Increasing The Potential of Bolivian Manufacturing Systems Through Factory Physics and The Theory of Constraints: A Case Study

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Abstract

Companies in Bolivia and other developing countries face challenges in staying competitive in the global market. One issue is the lack of defined work methodologies, leading to disorganization and waste of resources. This paper proposes to address this problem by combining two theories, Factory Physics and the Theory of Constraints (TOC), to improve production processes in Bolivian manufacturing firms. Factory physics looks at relationships between quantities and performance, while TOC focuses on identifying and addressing constraints preventing desired performance levels. By combining both methodologies, we developed an improvement strategy and evaluated it through computational simulation models for a Bolivian furniture manufacturing firm. The results suggest that combining these methodologies can significantly increase productivity for Bolivian manufacturing firms.

Keywords

Theory of constraints, Factory physics, Simulation, Productivity, Furniture industry.

1. Introduction

Globalization and the growing market needs require companies to adopt innovative techniques that allow them to be competitive in the face of customer demands. In Bolivia, as in other developing countries, the operational characteristics of industries are based mainly on improvised work. In other words, compared to developed countries, no defined work methodology allows them to optimize their processes or efficiently allocate manufacturing resources. This aspect leads, among other problems, to a lack of understanding among workers of the importance of basic production measures, disorganization in production planning, poor management, and waste of productive resources. Considering these limitations, our research aims to combine two production theories (Factory physics and the Theory of constraints-TOC) to improve the production processes of a manufacturing firm in Bolivia. In particular, Factory physics and TOC aim to enhance the performance of manufacturing systems by identifying and addressing the constraints limiting their efficiency and productivity. However, while factory physics focuses on the relationships between manufacturing quantities and the performance of the production process, TOC focuses on identifying and addressing the constraints preventing the organization from achieving its desired performance levels. Hence, combining both methodologies, we studied a low-productivity Bolivian firm dedicated to producing custom-made furniture. After analyzing their manufacturing system through factory physics and TOC, we proposed an improvement production strategy. Based on these analyses, we simulated the improved production system to evaluate the impact of the improved production strategy. Our results suggest that Bolivian manufacturing firms can significantly increase their productivity by combining both methodologies in their day-to-day operations.

2. Literature review

2.1. Factory Physics

Factory Physics provides the essential relationships between fundamental manufacturing quantities such as inventory, cycle time, yield, capacity, variability, customer service, etc. (Hopp and Spearman 2011). Additionally, it provides a description expressed in the form of laws of the behavior of a production system. This information helps decide which performance measures to collect, which alternatives to evaluate, and interpret the results in a simulation (Standridge 2004).

Some necessary definitions presented by Pound et al. (2014) to better understand the physics of factories are detailed below:

- Throughput (TH): A product's average production rate. In other words, the amount of materials or elements per unit of time flowing through a system or process.
- Work in process (WIP): It refers to any intermediate product between the initial and final points of the production line.
- Cycle time (CT): It is the average time from the release of a job at the start of the production line until it reaches an inventory point at the end of it.
- Bottleneck rate (rb): It is defined as the production rate of the workstation with the highest utilization.
- Uninterrupted process time (T_0): The sum of the average times of the different processes that make up the production line.
- Critical amount of work in process (W_0): The level of unfinished products a production line must have to achieve maximum performance.

Little's Law

There are three essential measures of a production line: the throughput (TH), the amount of work in progress (WIP), and the cycle time (CT). These three fundamentally relate to Little's Law (Hopp and Spearman 2011). It is usually written as:

$$WIP = CT \times TH$$

Little's Law can be applied to a single station, a production line, or plant. As long as the three quantities are measured in coherent units, the above relationship will hold in the long term.

Internal Benchmarking

The internal benchmarking methodology compares three cases: the best case, the practical case, and the worst possible case. As Figure 1 shows, by collecting data on the average WIP, production rate, and cycle time of an actual production line, it is possible to quantitatively establish the current performance of the line compared to how well it could function (Hopp and Spearman 2011).

a. *Best performance case*: shows the results that the production line would have under ideal conditions. That is, the minimum cycle time and maximum performance while also having a minimum waiting time.
b. *Worst performance case*: determines the production line's maximum cycle time and minimum performance.
c. *Practical worst-performance case*: refers to an intermediate performance between the previously mentioned cases. This case, unlike the others, involves randomness (Standridge 2004).

