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Benefits of Restricted Optimization in Production Engineering: A Case Study in a Plastic Industry

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ABSTRACT

This study aims to investigate constrained optimization problems in a plastics company, leveraging existing research data to deepen understanding of constraint theory and linear programming. Additionally, it seeks to construct a problem model within a specific company in this sector. Following a literature review, and with the aid of the Solver/Excel tool, data from COMPANY X was inputted into a spreadsheet to address its issue and thereby enhance profits. The developed mathematical model was applied to an industrial problem involving two types of products (PRODUCT A and PRODUCT B). Through analysis of the problem conducted by the Solver/Excel, it was observed that PRODUCT B would increase profits for the company, highlighting the need for machinery investment in one of its sectors. Consequently, it can be concluded that the application of constraint theory is a vital tool for profit enhancement and decision-making in a company.

***Keywords**: Optimization; Constraint Theory; Linear Programming; Decision Making.*

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I. INTRODUCTION

One of the primary concerns across all engineering disciplines is safety, cost reduction, and minimal material consumption, and production engineering is no exception. In any demand scenario, there is always a strive for better efficiency in executing tasks, and optimization plays a crucial role in meeting engineering needs. [1]

Optimization seeks the best possible outcome for a given problem in the most efficient manner through mathematical techniques that provide optimal solutions. Optimization problems can be understood akin to root-finding problems, as both involve estimating and seeking a function's point. Root-finding involves searching for zeros of a function, while optimization involves finding points of minimum and maximum. Mathematically, it is known that a function's critical point occurs when its derivative is zero. Hence, deriving the function to find the root and subsequently determining the optimal point. Thus, the optimization problem boils down to a determination problem. [2]

According to Vieira and Abreu (2011), after grasping the basic principles of optimization, it is applied within a company to achieve a competitive advantage, meaning that the company creates more value than its competitors. This depends on the quantity of resources and competencies that emerge with its usage within the company. To attain these competitive advantages, the company needs to adopt strategies with methodological relations to production planning and control, leading to cost reduction and consequently increased profitability. [2]

When discussing the theory of constraints, it's crucial to understand that solutions utilizing mathematical methods for solution seeking involve linear equations during the application of two problems. In other words, the theory of constraints suggests linear programming, aiming for maximum gain at each moment, both presently and in the future, through scenario creation. It is incumbent upon the company to control this entire process through information technology tools capable of managing all variables involved in the application process of this theory and also in linear programming calculation. [3]

Bezerra (2015) further clarifies that inherently, with the increase in complexity of the function to be optimized, usually due to the increase in the number of variables and their relationships, there is an amplification of difficulty in finding a set of optimal solutions. It's not always possible to minimize functions of multiple variables through an analytical solution. [3]

Within this context, there arises a need to develop numerical methods, based on a model with directional search, which defines the optimization process, widely used to solve engineering problems, given that optimization integrates the essence of this field. These methods are divided into two groups: mathematical programming methods and probabilistic (random) methods, with some methods from the first group being studied in this work.

This work was developed from a fictional scenario involving a company operating in the plastics industry, which includes the manufacture of various types of packaging, including PRODUCTS A and B, in its portfolio.

In this company, the engineering department requires the operation of documents reporting on the effectiveness of each type of product. In this regard, the responsible parties wish to conduct a survey to determine which type of product will yield the highest profit for the company.

Consequently, there is a perceived need to implement a study of constraint theory using the Solver/Excel tool to analyze which product should be invested in terms of time and money to achieve future profitability. In this context, the problem arises: Is the use of constraint theory in conjunction with the Solver/Excel tool viable in the decision-making process of a company?

The general objective of this study is to propose the maximization of gains for COMPANY X, using the concepts of constraint theory and linear programming. COMPANY X has a production control process focused on meeting sales order demand and increasing profits.

The specific objectives are as follows: Conduct a literature review on optimizations and Constraint Theory; Construct a linear programming model using the Solver/Excel tool; Study the best solutions to maximize profits at COMPANY X.

