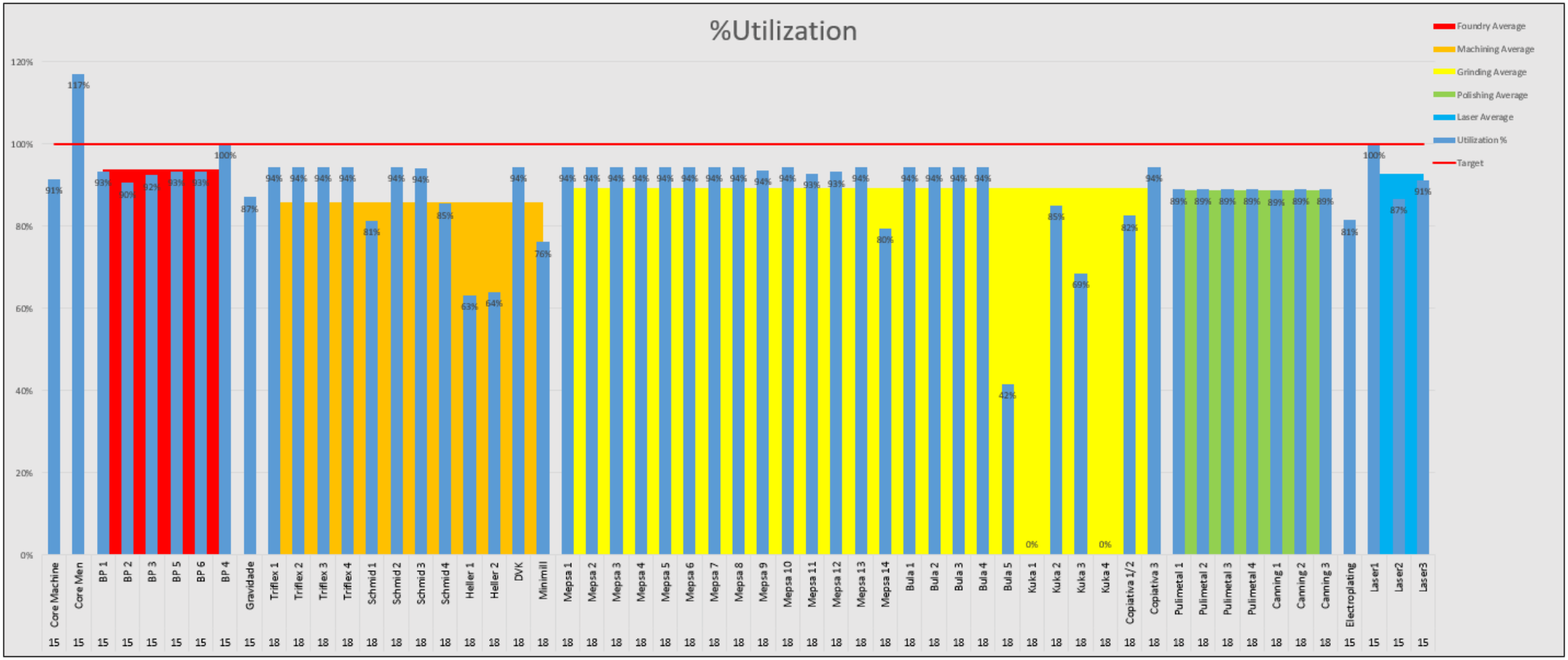
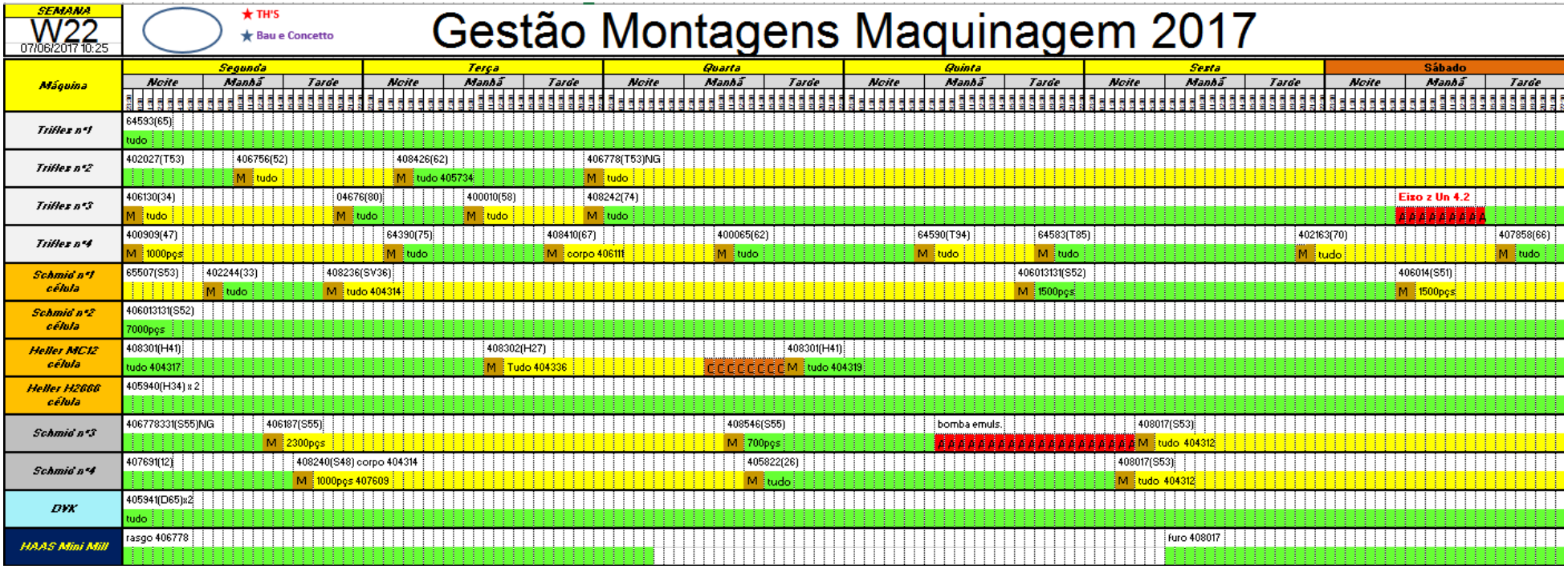
APPENDIX A: Manual de Instruções do Programa de Cálculo de Utilização e Capacidade

