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Enhancing Safety Fuse Manufacturing Productivity: An Analytical Approach Using Factory Physics and Simulation Techniques in Bolivia

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Abstract

Due to limited resources and economic challenges in the Bolivian manufacturing sector, increasing productivity without extra investments has become a strategic priority. This study explores the use of tools like the Factory Physics methodology and computer simulations in the production system of a Bolivian explosives company's safety fuse manufacturing process. The main goal is to improve productivity by using the resources available. A time and motion study, value-added activity analysis, internal benchmarking, line balancing, and simulations were conducted. The results showed that productivity could be significantly increased by better managing production time and resources. These improvements included a 0.7% reduction in cycle time, a 2.4% increase in production rate, and a 13% reduction in work in progress. Consequently, these changes boosted the system productivity by 25%, thanks to a more effective use of the company's resources (i.e., time, personnel, and machinery). These findings suggest that applying the Factory Physics methodology and simulation allows for improving production system performance without additional investments by optimizing existing resources. This strategy represents a viable alternative to improving operational efficiency in the Bolivian manufacturing sector.

Keywords

Productivity, Factory Physics, safety fuse manufacturing, Time and motion study, Production System Simulation.

1. Introduction

As globalization continues to grow, Bolivian companies need to enhance their productivity to stay competitive and sustainable continually (Slack et al., 2010). To achieve this goal, they need to optimize the use of existing resources without requiring additional investment (such as improving processes, training, and scheduling) (Heizer & Render, 2014). However, there are trade-offs when implementing these changes; for example, minimizing production time tends to increase resource utilization (Krajewski et al., 2016). Therefore, Bolivian companies should not simply focus on making single changes, but rather on finding the right balance between these contradictions. For example, a company should decide on production time minimization while utilizing resources efficiently to achieve maximum production.

Based on the above arguments, this study employed a combination of the Factory Physics methodology and computer-based simulation to enhance the productivity of the safety fuse production system at a Bolivian explosives company. This analysis offers a unique perspective on the utility of these tools in a developing country that lacks sufficient resources yet seeks to remain competitive. In the following sections, we present the literature review, methodology, results, and conclusions.

2. Literature Review

2.1. Factory Physics

Factory Physics is a practical methodology that can deliver positive results in both the short and long term (Jacobs & Chase, 2018). Notably, it establishes relationships among demand, capacity, inventory, lead time, and variability through specific laws (Chen & HengQuing, 2002). Hence, due to its versatility, it can be applied across different industries, regardless of process complexity.

The methodology within its framework includes three key concepts: cycle time (CT), which measures the total duration a product spends in the system from entry to exit; work in process (WIP), representing the current inventory within the system; and throughput (TH), indicating the number of units produced per unit of time. (Hopp & Spearman, 2008). These variables are interconnected through laws that help explain the behavior of a production system. The power of the methodology can be amplified using computer-based simulation, which provides a framework for interpreting results (Strandridge, 2004). For example, Herbas Torrico and Lujan Sainz (2024) successfully combined Factory Physics's Little's Law with simulation to enhance the manufacturing layout of a food company.

2.2. Little's Law

Little's Law is a Factory Physics principle that connects cycle time, work in process, and throughput, and is applicable across all production systems regardless of their characteristics. Moreover, it enables prediction and control of system performance (Hopp & Spearman, 2008). According to Pound, Bell, & Spearman (2014), the three variables mentioned above are related through the following equation:

$$\text{WIP}=\text{Cycle Time (CT)}\times\text{Throughput (TH)}$$

This relationship provides a quantitative basis for decision-making, facilitating the optimization of production systems by allowing for the continuous measurement, analysis, and adjustment of processes to achieve a more efficient and productive system (Hopp & Spearman, 2011). For example, Little's Law allows us to explain the behavior of inventories or buffers that are considered work in process. Therefore, this predicts that the size of the buffer is directly proportional to the throughput and the cycle time. This law serves as a quantitative framework for assessing the impact of changes in buffers, thereby enabling the evaluation of their effects on production times (Medonos & Jurová, 2016).

