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Reduction of Work in Process in Manufacturing Systems by Means of a Theory of Constraints Approach and Discrete Event Simulation

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Abstract: In the manufacturing companies, within their main requirements, it is considered the introduction of strategies and tools to improve the management of resources and production processes, in order to generate higher revenues, meet the needs of the client and increase their level of competitiveness. The high WIP and low income caused by inadequate management of its constraint resources are one of the situations that occur in companies that prevent its optimal development. This article proposes a methodology based on continuous improvement programming systems known as DBR and simulation of discrete events using ProModel® software. Through the application of these principles, we seek to reduce the level of WIP, applying mainly the technique for the development of successful simulation projects such as the authors Harrell, Ghosh, and Bowden, altering the variables of production and identifying constraint resources in the system. In this work it is possible to identify the constraints of a system, harmonizing each of the operations at the demanded rate by the bottleneck with the help of a simulation scenario, resulting in a reduction in the WIP, a reduction in the inventory costs and with it, an increase in throughput.

Keywords: Theory of constraints; Drum-Buffer-Rope System; Discrete event simulation; Work in process; Throughput; Bottleneck

I. INTRODUCTION

Manufacturing companies seek to achieve a good level of competition with their resources, in addition to maintaining and improving production plans and compliance levels, as well as reducing inventories of raw materials, work in process (WIP) and finished products[1].The mismanagement of the constraint (i.e., bottlenecks) is one of the causes that prevent manufacturing companies achieve their maximum performance and efficiency in their production systems. Theory of constraints (TOC) allow us to determine a better way to administer these constraints, which was developed by Goldratt in the early 1980s, was applied for the first time in planning and scheduling production to maximize the benefits and effectiveness of companies with respect to market requirements by identifying and exploiting constraint resources [2].

During the last decades, many methodologies where developed which were used to improve the quality and performance of any organization, some of these methodologies are Total Quality Management (TQM), Just in Time (JIT) and Theory of constraints. Each one of them deals with administrative philosophies with different characteristics, advantages, and disadvantages. Unlike these philosophies, the theory of constraints characterized by a focus on reducing and eliminating constraint resources that prevent the organization reaches the goal is usually to make money [3].

Within the philosophy of TOC, there are some tools to solve this problem in manufacturing constraints once bottleneck resources are identified, one is the programming of the drum-buffer-rope (DBR) system. In [4]show that the DBR system is to release the material according to the requirement of lower productivity, if a resource generates lower output than that demand, this becomes the bottleneck of the system, which impacts mainly on control WIP, because if the synchronization of resources does not match the bottleneck, production time and increase WIP system. In addition, this method guarantees a constant inventory level between the constraint resource and the raw material selection process [5]. WIP reduction leads to increased liquidity, improved cash flow, better customer service, and lower commercial risks [6].

There are a large number of systems and tools applied to the management and reduction of the WIP. For example, [7]managed to control the level of WIP in a metal-mechanical company using simulation with the IRIS tool and the electreTRI method, likewise [8]WIP management was carried out using the Kanban system and simulation by means of the ProModel® software in a company dedicated to harnessing wiring. On the other hand, [9]they made use of the value stream mapping (VSM) tool, managing to reduce the WIP and the cycle time in a company dedicated to the production of bearings, to mention some applications.

Furthermore, [10]pointed out that in recent years a series of tools linked to simulation have appeared that have seen rapid growth in their adaptation in industrial environments to improve the quality of the decision-making process. Recently [11]used the theory of constraints optimization considerations to detect the constraint resource and improve decision-making and profitability analysis in a company in the plastics sector. Taking into account these contributions, the main contribution of this work is to address the problems caused by inadequate management of constraint resources in production systems, which effect high levels of WIP. This was carried out through the TOC principles, the DBR programming system and discrete event simulation models (DES) specifically the ProModel® software, which will allow to appreciate a full scenario to obtain a reduction in the WIP and with it an increase in throughput ("the rate at which the system generates money through sales").