This work seeks to strategically demonstrate the use of constraint theory to develop solutions for the problems encountered at COMPANY X, thereby making the company more competitive and profitable compared to others in the same sector. In this case, the technology of the Solver/Excel tool and knowledge of constraint theory were applied to address the problems faced at COMPANY X, which is a plastics company aiming to become more competitive and profitable in the market, considering that a company failing to achieve these objectives may face complete closure of its activities.

The company can derive many benefits from implementing optimization, specifically utilizing the Solver tool in Excel, one of whose objectives is to solve linear programming problems. Hence, this tool is widely used in companies when it comes to optimizing production processes. Therefore, the realization of this work stemmed from both the need to deepen knowledge about this type of tool when used in production engineering and to implement it practically at COMPANY X.

II. MATERIAL AND METHODS

The research was conducted adopting a mixed-method approach, developing an exploratory case study. Yin (2008, p. 66) comments, "Exploratory studies, when there is no information about a particular topic and one wishes to understand the phenomenon." [4]

The sources used for information will be both primary, i.e., raw collected data, which already contain information regarding product composition, as well as the value of operational expenses, among other details. Regarding secondary information, it will be collected through journals and books, characterizing a bibliographical theoretical foundation. Once the information regarding the production process of a plastics company was found, the data was used to feed the Solver/Excel tool with the purpose of achieving the study's results. The research strategy developed was a case study.

According to Yin (2002), a case study is an empirical investigation that examines a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly defined. Based on this logic, data from the company were collected to analyze the research problem. In order to achieve the study's objectives, the researchers developed a quantitative analysis of the data through a linear programming model, based on concepts from the theory of constraints. [4]

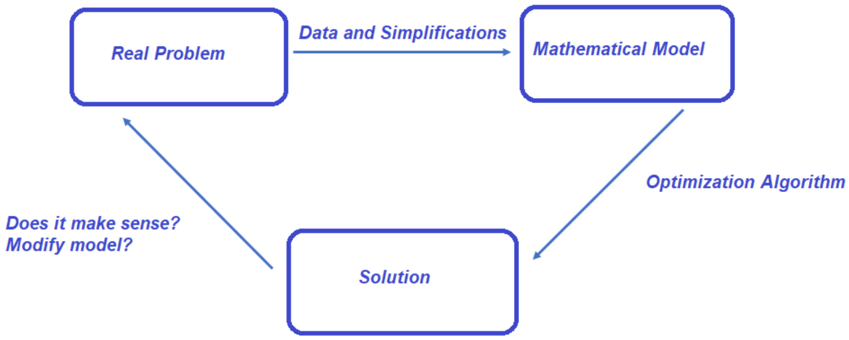
III. THEORETICAL FRAMEWORK

In this chapter, a concise literature review is being conducted, addressing topics from the areas involved in the research, as outlined below.

3.1 Optimization

According to Oliveira, Rangel and Bonamigo (2020, p. 5), optimization can be understood as the process of seeking a solution that provides the maximum benefits, more precisely, the search for the optimal condition, utilizing techniques that select the best alternatives through appropriate strategic planning, aiming to achieve efficient management. [5]

Figure 1 presents the basic fundamentals of optimization.



Source: [6]

According to Carvalho and Carneiro (2019, p. 02):

Mathematical optimization essentially involves seeking optimal solutions (maximizing or minimizing) for a given problem. It is an area that has grown considerably in recent years, despite being relatively recent. This growth has led to increased specialization and diversification within the field. As a result, specializations in nonlinear optimization, discrete optimization, combinatorial optimization, and more recently, stochastic optimization, can be observed. The growth is partly due to the fact that optimization problems arise in various practical applications of sciences such as engineering and economics. [7]

According to Tortelli (2020, p. 3), “optimization began around 300 b.C. with Euclid”. [6] Between the 16th and 18th centuries, optimization was implemented by several mathematicians, including Newton, Bernoulli's, and Cauchy, who presented various methods, such as the gradient method. In the 19th century, Hamilton and Jacob introduced the first algorithms, however, it was in the years following the 20th century that optimization began to be more widely used in various areas with the assistance of computers.