2.3. Buffers

Buffers or inventories are mechanisms that protect the production system against variability, such as uncertainty in process times, demand fluctuations, machine failures, or delays. While variability cannot be eliminated, it can be managed through three types of buffers: time, inventory, and capacity (Pound et al., 2014). Particularly, buffers are often used to absorb variability in a process (e.g., machine breakdowns, late material arrivals) to maintain a steady throughput. However, Little's Law demonstrates that these buffers come at the cost of increased cycle time. Therefore, the optimal strategy for a production system is not to eliminate buffers entirely but to manage their size to balance throughput, cycle time, and the inevitable variability of a process.

2.4. Internal Benchmarking

Internal benchmarking is the process of comparing the performance of different departments, teams, or production lines within the same organization to identify best practices (Harrington & Harrington, 1996). The Factory Physics methodology develops a specific kind of internal benchmarking, which is an ongoing process of identifying, understanding, and adjusting organizational actions aimed at improving internal processes based on Little's Law (Hopp & Spearman, 2011). This analysis compares three possible scenarios by examining key variables. The first variable is the bottleneck rate (rb), which is defined as the rate at which the workstation with the highest long-term utilization operates, measured in parts per unit of time (Spearman, 2014). The second variable is the raw cycle time (T_0), which represents the time a unit spends moving through the production system without interruption. The third variable is the critical work in process (W_0), which indicates the level of work in process required to achieve maximum throughput. Additionally, the work in process for the case under analysis (w) is considered, following the framework outlined by Hopp & Spearman (2008). Figure 1 illustrates the three possible scenarios:

- *Best-case performance:* shows the results the production line would achieve under ideal conditions.
- *Worst-case performance:* represents the results under the worst possible conditions, leading to maximum cycle time, minimum system throughput, and high waiting times.
- *Practical worst-case performance:* shows an intermediate level of performance compared to the two cases above, in which randomness in the production system is considered.

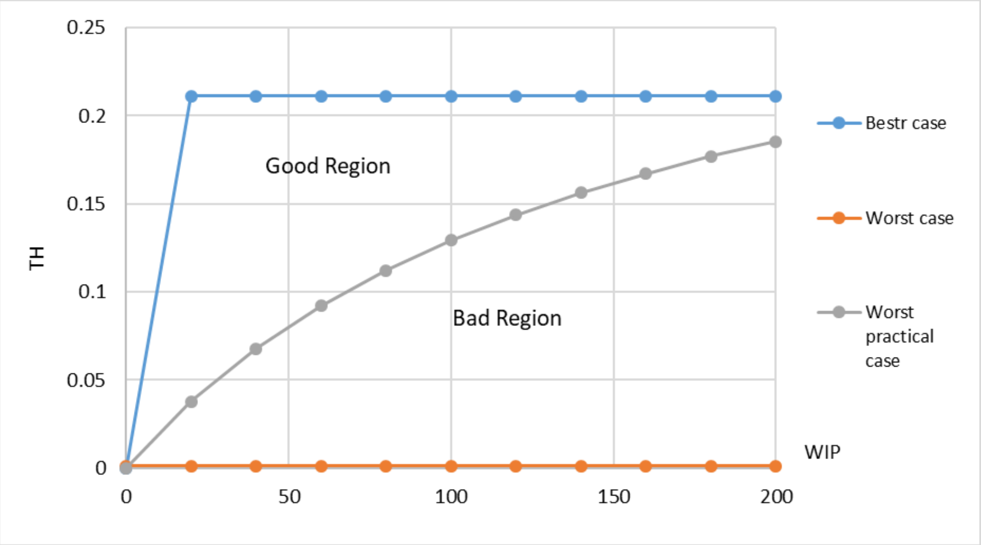

Figure 1. Internal Benchmarking Chart

2.5. Time and Motion Study

A time and motion study is a technique used to determine, with the highest possible accuracy, the time required to perform a given task based on a limited number of observations, according to a pre-established performance standard (García, 2018). The number of observations to be conducted can be determined mathematically, regardless of the duration of the operation, to minimize error (Niebel & Freivalds, 2012). According to Meyers (2012), motion study involves the recording and critical examination of different methods of performing activities to identify improvements that allow for a more straightforward, faster, and safer way of carrying out the task, thereby positively affecting the quality achieved.