II. Methodology

All paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified.This section includes a series of stages and activities that lead to reaching the previously established objectives. For the development of a successful simulation project, it is advisable to carry the execution of a series of activities, for which the stages proposed by [12]considered in addition to the application of the five focal points of TOC [13]and principles of the DBR system [14]. A methodological process proposed, which will lead us to develop a simple simulation project in manufacturing processes through TOC approaches as shown in Figure 1. The following describes each of the proposed stages.

After establishing the objectives of the study, the first stage of this methodology is to define the operating characteristics of the system, in this stage the variables of interest and performance measures are defined [15]. Subsequently stage two corresponds to data collection, this is one of the most critical stages, since it is necessary to define with clarity and accuracy the data that the model requires to produce the desired results and that these are reliable [16].In addition, at this stage, the data referring to previously defined variables must be analyzed in order to establish their statistical behavior.

Stage three consists of the development and verification of the model which requires a total understanding of the entire system so that the model is as close as possible to the system under study, identifying the locations, arrivals, resources and the logical sequence of the process. The verification of the model is a necessary process that evaluates all the parameters used in the simulation, to corroborate that they work correctly. Since simulation requires programming operations involving complex probability distributions, any change can cause the simulation to behave very differently than expected [12].

Once a stable model is available, stage four consists of carrying out tests to demonstrate that the model is a representation like the real or proposed system. The validation can be carried out through experimentation, sensitivity analysis, expert opinion or hypothesis testing, making a comparison of the output variables and results obtained in the simulation [16]. If the system fails the validation test, it is necessary to return to stage one to rule out any failure in the previous steps.

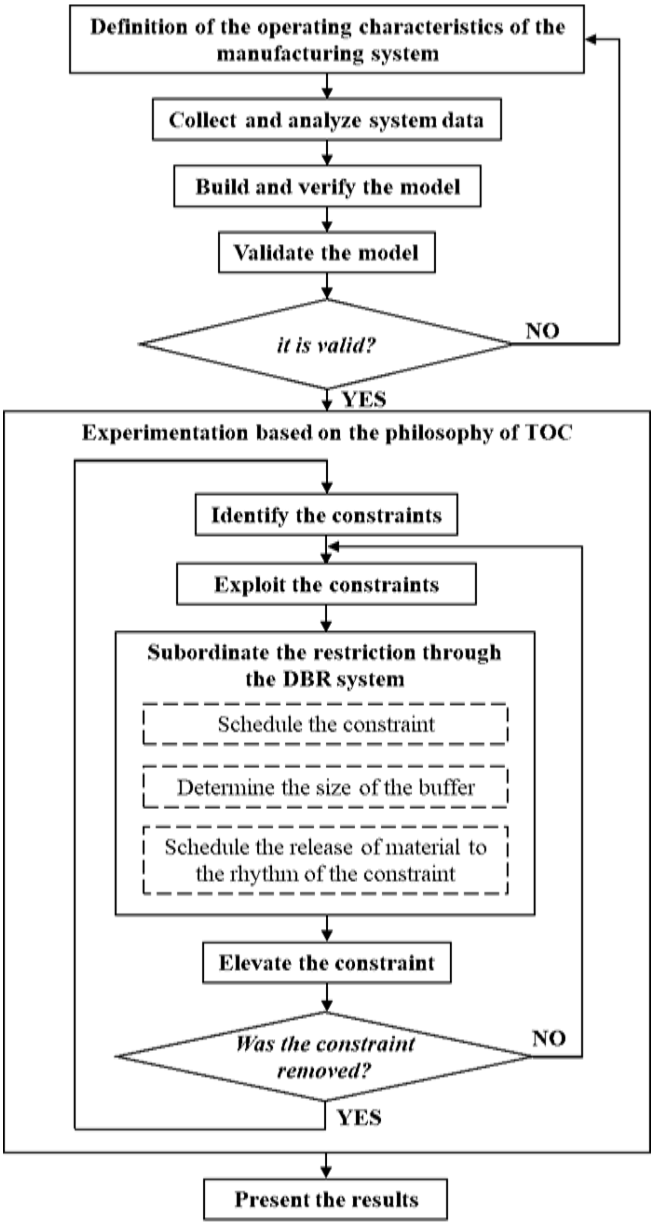

Figure 1. Proposed methodology.