According to Oliveira, Rangel and Bonamigo (2020, p. 5),

Optimization can be applied to solve various problems in engineering, such as: planning the operation of power electrical systems, reducing processing time in production systems, optimizing control systems, minimizing the cost of products in construction or transformation processes, determining the ideal layout for electrical networks, roads, loads, pipelines, and planning for equipment replacement and maintenance to reduce operational costs. [5]

Optimization is a versatile tool applicable to various engineering problems, including power system operation planning, production system time reduction, control system optimization, product cost minimization in construction or transformation processes, determination of ideal layouts for electrical networks, roads, loads, pipelines, as well as equipment replacement and maintenance planning for operational cost reduction. Its wide-ranging applications highlight its importance in enhancing efficiency and cost-effectiveness across diverse engineering domains.

3.2 Theory of Constraints

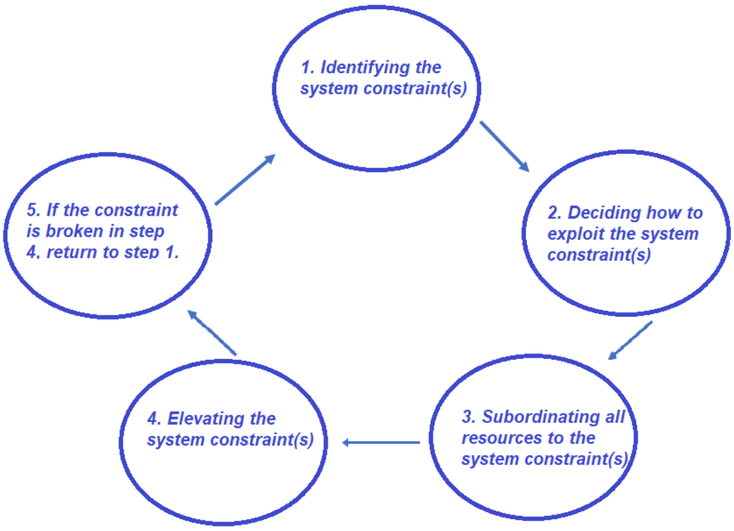
Discussing the Theory of Constraints, also known as TOC, Fernandes and Godinho Filho (2017) define it as a method used to identify and enhance the limiting factors within organizational processes. Consequently, the fundamental idea of TOC is to improve a company's profitability by identifying and exploiting constraints, which can be anything—be it a process, a machine, a layout, a methodology—that hinders the organization from achieving its goal, whether they are external or internal, physical or non-physical, to the organizations. This principle furnishes a set of tools to ensure that the constraint, or bottleneck, no longer serves as a limiting factor. [8]

According to Maher (2001, p. 508), the theory of constraints can be delineated as limitations within a flow, implying obstacles that hinder or impede the flow of a given process. The author further adds that the theory of constraints can also be referred to as the theory of limitations, focusing on bottlenecks and emboldening administrators to devise means to increase profitability by eliminating constraints and augmenting the throughput of the bottleneck. [9]

According to Vieira and Abreu (2004, p. 4), the focus of the theory of constraints encompasses up to five sequential and logical stages, aiming at the elimination of constraints and consequently the emergence of a new constraint, akin to a continuous improvement process. [2]

Figure 2 illustrates the operational process of the theory of constraints with its five steps.