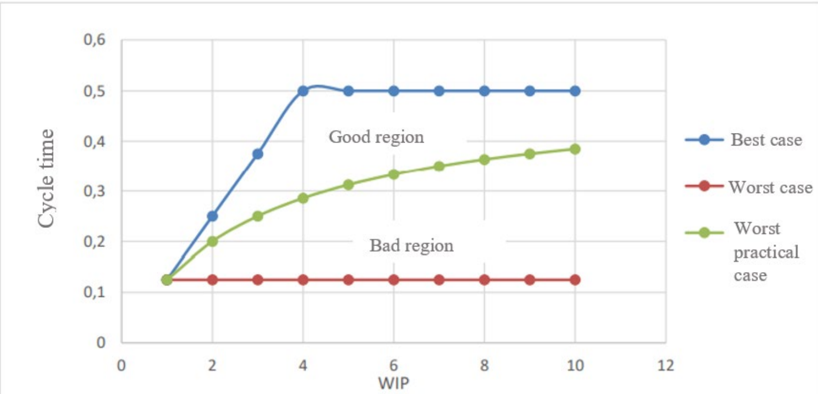


Figure 1. Internal Benchmarking Chart

2.2. Theory of constraints

The Theory of Constraints (TOC) is a management philosophy introduced by Dr. Eliyahu M. Goldratt in 1984 (Voehl, Harrington, & Charron, 2014). It is based on the principle that complex systems exhibit inherent simplicity.

According to Goldratt (2014), in the TOC, activities in a company are similar to a chain, and every chain has a weak link defined as a constraint. Since the chain's strength depends on the weakest link, the weakest link must be strengthened first. Strengthening the most vulnerable link means eliminating the constraint to improve the system. According to this theory, at least one constraint in any company prevents management from achieving its objectives. Therefore, defining and eliminating constraints is necessary to increase the company's production capacity (Blackstone, 2013).

TOC has five steps:

1. Identify the constraints.
2. Exploit the constraints effectively.
3. Subordinate all decisions related to the constraints.
4. Elevate the constraints.
5. Start again from the first step when the constraint is elevated.

2.3. Factory physics and theory of constrains

Factory physics and theory of constraints (TOC) are both management philosophies that aim to improve productivity and efficiency in manufacturing systems. Both seek to optimize the performance of a production system. However, they approach the same problem from different perspectives.

While factory physics uses mathematical models to analyze and improve the flow of materials, information, and resources through the system, TOC focuses on identifying and resolving constraints that limit the system's productivity. In particular, TOC provides a framework for identifying the key constraints in a manufacturing system and then using that information to focus improvement efforts. On the other hand, factory physics offers the tools and techniques for analyzing the behavior of those constraints and understanding how they impact the overall system performance. Therefore, factory physics and TOC are complementary approaches that can be used together to improve the performance of manufacturing systems. By combining the scientific insights of factory physics with the management philosophy of TOC, organizations can significantly improve efficiency, quality, and profitability.

2.4. Manufacturing systems in developing countries

Due to globalization, developing countries often face significant challenges in designing viable manufacturing systems and thus rely on service sectors, mining, and agriculture (Atieh at el. 2022). Some of the most significant issues faced by firms from developing countries are economic challenges, political instability, and social and environmental problems (Akamp and Müller 2013). Specifically, the most significant issues within the production processes are related to increased use of resources, excessive goods-in-process, lack of standardized work methods, low product quality, and high inventories (Goonatilake 1990). In addition, managers of these manufacturing firms have little to zero knowledge of basic concepts and elemental production measures that could help them optimize their production systems.

Mainly, Bolivia is one the least developed countries in the Americas, and its firms suffer many management problems mentioned above (Herbas-Torrico et al. 2021). Moreover, it's important to note that the Bolivian economy is not industrialized and has few large and many small firms. Eight out of ten jobs are related to these small firms, constituting 83% of total Bolivian employment (Opinión 2017). Furthermore, after a bibliographic review, we did not find literature on implementing production methodologies in Bolivian firms, such as the TOC, lean manufacturing, factory physics, kaizen, etc.