On the other hand, if the validation was successful, in the next stage the experimentation and evaluation of the behavior of the system are carried out. Accordance with the proposed objective, a sensitivity analysis is performed to validate that these are the best results presented. In this section, the five focal points of the TOC will be applied to ensure that a production system meets its objectives, this through the use of the DBR system. This technique allows identifying the limitations with the following steps:

1. Identify the constraints

At this point, it determined which is the resource that limits the performance of the system, that is, detect the bottleneck analyzing the workload and the operation time of each resource identifying the operation with the highest percentage of use or with the highest number of inventories to process.

2. Exploit the constraints

By means of the simulation model, analysis and manipulation of the involved variables will be done to take advantage of the 100% system constraint, avoiding that the bottleneck has downtime. The exploitation of the constraint seeks to achieve the highest possible rate of return using the current resources of the organization.

3. Subordinate everything else to the above decision

The third step is to subordinate the other steps of the process, this is because the constraint determines the performance of the entire process. Therefore, an administration of the constraint will be carried out as a priority, trying to harmonize each of the resources according to the constraint, preventing it from having downtime. For this, the DBR system will be used, which has the following three principles [14]:

a. *Schedule the constraint.* Once the constraint identified, this will be the system drum, which determines the performance of the system. The function of the drum is to protect the shipping dates.
b. *Determine the size of the buffer*. The buffer is a small warehouse that protects the deliveries promised for the orders, from the unavoidable variations of the plant. A buffer is placed before the bottleneck resource to ensure that it always has something to operate. For this, there are three types, which are: constraint buffer (before bottleneck), sending (finished product inventory) and time (WIP time) [17].
c. *Schedule the release of material to the rhythm of the constraint.* This stage is known as the rope of the system its function is to communicate to the drum until the beginning of the process, with it the system will be subordinated to the rhythm of the constraint. If the bottleneck almost runs out of material to produce, the rope releases material at the first operation at a rate determined by the bottleneck.

4. Elevate the constraints

It means raising performance by adding capacity to the system at the constraint location. This may result in the acquisition of additional capacity, new machines or new technology to build or break the constraint [18].

5. If the constraint was removed, return to step one

Once the results are analyzed, the last step consists of collecting all the information and documentation of the model. Finally, the conclusions and results obtained in the simulation project presented by comparing the established performance measures.

III. MANUFACTURING SYSTEM DESCRIPTION

The present manufacturing system is of shared resources [19]. It will be analyzed using the methodology proposed in the previous section. This system can see in Figure 2, consists of three operations of which two of them shared (Machine B and C) and an independent (Machine A), which process three types of raw material (RM1, RM2, and RM3) with a cost of $60, $40 and $40 dollars respectively, to be processed and produce two types of products (product M and product N), each machine has 2,400 minutes a week.

The total of operating expenses is a constant of $12,000 dollars per week, raw materials not included in the weekly operating expense. The finished product is immediately delivered to the customer with a constant demand for product M 100 units per week with a selling price of $ 190 per unit and 50 units per week Product N with a selling price of $ 200 per unit. The system presents demand compliance problems.

In the next section, each of the stages of the methodology developed to the proposed system to later analyze if the expected results fulfilled.

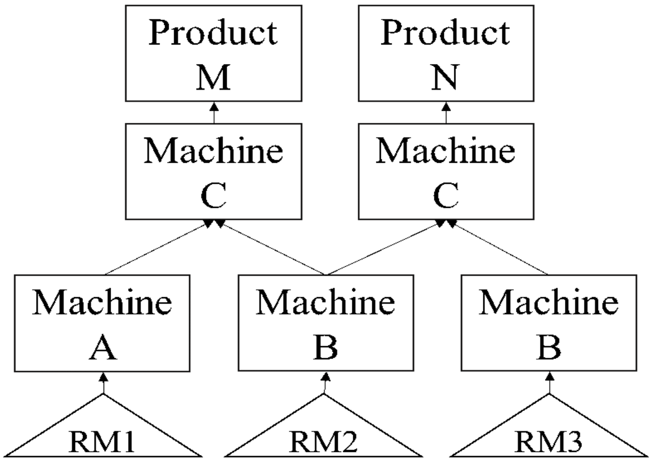

Figure 2. Operation diagram of the manufacturing system.