Figure 2 - Theory of Constraints Process



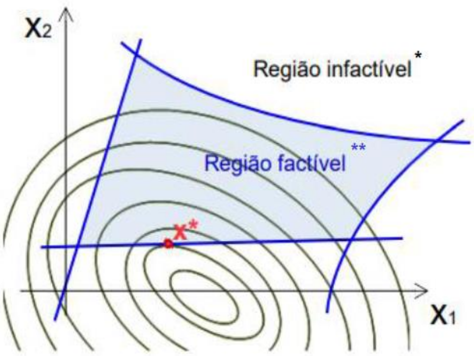
Source: [10]

Oliveira, Rangel and Bonamigo (2020, p. 01) further elaborates on the five steps for applying the theory of constraints.

In step 1, the constraint can be explained as the available time or the capacity of a machine, department, or workstation. In service or high-tech companies, the constraint revolves around the available time of employees with the most capacity. Step 2 involves calculating the profitability per unit of resource consumed at the constraint, while step 3 entails subordinating to the constraint, meaning providing only what is necessary to achieve the constraint's objectives. Step 3 may result in the idleness of non-constrained resources, typically referred to as the drum-buffer-rope subordination. [5]

Step 4 entails breaking or increasing the system constraint through continuous improvement of operations, capacity acquisitions, or demand fluctuations. In other words, a new acquisition will assume the previous role. Finally, step 5 refers to the new system constraint, i.e., if the old constraint is broken. [5] According to Vieira and Abreu (2004), a company's primary objective is generating results, utilizing predetermined variables analysis to compare and evaluate projected results with achieved ones. In essence, the company's goal is to maximize its financial position both presently and in the future. [2] As Guerreiro (1999, p. 18) suggests, the theory of constraints defines parameters contributing to measuring the degree of goal achievement, where net profit and return on investment serve as essential indicators, as well as cash flow. [11] As Maher (2001, p. 508) elucidates, imposing a constraint on a particular problem limits the feasible region for problem-solving. However, to apply this constraint effectively, a proper definition of the desired objectives is necessary. [9] Figure 3 illustrates practically the feasible region within a constraint problem.

Figure 3 - Feasible Region.



Source: [6]
* Feasible Region
**Infeasible Region

For many companies, this objective is profit itself. This constraint can be divided into two parts: the physical, which corresponds to resources, equipment, facilities, etc., and the non-physical, which is related to the demand for a product, a corporate procedure, or even a mental paradigm for addressing a certain problem. [12]

3.3 Mathematical Programming and Linear Programming

According to Arenales et al. (2006, p. 08) “mathematical programming addresses decision problems in finite-dimensional spaces, employing mathematical models”. [13] Variables are determined, and mathematical relationships among these variables are established to describe the system's behavior (objective function and constraints).

Linear programming has been one of the most significant scientific advancements since the mid-20th century, with its extraordinary impact on science dating back to the 1950s. Nowadays, it is a standard tool that has saved many dollars for numerous companies or even medium-sized businesses across various industrialized countries worldwide. [14]

Passos (2008, p. 8) defines linear programming as follows:

> Linear programming is an optimization technique applied to systems of linear equations (or inequalities) representing previously developed models. An optimization problem in linear programming aims to maximize or minimize a linear function, subject to some linear constraints. In other words, in linear programming, one seeks to determine the values of variables that minimize or maximize an objective function, subject to certain constraints, which are linear equations (equalities) or inequalities. [15]

As Barbosa (2014) notes, optimization problems involving linear functions subject to constraints originated from Fourier's studies on systems around 1926. However, it was only in 1939 that Kantorovich highlighted the practical importance of these problems, creating an algorithm for their solution. The following year, in the United States, Dantzig not only formulated a linear programming problem but also developed the simplex algorithm. [16]