3. Case study

We studied a small Bolivian firm dedicated to furniture manufacturing as a case study, aiming to analyze its current processes to improve them and become more competitive. Specifically, the study's objective is to understand and analyze the manufacturing practices of firms in developing countries. Similarly, we want to determine the applicability of renowned manufacturing methodologies, such as factory physics and TOC, in a firm from a developing country.

3.1. Company specification

We studied a manufacturing firm with 25 years in the Bolivian market dedicated to manufacturing and commercializing custom-made furniture. It currently has four production lines, with the main line being the BP line, which is the focus of this analysis. The production line has fifteen operators, three primary machines, and eight sequential processes: cutting, selection, edging, machining, assembly, cleaning, and packaging.

3.2. Improvement strategies

Initially, we analyzed the main production line. To achieve this goal, the following activities were done: (a) graphic representations of the production line (flowchart, process diagram, value-added diagram, and travel diagram), (b) time study, and (c) simulation of the current production process. Next, we moved to the strategic phase with the following activities: (a) determination of variables and parameters, (b) development of improvement strategies, (c) benchmarking of the current and improved process, (d) improved process simulation with improvements, and (e) statistical analyses.

4. Results and discussion

4.1. Production line specification

The production line we analyzed has eight sequential processes, as shown in Figure 2.

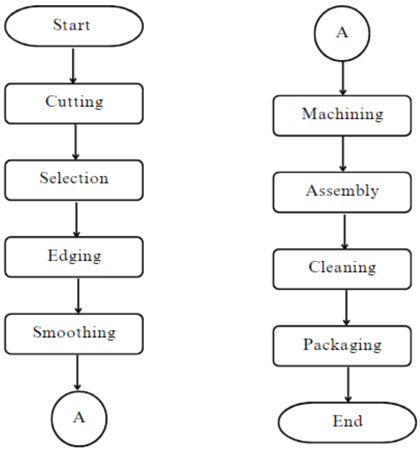


Figure 2. Flowchart of the production line

To better understand the production process, Table 1 presents activities from Figure 2 and defines the type of process, the machinery involved, and the operators in charge.

Table 1. Detail of machinery and workers

Num.	Operation	Type of process	Machinery	Worker
1	Transport 1	Manual		Workers 1 y 2
2	Cutting	Semi-automated	Sektor 450/750	Worker 1
3	Transport 2	Manual		Worker 2
4	Selection	Manual		Worker 3
5	Transport 3	Manual		Worker 4
6	Edging	Semi-automated	Akron 400	Worker 5
7	Smoothing	Manual		Worker 6
8	Transport 4	Manual		Worker 7
9	Machining	Semi-automated	Skipper V31	Worker 8
10	Transport 5	Manual		Worker 15
11	Assembly	Manual		Worker 9 y 10

12	Transport 6	Manual		Worker 9 y 10
13	Cleaning	Manual		Worker 11 y 12
14	Transport 7	Manual		Worker 13
15	Packaging	Manual		Worker 14
16	Transport 8	Manual		Worker 13

4.2. Time study

We followed the methodology outlined by Niebel and Freivalds (2009) to conduct the time study. The data collection for the time study consisted of timing the operations for three months. Considering these measurements, we calculated each operation's average, standard deviation, and necessary sample size. Subsequently, we performed statistical tests for normality on the collected times. Next, we used the Westinghouse Rating System to calculate the normal time. Finally, tolerances were assigned, and we calculated the standard times for all operations. The results are presented in table 2.