IV. ANALYSIS OF THE RESULTS

Stage 1. Define the operating characteristics of the system

Here the variables in the current system were defined in order to establish their behavior, as well as the performance measures to evaluate it, which introduced in the software.

- *Locations:* The system consists of three different machines, each with a unit capacity and a warehouse with unlimited capacity for each of the raw materials.
- *Entities:* Three different types of raw materials are declared RM_1, RM_2, and RM_3 plus two types of finished products Product M and Product N.
- *Arrivals:* Raw material 1 inscribe to the system one piece every 20 minutes, the raw material 2 arrives in the system one piece every 15 minutes and rawmaterial 3 enters the system one piece with a frequency of 75 minutes.
- *Process:* Each of the raw materials arrive at a warehouse destined for each one of them, later they start their transformation process in machine A and B with their corresponding processing times. Next they proceed to machine C, which is in charge of assembling the product M by means of a piece of raw material 1 with a piece of raw material 2, likewise the machine C assembles a piece of raw material 2 and one of raw material 3, to make a part of the product N. The pieces are transported from one machine to another at a time without transfer time.

The performance indicators established in [20] to determine the effectiveness of the proposed strategies are shown below, which were analyzed to detect how the WIP reduction affects each of them, these indicators can be calculated automatically by generating global variables provided by the ProModel® software.

- *Work on processes (WIP)* is partially completed goods of a company that awaits finalization and final sale.
- *Units produced (PT)* by means of this indicator will measure the production capacity.
- *Inventory (I)* is the money that the system has invested in buying material that it expects to sell.
- *Throughput (TH)* is the speed at which the system generates money through sales.

Stage 2. Collection and analysis of data

For this case, the data will be taken directly from the proposed problem, it will only be necessary to analyze them and check the results in the simulation model. The processing time of each machine per piece detailed in table 1:

TABLE 1. THE PROCESSING TIME OF EACH MACHINE PER PIECE.

Machine	***Processing time***
Machine A	20 minute / piece
Machine B	15 minute / piece
Machine C	15 minute / piece

Step 3. Build and verification model

Once the variables and data of the system were established, they were entered into the program to build the simulation model that will reproduce the behavior of the current manufacturing system. The verification was carried out through the use of tracking provided by the ProModel® software, called Trace, which allowed analyzing the behavior of the system step by step and verifying that it operates as expected. The design of this system is shown in figure 3.

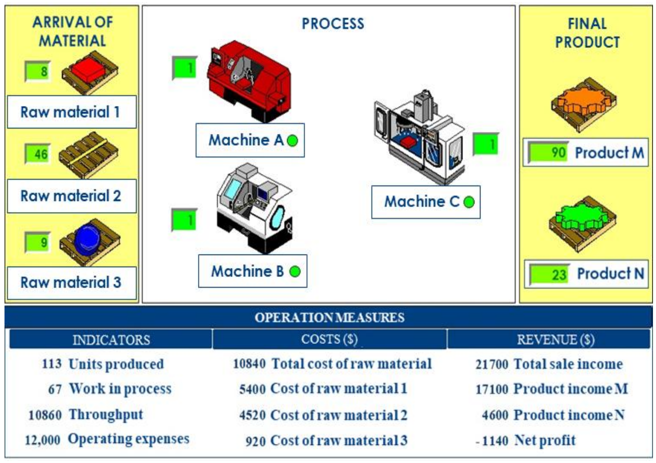

Figure 3. Representation of the current ProModel® system layout.

Stage 4. Validation of the model

In this stage a failure was caused to validate that the system worked as expected, small changes were made in the parameters in the arrivals of material, causing small changes in the results of the simulation which were expected. By introducing the faults into the model, the behavior of the model presents expected changes, thus demonstrating that the model adjusted to the proposed model.