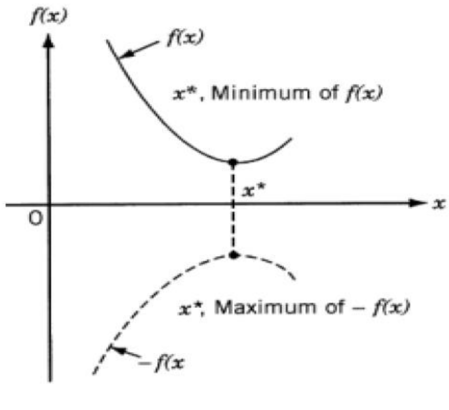
Barbosa (2014) further states that linear programming is applied in companies to solve problems related to distribution optimization, production scheduling, and resource allocation. Linear programming has also been used to seek solutions to optimization problems in various activities, such as industrial operations, banking, and transportation companies, with the latter yielding the highest profits. [16]

The extensive applicability of linear programming (LP) stems from the linearity of the mathematical model, which involves maximizing or minimizing a linear function, known as the objective function, subject to a system of linear equalities and inequalities. [17]

$f(X_1,\dots, X_n)$
$hi(X_1, \dots, X_n) = 0$
$hi(X_1, \dots, X_n) \geq 0$

Figure 4 illustrates the foundation of linear optimization. [17]

Figure 4 - Foundation of linear programming.



Source: [18]

As a tool to meet the demand for implementing new strategies, linear programming can assist decision-makers in creating scenarios. As mentioned by Donado et al. (2008), in the case of product development, the model can identify the most profitable products with existing demand and suggest replacing or eliminating products with low profitability and demand. [19]

Studies on the use of the theory of constraints and linear programming have grown recently. According to Oenning (2004), they share common objectives such as a system-wide perspective, the pursuit of result optimization, and attention to production constraints. However, the theory of constraints and linear programming can be differentiated based on their structure. [20]

Oenning (2004, p. 215) explains:

> The Theory of Constraints and Linear Programming can be differentiated based on their structuring. The Theory of Constraints constitutes a theory aimed at result maximization, whereas Linear Programming consists of a mathematically structured technique for the pursuit of maximizing or minimizing a study object. [20]

3.4 The Plastic Industry in the Current Market

The plastics industry plays a pivotal role in the global economy, as plastic is ubiquitous in virtually every product used by humans, ranging from bumpers, supermarket bags, and cell phones to construction pipes and hospital serum bottles, thus penetrating almost all production chains. Consequently, the primary challenge facing industries in the current moment is securing raw materials, particularly as 2022 ostensibly represents the aftermath of a pandemic during which almost all sectors were either halted or diminished.

Between 2011 and 2016, the packaging market grew by 6.2%, positioning Brazil as the fifth-largest industry in this sector globally. In 2019, production increased by 2.3% compared to the previous year, and according to the Brazilian Packaging Association (ABRE), it is projected to grow by 1.6% until 2024, driven by the innovation market.

The packaging market is influenced by the country's economy, and Alves (2015) explains that 2022 will be a challenging year for industries in this sector due to a reduction in public spending compared to the previous year, which stimulated the economy. Additionally, money is now less valuable due to inflation. [21]

Another significant factor in the plastics industry is recycling. While municipalities have recycling policies for packaging, not all locations strictly adhere to these laws, leading to an increased demand for raw materials. Thus, a policy for maximizing recyclables utilization is necessary. [21]

According to the Brazilian Plastics Industry Association (ABIPLAST), in 2019, this sector was the fourth largest job creator and the second highest-paying industry. The association further reports that in 2021, Brazil had over 300 thousand plastic companies, with 13 thousand dedicated to recycling.

In the same year, the revenue exceeded 127 billion, making Brazil one of the largest plastic users globally. Compared to the previous year, 2021 saw a positive outcome with a 3.9% increase.