Table 2. Standard time per operation

Operation	**Average time**	**Performance rating**	**Normal time**	**Tolerances**	**Standar time**	**Units**
Transport 1	0.247	1.130	0.279	8	0.302	min/tab
Cutting	8.229	1.130	9.298	10	10.228	min/tab
Transport 2	0.133	1.130	0.150	5	0.158	min/part
Selection	0.615	1.190	0.732	23	0.901	min/ part
Transport 3	0.134	0.950	0.128	8	0.138	min/ part
Edging	1.072	0.950	1.018	18	1.201	min/ part
Smoothing	0.216	1.080	0.234	20	0.280	min/part
Transport 4	0.256	1.140	0.291	7	0.312	min/part
Machining	2.688	1.160	3.118	10	3.430	min/part
Transport 5	1.655	1.130	1.870	6	1.982	min/mod
Assembly	9.480	1.130	10.712	21	12.961	min/mod
Transport 6	0.684	1.130	0.773	14	0.881	min/mod
Cleaning	12.400	1.200	14.880	16	17.261	min/mod
Transport 7	1.484	1.030	1.529	14	1.743	min/mod
Packaging	3.906	1.030	4.024	9	4.386	min/mod
Transport 8	3.185	1.030	3.281	14	3.740	min/mod

4.3. Simulation of the production process

With the standard times for each operation defined, we developed a production line simulation using the Tecnomatix plant simulation software, following the guidelines provided by Bangsow (2016). The layout of the model, presented in Figure 3, was designed considering the actual dimensions and distribution of the production line.

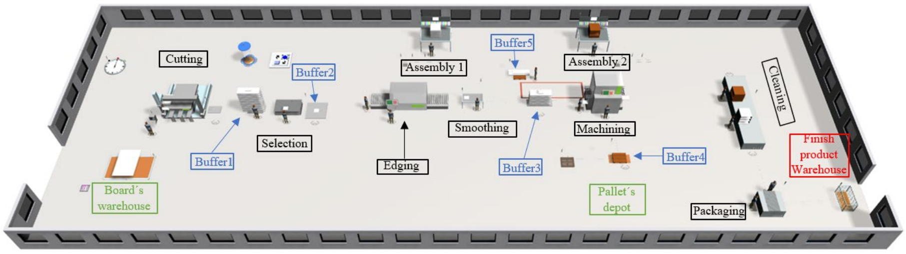


Figure 3. Simulation model of the current production process

The simulation model allowed us to extract the following results: (a) time distributions at each station, (b) time distributions for each worker, and (c) time distributions for each operation. These are shown in figures 4, 5, and 6.