2.6. Simulation

Simulation enables the exploration of multiple scenarios within a production system, allowing for a thorough analysis of process performance. It facilitates the identification of bottlenecks and inefficiencies, optimizes production schedules, and reduces lead times. Moreover, simulation allows testing different design alternatives and detecting potential issues before physical implementation, thereby saving both time and costs in the production process (Hovanec et al., 2023).

The Factory Physics methodology provides a solid quantitative framework for simulation. By leveraging the relationships between inventory, cycle time, throughput, variability, and capacity analysis, it guides model design, ensures result verification, and—most importantly—supports meaningful interpretation of outcomes (Standridge, 2004). Together, these tools complement each other, minimizing modeling errors and delivering more reliable and actionable results for informed decision-making.

3. Methodology

This case study was conducted on the safety fuse production system of an explosives company in Bolivia and included the following stages:

- *Current production system evaluation:* A detailed description of the current production flow, including machinery specifications, layout, and work shifts.
- *Time and motion study:* Collected data over three months for developing flowcharts and calculating production times for each process.
- *Analysis and simulation of the current process:* Development of a computer-based simulation of the production system and validation of the collected data.
- *Identification of improvements:* Value-added analysis for each process to identify improvement opportunities.
- *Simulation of the Process with Proposed Improvements:* Use of the proposed improvements in simulation to see their effect on productivity.
- *Internal benchmarking:* Comparison between the benchmarking of the current case and the proposed improvements.
- *Analysis and simulation of the proposed production system:* Simulation of the production system incorporating the identified improvements and impact evaluation.
- *Analysis of results:* Statistical analysis of the identified improvements.

4. Results and Discussion

4.1. Current Production System Evaluation

The production system for this product consists of four primary operations: (i) coating, (ii) wrapping, (iii) winding, and (iv) packaging. Additionally, waiting and transportation times between operations were taken into account (see Figure 2).