Stage 5. Experimentation based on the philosophy of TOC

As mentioned in the previous section, in this stage the implementation of the TOC philosophy is carried out, obtaining the following results.

Identify the constraint

Table 2 shows the status of the resources obtained by the software where *% Op* refers to the percentage of time the location was in operation, *% Setup* is the percentage of time the location was in preparation, *% Idle* means the time that the location was idle due to lack of material, *% Waiting* is the percentage of time expected by an entity to assemble, *% Blocked* is the time that the entities remain blocked in the location and lastly *% Down* to the percentage of time for stoppages not programmed. In this table, you can identify the constraint as the operation that its percentage of use is elevated than the rest of the resources, in this case, the machine B wants 15 minutes to process the product M in addition to another 15 minutes to process the product N, obtaining as Result 85.83% of operation as shown in Table 2, which identifies it as the bottleneck resource.

TABLE 2. GENERAL REPORT. LOCATION STATES SINGLE (PROMODEL®).

Name	*% Op.*	*% Setup*	*% Idle*	*% Waiting*	*% Blocked*	*% Down*
Mach A	76.04	0.00	0.00	0.00	23.96	0.00
Mach B	85.83	0.00	0.00	14.17	0.00	0.00
Mach C	70.83	0.00	14.79	14.38	0.00	0.00

Exploit the constraint

Table 2 shows that the constraint resource has an operating percentage of 85.83% and a waiting time of 14.17%. To attack this percentage of waiting time is analyzed that the raw material 2 that is processed remains to wait to be assembled while the machine C is kept assembling. Therefore, it proposed to change the number of pieces transferred from the machine B to the machine C, converting it to lots of transfer of 4 pieces, thus avoiding that the bottleneck is kept on hold. By making this change, a 100% utilization percentage was obtained in the bottleneck as shown in Table 3.

TABLE 3. GENERAL REPORT.LOCATION STATES SINGLE (PROMODEL®).

Name	*% Op.*	*% Setup*	*% Idle*	*% Waiting*	*% Blocked*	*% Down*
Mach A	83.33	0.00	0.83	0.01	15.83	0.00
Mach B	100.00	0.00	0.00	0.00	0.00	0.00
Mach C	77.50	0.00	20.21	2.29	0.00	0.00

Subordinate the constraint

To subordinate theconstraint the following three stages were developed:

*Schedule the constraint:*The bottleneck or constraint is the drum, which determines the performance of the system. The function of the drum is to protect the shipping dates and as can be analyzed in the description of the system, the customer demands 100 units of product M and 50 units of product N a week, but the system only has the capacity to produce only 100 units of product M and 30 units of product N with an availability of 40 hours per machine. Therefore, we can observe that the bottleneck resource does not have enough capacity even working with 100% of its capacity, to cover the weekly demand of the client.

Determine the size of the buffer: The size of the buffer that will protect the constraint of fluctuations in the system was calculated, such as the delay in the arrival of the raw material 2 to machine B. The size of the constraint buffer was chosen intuitively on the basis of several simulated initial executions made to give some kind of instinct since the initial decision must take into account that the size of the buffer must be quite long until it is realistic. The size of the buffer can be three times greater than the average time of the constraint. So a buffer was placed before the constraint with a protection time of one hour for the raw material 2.

Schedule the release of material to the rhythm of the constraint: After establishing a protection buffer it is necessary to modify the arrivals, this is the system's rope. Depending on the production rate of the bottleneck resource, therefore, when manipulating the input variables of the system it was decided to schedule the arrival of raw material 2, in lots of 10 units every 3 hours and raw material 3, they will arrive 8 pieces every 12.25 hours.

Elevate the constraint

At this stage, it is necessary to increase the capacity of the resource through an economic investment. This is only done if steps 2 and 3 do not increase the restraint capacity in such a way that it does not meet the client's requirements, this decision will depend on the interests of each company. In this case, when analyzing the results of the system, even with 100% capacity in the constraint resource. So, a solution to be able to meet the client's demand could be to work overtime hours each week, but the company would raise operating expenses while maintaining this demand. Therefore, it will be advisable to invest in the purchase of a second B machine in which an initial investment would be made but the capacity to meet the current customer's demand would be increased, as well as having the capacity for more orders.