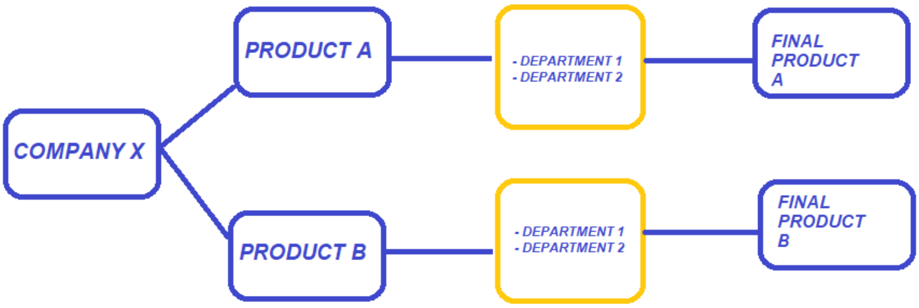
Regarding geographical distribution, São Paulo state holds the highest concentration of companies at 44.6%, followed by Rio Grande do Sul with 11%, Santa Catarina and Paraná with 8%, Minas Gerais with 7%, and Rio de Janeiro with 5%. This concentration places the South and Southeast regions at 85% of plastic companies.

In terms of global plastic industries, the major producers are the members of the North American Free Trade Agreement (NAFTA) – the United States, Canada, and Mexico – the European Union, and Japan, which collectively accounted for 100.953 million tons in 2000. However, the primary resin consumer markets are North America, Western Europe, and Japan, representing 90% of global consumption. Brazil ranks seventh as a plastic consumer market. [22]

IV CASE STUDY

To develop a fictional case of a company aiming to increase its profits, Figure 5 provides a summarized overview of the production process of COMPANY X.

Figure 5 - Production process of COMPANY X



Source: Researchers' data

Table 1 displays the observations of the fictitious case study for each product developed by COMPANY X, considering that DEPARTMENT 1 operates for 80 hours per week while DEPARTMENT 2 has a total of 100 hours per week, and the company does not produce more than 40 units per week of PRODUCT A, which is its maximum demand.

Table 1 - Summary of data for COMPANY X

	Raw Material	Labor plus Indirect Costs	Number of hours in Department 1	Number of hours in Department 2	Selling Price
PRODUCT A	R$ 5.00/unid	R$ 7.00/unid	1 hour	3 hours	R$ 15.00
PRODUCT B	R$ 9.00/unid	R$ 10.00	1 hour	1 hour	R$ 20.00

During the study of the Theory of Constraints, one of the steps is to define the variables, which represent the desired outcomes. For the case under study, it was determined that X1 represents the quantity of PRODUCT A to be produced per week to optimize profits, and X2 represents the same for PRODUCT B. Therefore, the variables for these equations are:

- $X1$ = Quantity to produce of Product A per week
- $X2$ = Quantity to produce of Product B per week

The objective function aims to improve or minimize a mathematical function, i.e., it contains optimization. For the study of COMPANY X, the objective function is to maximize the profit from the sale of its products. Since profit is calculated simply by subtracting the selling price from the manufacturing cost, the profit for each product is:

- PRODUCT A = R$ 15.00 – R$ 5.00 – R$ 7.00 = R$ 3.00 / UNIT
- PRODUCT B = R$ 20.00 – R$ 9.00 – R$ 10.00 = R$ 1.00 / UNIT

Hence, the objective function of COMPANY X will be:

$Max(profit) = 3*X1 + 1*X2$

The case under study has five constraints. The first constraint from DEPARTMENT 1 specifies a production capacity limited to 80 hours, and both PRODUCT A and PRODUCT B need to perform activities in this department. Therefore, the constraint from DEPARTMENT 1 is described by the formula:

- $1*X1 + 3*X2 \leq 80$

Each of the products also needs to perform activities in DEPARTMENT 2, which has 100 weekly hours for production activities. Hence, the formula for the constraint would be:

- $1*X1 + 1*X2 \leq 100$

It was also identified in the case study that the production of PRODUCT A cannot exceed 40 units since this is its maximum demand per week. The formula for this constraint is:

- $X2 \leq 40$

The last constraint concerns non-negativity, which is common in linear programming problems using solver/Excel. It represents that the results must be greater than or equal to zero, meaning that no result should be calculated with negative values. The constraint is formed by the following formula:

- $X1 \geq 0$
- $X2 \geq 0$

V RESULTS AND DISCUSSION

According to the presented results, the quantity to be produced per week of PRODUCT A will be 40 units and of PRODUCT B 13 units, resulting in a profit of R$ 133.33 per week. When examining the results of the constraints, Figure 5 illustrates which directly influenced the outcome of the equation.