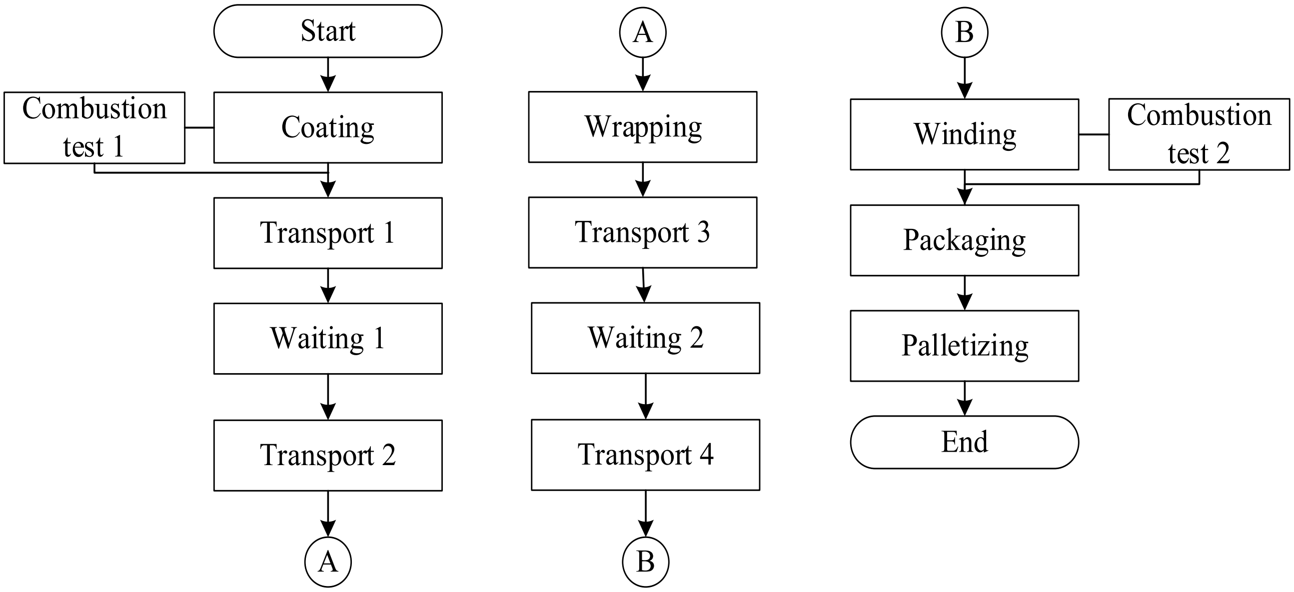

Figure 2. Flowchart of the Safety Fuse Production System

4.2. Time and Motion Study

A time study was conducted to determine the required time to perform each process, and each process was divided into elements or work units (García, 2018). Each work unit was descriptive, brief, separated by operations controlled by an operator or a machine, and listed in the order in which they occur, as suggested by Meyers (2012),

For each work unit, 45 time records were collected, and the mean time was calculated (average time). Next, the normal time was calculated, which is the time required by a standard operator to operate at a standard pace, without delays due to personal reasons or unavoidable circumstances (Palacios, 2009). To calculate the normal time, the Westinghouse method was used to rate performance, which considers four parameters: skill, consistency, effort, and working conditions.

Finally, the standard time was calculated, which is the time required by a qualified operator working at a normal pace to produce a product under normal conditions (Suñé & Gil, 2004). This time is obtained by adding an allowance to the normal time, corresponding to a percentage of time added so that the average operator can recover from fatigue caused by work, attend to personal needs, and achieve the standard when working at a normal pace (Kanawaty, 2008). Table 1 presents the results of the time study for safety fuse production.

Table 1. Results obtained from the time study

Operation	Average Time [s]	Normal Time [s]	Standard Time [s]
Coating	6466.48	7307.12	7316.62
Combustion test 1	647.44	679.81	680.70
Transport 1	14.12	14.55	14.56
Waiting 1	86400.00	86400.00	86400.00
Transport 2	8.54	8.79	8.80
Wrapping	940.66	1062.94	1064.32
Transport 3	3.21	3.31	3.31
Waiting 2	0.19	0.19	0.19
Transport 4	6.13	6.32	6.32
Winding	744.42	826.30	827.19
Combustion test 2	1020.74	1071.78	1073.17
Packaging	18372.76	20210.36	27283.97
Palletizing	215.42	219.73	220.17

Based on the information above and additional information from the production process, we calculated the necessary variables to implement the Factory Physics methodology for Cycle Time (CT), Work in Process (WIP), Throughput (TH), Critical WIP, and Bottleneck rate. Table 2 below presents the study variables:

Table 2. Study Variables of the Safety Fuse Production System for the Current Production System

Variable	Units
Cycle Time	112740.41 seconds
WIP	180.00 rolls
TH	46.00 rolls/day
Bottleneck rate	0.01 boxes/min
Critical WIP	154.98 rolls

4.3. Analysis and Simulation of the Current Process

The process was simulated using Tecnomatix Plant Simulation, where each operator's activities were divided by the percentage of time spent on the following:

a) **Working:** Time during which the operator performs an operation that adds value to the product.
b) **Setting up:** Time during which the operator configures a machine on the production line.
c) **Repairing**: Time during which the operator repairs a machine on the production line.
d) **Transporting**: Time spent by an operator moving entities through the system.
e) **In route to work:** Time spent by an operator moving from one point to another along the production line.

f) **Waiting:** Time during which an operator is waiting to perform an activity.
g) **Failing**: Time lost due to a failure in a task or activity.