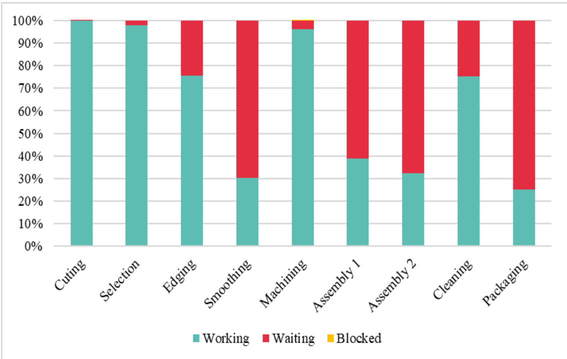


Figure 4. Distribution of time at stations

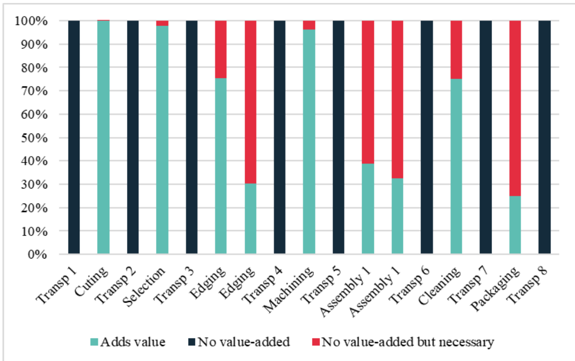


Figure 5. Distribution time of identified operations

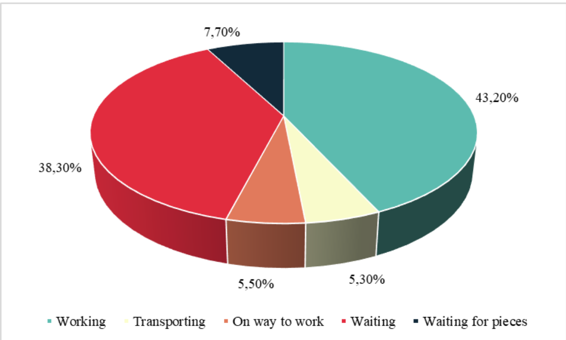


Figure 6. (a) General distribution of worker's time

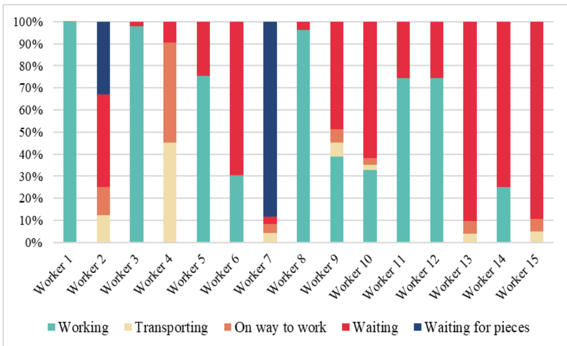


Figure 6. (b) Individual distribution of worker's time

The different operations in the production line present various states throughout the simulation run. These can be working, waiting, and blocked.

Figure 4 shows that the cutting, selection, and machining operations have the highest percentage of time working (on average 98.0%), which implies greater utilization. On the other hand, the assembly, cleaning, and packaging operations have waiting times percentages above 60%. This result occurs because they are downstream operations and require the previous stations to finish processing their parts before they can begin their activities.

Regarding figure 5, four of the sixteen operations show high percentages of non-added value processing times (over 50%). On the other hand, the figure also indicates that transportation operations do not add value but are necessary for the production line. Although currently, the firm cannot eliminate them, efforts should be made to reduce transportation distances.

Additionally, Figures 6. (a) and 6. (b) show the distribution of workers' time. These figures show that a high percentage of workers' time is spent waiting (38.3%), and their value-added time is only 43.2%.

4.4. Determination of variables and parameters

Through the simulation of the current production process and information on the study variables, we collected data regarding: (a) cycle time, (b) average production, and (c) the amount of work in process. Based on this information, we calculated the following parameters: (i) cycle time without interruption, (ii) critical amount of work in process, and (iii) bottleneck rate. Table 3 presents the variables and parameters of the current production process:

Table 3. Variables and parameters of the current production process

Variables	Cycle time	1 hr 43 min 49 seg
	Throughput	27,8 products
	WIP	69 parts
Parameters	Cycle time without interruption	1 hr 40 min
	Bottleneck rate	0,036 min/prod
	Critical level of WIP	3,66 parts

4.5. Development of improvement strategies

We developed improvement strategies iteratively following our theoretical framework (TOC). This way, we identified different limitations and bottlenecks that negatively influenced production line efficiency.

Since there are no reworking processes in this line, the limitations were identified by calculating the production rate of each value-adding process. i.e., we identified the process with the highest utilization rate as a constraint, and afterward, we proposed improvement initiatives.

In Table 4, the production rates for each process are shown:

Table 4. Production rate of processes current model

Process	Stations	Throughput (prod/min)
Cutting	1	0.159
Selection	1	0.139
Edging	1	0.104
Smoothing	1	0.446
Machining	1	0.036
Assembly	2	0.154
Cleaning	2	0.116
Packaging	1	0.228

Identification of constraint 1 and improvement

The process with the highest utilization rate is machining, making it the first bottleneck. We considered that the company owns a different machine to overcome this restriction. However, this machine requires more operator intervention and is located far from the machining area of the production line. This means that the standard processing time for each piece will be longer, but it will increase the overall production rate of the process. We proposed positioning a multiple machining machine in the machining area parallel to the Skipper V31 machine to reduce transportation times.

We implemented a pilot test to find the processing time of a product using the multiple machining machine, which subsequently allowed us to determine the standard time of this new workstation called Machining 2. As a result, the machining production rate increased by approximately 49%. While it is still lower than the production rate of other processes in the line, implementing the machine will allow more pieces to be processed during the workday and the line balancing to improve.

Identification of constraint 2 and improvement
The new bottleneck of the production line is the edging process, with a production rate of 0.10 modules per minute. We suggest the company refurbish its other edging machine to improve this bottleneck, which currently requires maintenance.