Stage 6. Documentation and presentation of results

Next, the results obtained are shown when evaluating each of the established performance measures, making a comparison between the current state of the system and the results obtained by applying the proposed methodology.

Work in process (WIP)

In Figure 4, a comparison of the WIP behavior is shown in each of the modifications made to the analyzed manufacturing system. It can be seen as in the current system, the number of pieces that were kept in the system at the end of the week was 66 units, were subsequently applied the principles of TOC and DBR system obtaining a reduction in the number of parts in the system at the end of the week of 16 pieces. Finally, it is observed that by applying each of the stages of the methodology and also making an investment when buying a second B machine, the WIP inventory was reduced to only 7 units in the system.

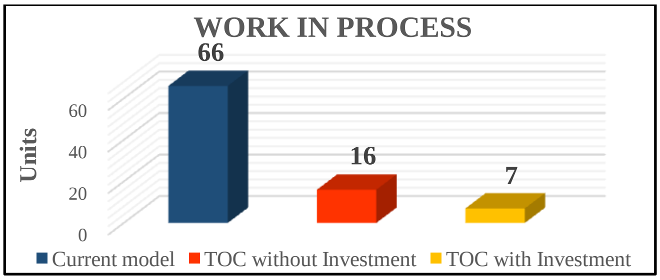

Figure 4. Results of the WIP in each of the systems analyzed.

Units produced (PT)

As mentioned in previous sections, the current system did not have sufficient capacity to satisfy the needs of the client, producing only 113 units, 90 parts of product M and 23 parts of product N, by implementing the proposed methodology a total of 128 units, 100 and 28 respectively. Finally, when carrying out the methodology and an initial investment, a total of 156 units is obtained, achieving that the system meets the demand needs as shown in figure 5, this is due to the fact that in the model that operates under the developed methodology is considered an initial stock buffer so that the restrictive resource, which is the one that determines the number of pieces that leave the system, start and maintain its maximum capacity.

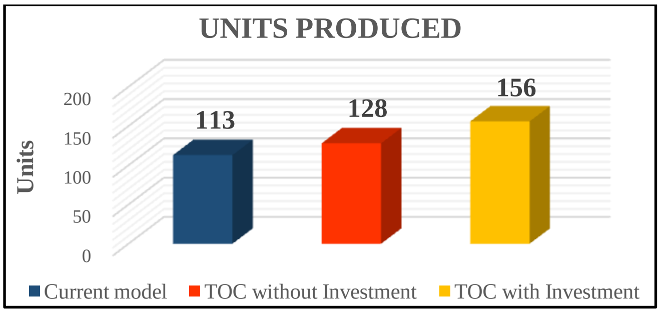

Figure 5. The result of the units produced in each of the systems analyzed.

Inventory (I)

This indicator is directly related to the amount of WIP. The results of the inventory for each of the models are shown in Figure 6, where you can see how the current model shows an investment in raw material of $ 2,840 dollars, the model developed with the methodology shows an inventory level of $ 640 and the Improvement model with initial investment shows a result of $ 280 dollars of inventory. This is because in the model operating under the methodology developed, the material is released in a controlled manner and this leads to the generation of a smaller amount of WIP and with it a lower investment of raw material.

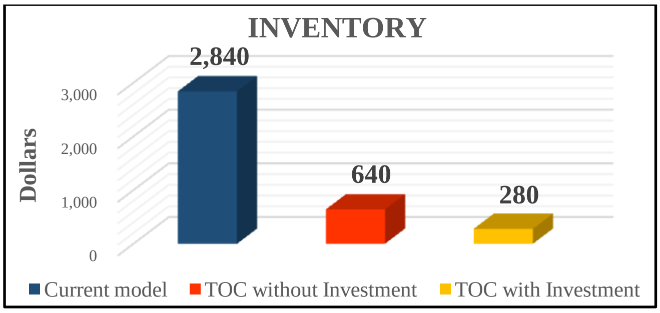

Figure 6. The result of inventory costs in each of the systems analyzed.