Figure 3 shows the physical layout of the machines, operators, temporary storage areas, and buffers in the safety fuse production system.

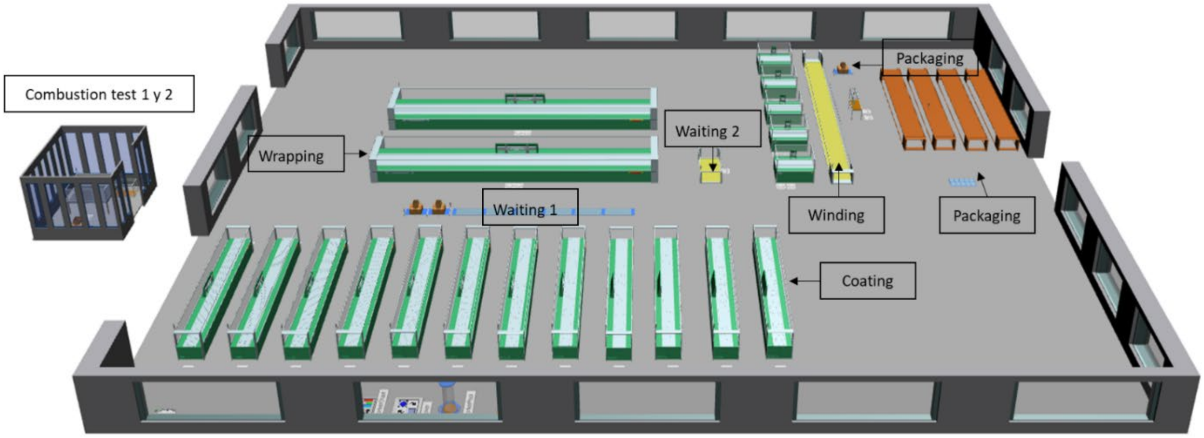

Figure 3. Simulation of the current safety fuse production system

The simulation results were validated through statistical comparison using a Student's t-test between the actual production system results and those from the simulation. The Student's t-test indicates that at a 95% confidence level, there are no statistically significant differences between the average safety fuse production (M = 44.70) and the average production from the simulation (M = 46.00; t(29) = -0.676; $p > 0.05$).

4.4. Results Obtained from the Simulation of the Current Process

After validating the results obtained from the computer-based simulation, we computed the distribution of time for each operator in the safety fuse production system (see Figure 4). Moreover, the time distribution of activities carried out during a work shift was calculated. The results showed that 58.7% of the product time was spent on production, 35.4% waiting, and 5.9% in transportation (see Figure 5).

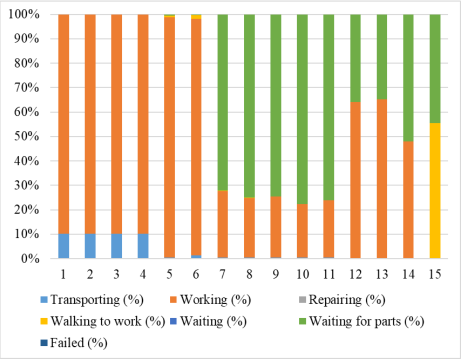

Figure 4. Time Distribution at Each Workstation in the Current Production System

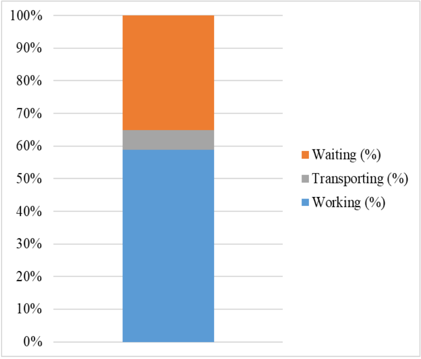

Figure 5. Overall Time Distribution of the Product in the Production System of the Current Production System

4.5. Identification of Improvements

4.5.1. Analysis of Non-Value-Added Activities

To improve the production system, an analysis of non-value-added activities was carried out. Value-added flowcharts were developed for each process to identify and eliminate activities that do not add value, thereby reducing cycle time. Figure 6 illustrates the overall percentage of value-added operations (VA), non-value-added but necessary operations (NAVN), and non-value-added operations (NVA) in the current production process. Based on these insights, we recommended reducing all operations that do not add value to the process.