Since this machine has been in operation for a considerable period and has undergone depreciation, the maintenance technician advised that its speed will be approximately 20% lower than indicated in the manual. This result means its standard processing time will be 20% longer than the current machine's. To determine the improvement's effect, we again calculated the production rate per process. It increased from 0.10 to 0.19 minutes per product.

Identification of constraint 3 and improvement
The process with the highest rate now corresponds to cleaning, with 0.12 minutes per product. In addition to being identified as a bottleneck, we note that this process has the highest standard time and more significant variability. This result occurred because the cleaning workers were responsible for cleaning the modules and correcting imperfections. Among the activities they perform are: refining the trimming of pieces, sanding cracks, removing excess glue, and fixing defects on the surface of the wood, among others.

To understand the percentage of time the workers spend removing glue, we implemented a pilot study to only measure the time for this specific task. Considering the standard times determined in the cleaning process, we found through calculations that the time spent removing excess glue from the products corresponds to 23.33% of the total time.

Since this percentage is high, the improvement strategy will be applied in the assembly process. We propose standardizing the glue used to apply only the necessary amount. This way, we will reduce the glue waste and, simultaneously, the cleaning time workers spend removing the excess.

The standard time of the cleaning process after applying the improvement will reduce from 17.26 to 14.21 minutes. The production rate will increase from 0.12 to 0.14 minutes per product.

Identification of constraint 4 and improvement
The fourth bottleneck corresponds to the selection process, with a production rate of 0.14 minutes per product. We proposed reducing the utilization rate by adding an extra operator for the improvement strategy. We carried out a pilot test to estimate the operation time of the new worker at this station. After receiving instructions from the selection operator on performing the job, we timed the new operator and determined the standard time.

The production rate of the selection process increased from 0.14 to 0.22, an approximate 36% increase.

Table 5 shows the production rates by process of the proposed model

Table 5. Production rate of processes in the proposed modelProceso	**Stations**	**Throughput (prod/min)**
Cutting	1	0.16
Selection	2	0.22
Edging	2	0.19
Smoothing	1	0.45
Machining	2	0.07
Assembly	2	0.15
Cleaning	2	0.14
Packaging	1	0.23

4.6. Simulation of the proposed model

We modified the initial production line according to the improvement strategies proposed above. The modifications made to the model were as follows:

1. Installation of the multiple machining machine on the production line.
2. Installation of the Homag edge banding machine on the production line.
3. New processing times in the cleaning station.
4. Addition of an auxiliary operator to the selection area (operator 16).

Figure 7 shows the distribution of the simulation model with the proposed improvements.

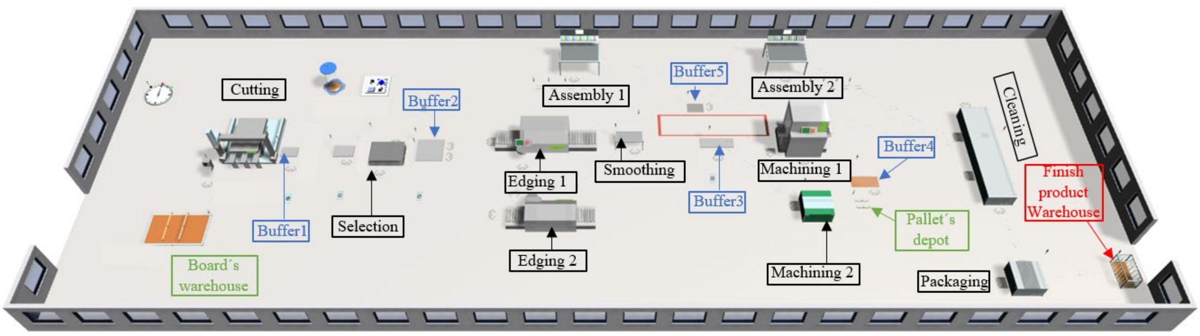


Figure 7. The layout of the production line in the proposed model

After modifying the simulated model, we executed 50 runs of the new production line (proposed model). As well as in the current model, we could extract results. Figures 8 and 9 present the time distribution for the stations and operators in the event of implementing the proposed improvements.