APPENDIX B: Resume of all Final Machine Utilizations

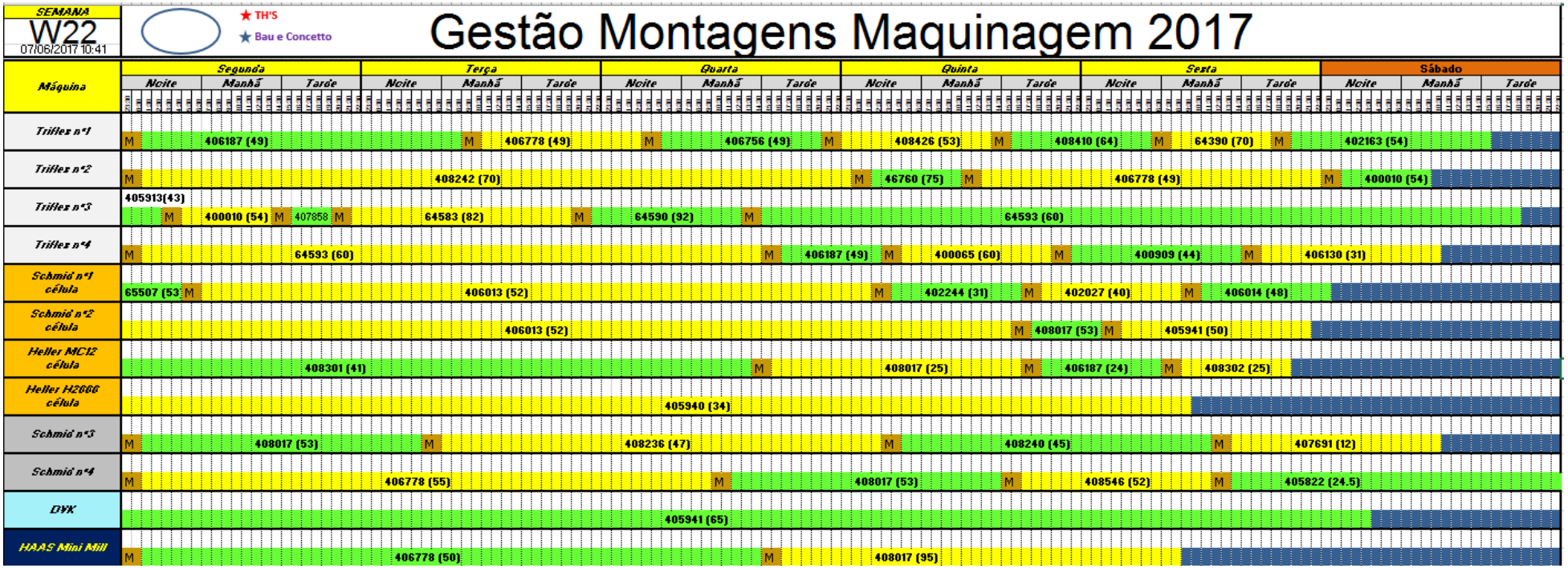


APPENDIX C: Initial production plan for week 22 of the Machining department



- Yellow and Green – Production
- Red with A – Failure
- Brown with M – Setup
- Orange with C - Preventive Maintenance

APPENDIX D: Production plan for week 22 of the Machining department using the tool



- Blue – Unused production time