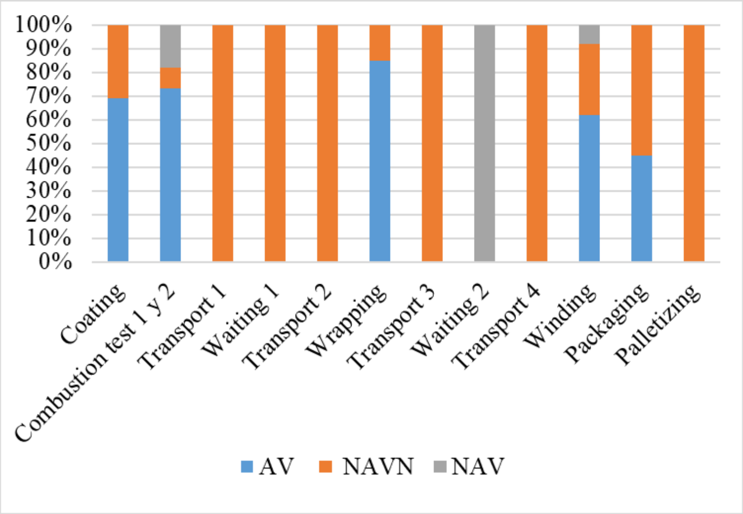

Figure 6. Analysis of non-value added activities in the Production System

It can be observed that, in each analyzed process, at least 33% of the operations do not add value. However, they are necessary for the process and therefore cannot be eliminated. Conversely, a waiting period (Waiting 2) was identified that neither adds value nor is required, and thus should be removed. To achieve this, it is recommended to enhance the production system flow so that the Winding process does not need to wait for work-in-progress items.

4.5.2. Analysis of Activities Performed by Operators

Based on the insights from the safety fuse production process, left-hand and right-hand diagrams were created to analyze in detail the actions performed by operators across the 13 different processes. Specifically, improvements were proposed for the packaging process, as it is entirely manual and thus allowed for identifying potential areas for improvement. One improvement considered was applying glue to the box lids with both hands, allowing the process to be completed more quickly. Next, we collected 45 time records for this process using the suggested improvements to compute its overall effect on the variables under analysis. Moreover, using the Factory Physics methodology, we identified the following improvements:

- *Improvement 1 (Machine use):* According to the simulation results, five operators from the winding area spent on average 75.12% of their time waiting for parts. Therefore, it was considered to assign two operators to other work areas, which could reduce waiting time by 30%.
- *Improvement 2 (Use of buffers):* We considered the three types of buffers presented by the Factory Physics methodology: time, capacity, and inventory (Pound et al. 2014). Regarding the use of a time buffer, we found it to be infeasible due to the nature of the safety fuse production system, which requires a 24-hour drying period. Regarding the use of a capacity buffer, we also found it to be unfeasible, as the machinery is already operating at full capacity, and the company currently lacks the resources to increase its capacity. Finally, the use of inventory buffers was considered. To achieve this, we examined the production scheduling system to find out how many workdays per year the safety fuse plant was idle. Production control records showed that, on average over the past three years, 115 shifts remained unused due to a lack of operators. Consequently, we deemed it appropriate to have four operators in the coating area during the last two weeks of the month,

when operators are typically not needed to work. Therefore, this would increase the overall capacity of the system with a corresponding reduction of WIP.