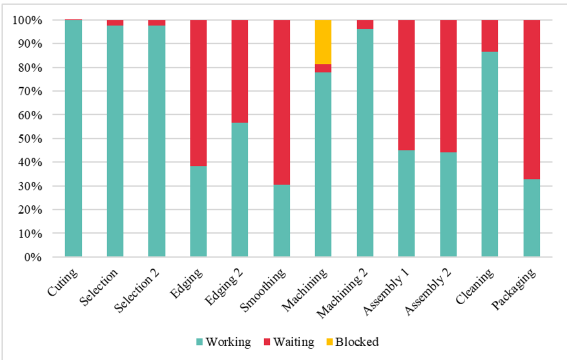
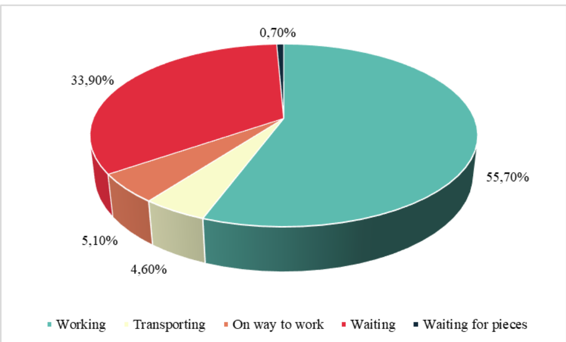


Figure 8. Distribution of time at stations



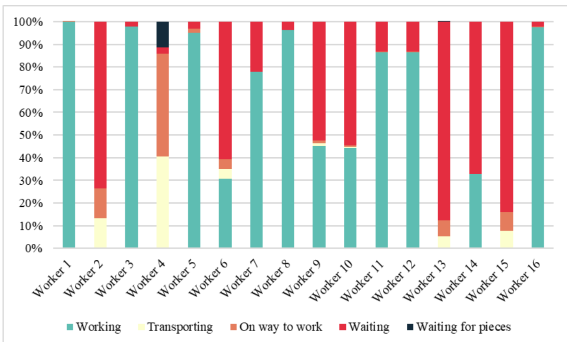


Figure 9. (a) General distribution of worker's time Figure 9. (b) Individual distribution of worker's time

Figure 8 shows that the assembly and cleaning stations have higher working time percentages than the current model, with an approximate increase of 10% in each station. Regarding the machining and edging stations, the waiting times in these processes increased due to the implementation of the machines, but their production rates also increased.

The distribution of operator time also shows improvements in the proposed simulation model. Operators spend 55.7% of the total time working in this model, an increase of 12.5% compared to the current model (43.2%). The results also indicate a significant reduction in the time workers spend waiting, approximately 12% (considering both waiting time and waiting for pieces). Altogether, this reflects better labor resource utilization in the proposed simulation model.

Table 6 presents the variables and parameters of the model with the implementation of the proposed improvements.

Table 6. Variables y parameters of the proposed simulated model

Variables	Cycle time	1 hr 30 min 56 seg
	Throughput	36,32 products
	WIP	43 products
Parameters	Cycle time without interruption	1 hr 22 min 47 seg
	Bottleneck rate	0,07 min/prod
	Critical level of WIP	5,81 products

4.7. Production benchmarking

We proceeded to develop the benchmarking of the production line with the improvement strategies. This activity allowed us to visualize the parameter values for the best theoretical performance case, the worst theoretical performance case, and the worst practical performance case. Additionally, we included in the graph the case of the current production line and the case of the line after each of the iterations using TOC (IT1, IT2, and IT3). The proposed simulated model corresponds to the last iteration carried out during the development of the improvement strategies.

The results obtained are presented in figures 10 and 11.