Throughput (TH)

In Figure 7, it shows how to implement the methodology based on the principles of TOC, the throughput of the system increases obtaining a result of up to $ 15,000 dollars, the original model worked making a throughput of $ 10,860 dollars per week. This is due to the fact that more units produced, which is an advantage that is reflected in higher revenues.

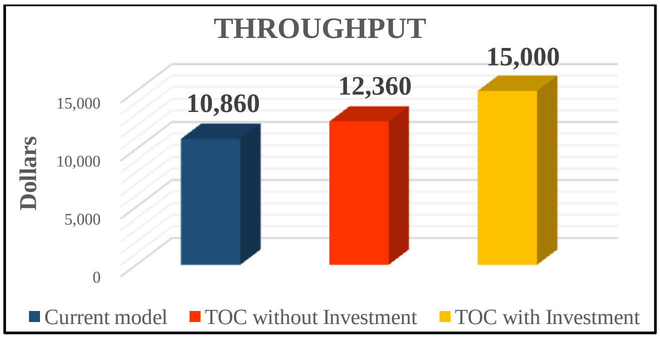

Figure 7. The result of the throughput in each of the systems analyzed.

By establishing each of the performance indicators previously evaluated, figure 8 shows the percentage of improvement in each of them, in addition to this section, it can analyze the net income (1) and the return on weekly investment (2) what the system generates before and after the methodology.

$$\text{Net income} = \text{Throughput} - \text{Operating expenses}(1)$$

$$\text{Performance} = \frac{\text{Net income}}{\text{Inventory}}(2)$$

The net profit that it presents in the current system does not satisfy the customer's demand with a total loss of $ 1,140 dollars per week, later the TOC system without investment makes a net profit of $ 360 dollars and finally the TOC model with investment makes a net profit of $ 3,000. On the other hand, the performance of the current system is 40%, then the TOC system without investment produces a yield of 56% and finally the TOC model with investment generates 107.1% yield.

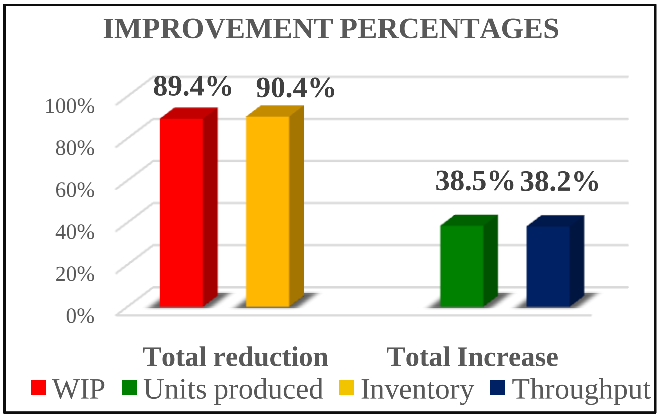

Figure 8. Percentages of improvement in each of the indicators.

V. Conclusions

In this research a methodological proposal was developed based on the principles of TOC and simulation of discrete events, to identify the constraint, exploit it to maximize the utility, harmonize the non-restrictive resources of the system to the constraint, increase the operation of the bottleneck by using the DBR continuous improvement system, making use of ProModel® software. The implementation of these strategies managed to improve the capacity of the constraint, increasing the production in the system by 38.05% and therefore allow compliance with 100% of the demand both in quantity and delivery times.

When analyzing the results obtained in addition to the productive improvement, the WIP was reduced by 89.4%, which generated a reduction in inventory costs by 90.14% and an increase in the Throughput of 38.12%, causing an increase in the net profit of $ 1,860 dollars weekly and an improvement in return on investment of more than 100%. This methodology shows a significant advantage in the decrease of the WIP, this fact has been confirmed by the simulation carried out using the ProModel software.

Taking into account the results of the research, it can be said that not only the application of the principles of the theory ofconstraint but the implementation of simulation tools, allow manufacturing companies to appreciate a clearer scenario for decision making in processes, generating a competitive advantage and being more productive, while increasing profits and return on investment. The implementation of the proposed methodology in a real-world production system and the documentation of results is purposed as future work.

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