Figure 5 - Excel Spreadsheet for the case study.

	A	B	C	D
1	VARIABLES	QUANTITY TO BE PRODUCED		
2				
3	PRODUCT A	40		
4	PRODUCT B	13,33333333		
5				
6				
7				
8	MAXIMIZE	133,3333333	*=3*B3+1*B4	
9				
10				
11				
12	CONSTRAINTS			
13				
14	TIME IN THE DEPARTMENT 1	80	<= (less than or equal to)	80
15	TIME IN THE DEPARTMENT 2	53,33333333	<= (less than or equal to)	100
16	NON-NEGATIVE PRODUCT 1 PRODUCTION	40	>= (greater than or equal to)	0
17	NON-NEGATIVE PRODUCT 2 PRODUCTION	13,33333333	>= (greater than or equal to)	0
18	PRODUCE UP TO 40 UNITS OF PRODUCT A	40	<= (less than or equal to)	40

Source: Developed by the authors

Still analyzing Figure 5, with this production, the amount of hours used in DEPARTMENT 1 (cell b14) equals the estimated weekly capacity, while the demand from DEPARTMENT 2 (cell b15) is lower than the demand stated in the constraint. In other words, Product B shows good results for the case under study. The constraint of DEPARTMENT 1 is limited by the "low" availability of its production resources, so investing in machinery for this department would increase production as well as the supply of its products. The time in DEPARTMENT 1 yields good results, as the time in this department was well below the weekly availability, allowing for more products to be made and increasing profits.

Regarding the non-negativity constraints, both variables were respected (both products had quantities greater than zero), and the constraint to produce up to 40 units of PRODUCT A per week was also respected, as the quantity suggested by the solver was 20, which is less than the 40 units specified in the constraint.

For future work, it is suggested to conduct research in a company with a different sector to obtain new comparison parameters for product development and decision-making regarding the obtained results. Along with the studies of the Theory of Constraints and linear programming, developing a mathematical model using more than one type of product for comparison could be beneficial. This would allow for an analysis of the results, determine the best product, and ultimately arrive at the best solution for the problems involved in the scenario.

IV. DISCUSSION AND CONCLUSION

Optimization, regardless of the industry it is applied in, is a valuable resource for improving a company's earnings. It is widely used to solve problems across various categories, and in the disposable industry, it is particularly important due to the limited availability of resources to fuel the production process of companies in this sector.

One way to optimize a company's profits is by using the Theory of Constraints in conjunction with linear programming to solve problems and achieve each company's objectives. Linear programming complements the Theory of Constraints by not only providing optimized results but also maximizing outcomes and assisting with decision-making alternatives within the company. In essence, linear programming is the same method used to solve problems aimed at minimizing or maximizing the objective function.

Linear programming follows the logic of the Theory of Constraints, maximizing results when using the linear programming tool with the solver/Excel feature. This allows the analyst to determine the best product for the company to increase its production process and profits. It is also important to note that while data analysis may show profit maximization in some cases, it may also indicate unsatisfactory results, thereby assisting the production engineer in making the best decision for the company.

Given the results obtained through modeling and mathematical programming, this optimization model can be regarded as efficient because it yielded good results for analysis and decision-making regarding the best product to be used by the company for profit enhancement.

In conclusion, this work highlights the importance of optimization in a company and identifies the best alternative for EMPRESA X to maximize its profits. As a result, the company should increase machinery in DEPARTMENT 1 and focus on the production of PRODUCT B. By making this decision, EMPRESA X will increase its profits and use less raw material.

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