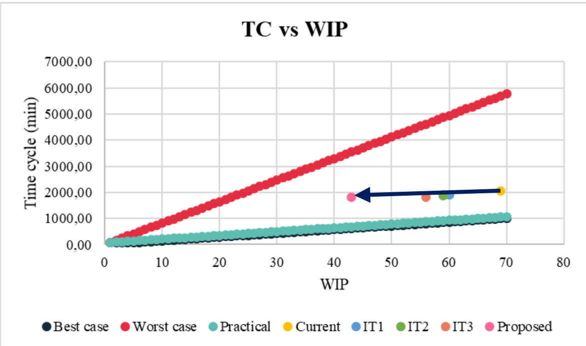


Figure 10. TC vs. WIP

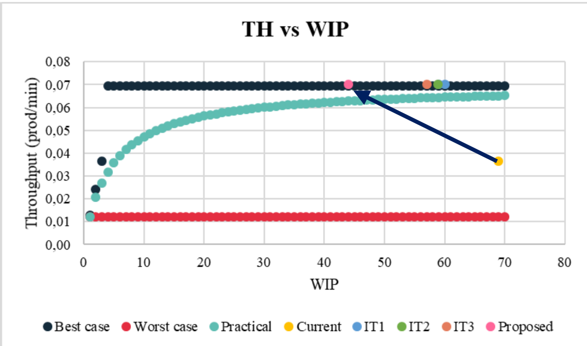


Figure 11. TH vs. WIP

Figures 10 and 11 show that if the proposed strategies are applied, the number of products in the process will significantly improve. Both figures show that with each iteration using the theory of constraints, the number of products in the process decreased.

On the other hand, we observed a significant improvement in benchmarking the relationship between throughput and the amount of goods-in-process between the actual case of the BP production line and the case of the proposed simulated model. The current situation of the BP line is far from the best performance case, indicating opportunities for improvement. The proposed model is close to the best case, reflecting an increase in the line's performance and, as a result, an improvement in the utilization of its resources.

4.8. Statistical improvement analyses

To better demonstrate that the proposed strategies improve the production line, we compared standard times using Student's t-tests between the study variables in the current situation and the proposed one. We compared the values of (a) the average cycle time (TC), (b) the average production rate (TH), (c) the number of products in the process

(WIP), and (d) the productivity of the operators, to see whether there is a significant improvement in the study variables.

Table 7. Comparison between variables of the current and proposed model.

Variable	**Current model**	**Proposed model**	**t-value**	**Improvement**
Cycle time	103,49 min	90,56	426,00	12,49%
Throughput	27,87 prod.	36,32 prod	63,50	30,32%
WIP	552,00 parts	349,00 parts	197,00	36,77%
Worker's productivity	43,12%	55,60%	939,00	12,50%

The results show that all the variables in the proposed simulated model show significantly better performance than the current production model. In summary, the results suggest that the proposed strategies greatly improve the production line's performance, decreasing the average cycle time, increasing the production rate, reducing the number of goods-in-process, and improving the operators' productivity.

5. Conclusions

This article examines the impact of implementing improvement methodologies on manufacturing systems in developing countries. We conducted a case study on a small furniture manufacturing company in Bolivia to achieve this goal, focusing on proposing ways to enhance its production system.

We began the study by identifying the firm's characteristics and the production line under investigation, and then we determined the production rates of the various processes in the production line through a time study. Next, we formulated improvement strategies using factory physics and TOC. As factory physics provides a scientific basis for understanding manufacturing system performance, TOC gives us a management framework for identifying and managing constraints within the system.

By calculating the production rate of each operation in the line, we identified the bottlenecks: machining, edging, cleaning, and selection. We formulated an improvement proposal for each of these operations to reduce the utilization and increase the production rates. After implementing the proposed improvements and recalculating the production rates, significant improvements were observed: the machining process increased its production rate by 48.57%, edging by 47.37%, cleaning by 16.67%, and selection by 36.36%.

To assess the effectiveness of the proposed improvements, we constructed the production benchmarking graph for both the current and proposed models, this provided us with greater visibility of the system's state and the improvement achieved for every iteration. Furthermore, we developed two virtual simulation models to replicate the current production line and one incorporating the proposed improvements. Both simulations enabled us to extract information about the time distribution of workstations and operators and the values of the study variables: production rate, number of goods-in-process, and cycle time.

In conclusion, the case study demonstrates that implementing improvement methodologies can significantly improve the production process of small companies in developing countries. Additionally, we proved that applying factory physics tools and the TOC produces positive results and provides a broader view of the system, allowing us to formulate better improvement plans. The proposed improvements resulted in an increase in throughput by 30.32%, a reduction of 36.78% in the number of products in process, and a decrease in cycle time by 11.65%. Steve Jobs once said: *"if you define the problem correctly, you almost have the solution."*

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