The purpose of maintaining a small buffer inventory is to safeguard the production system against variations in the WIP, ensuring that processes proceed with minimal disruption (Sett et al., 2016). Such variations may arise from products failing to meet the required specifications for transfer between processes or from delays at individual workstations.

4.6. Simulation of the Process with Proposed Improvements

The improvements were simulated for the 13 operators as shown in Figure 7. Specifically, for operators 7, 8, and 9 (winding area), the percentage of time spent working increased. This improvement can be attributed to the elimination of waiting times at the second workstation, the optimization of one of the three available winding machines, and the implementation of a buffer inventory, which enables a smoother production flow regardless of disruptions that may occur at the preceding workstation.

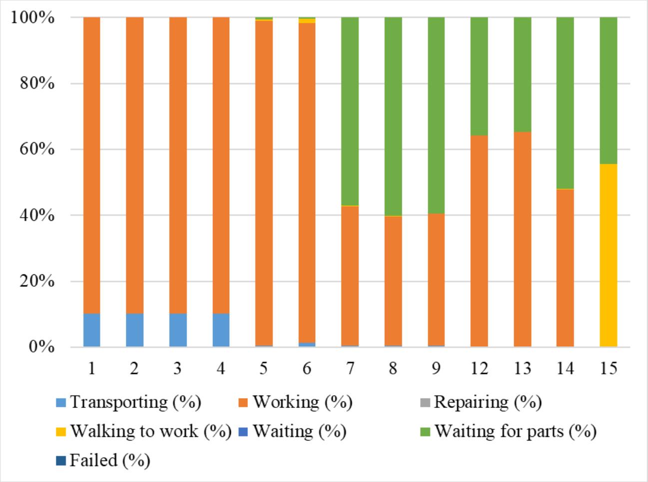

Figure 7. Time Distribution at Each Workstation in the Proposed Production System

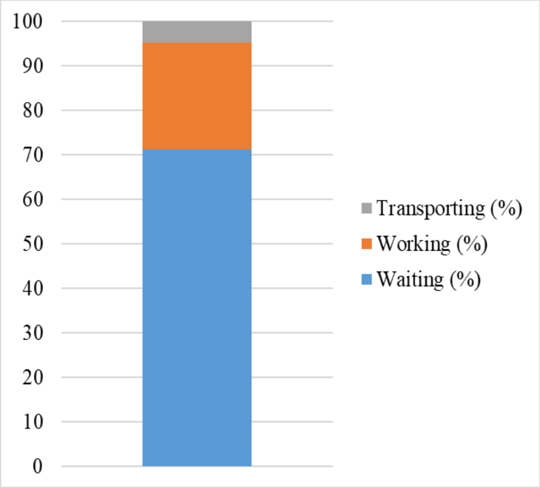

Figure 8. Overall Time Distribution of the Product in the Production System of the Proposed Production System

Additionally, the time distribution of the activities the product undergoes during a work shift (production, transportation, and waiting) was analyzed. As Figure 8 shows, the product spends 71.3% of its time in production, 23.9% waiting, and only 4.8% in transportation. Thanks to the proposed improvements, the percentage of time spent in production increased, while the waiting time for the product decreased. The effects of the suggested improvements on the variables under analysis are presented below (Table 3).

Table 3**.** Study Variables of the Safety Fuse Production System for the Proposed Production System

Variable	Units
Cycle Time	112.570.12 seconds
WIP	156.00 rolls
TH	50.70 rolls/day
Bottleneck rate	0.01 boxes/min

4.7. Internal Benchmarking

Finally, internal benchmarking was conducted to compare the current production system and the improved one. This procedure enables us to determine which scenario is closest to the best case, the practical worst case, and the worst-case scenario (see Figure 9). Notably, the results indicate that the current production system is between the worst and worst practical case scenarios. However, with the proposed improvements, the simulation shows that the safety fuse production system improves, positioning itself between the best-case and the practical worst-case scenario. This occurs because the proposed improvements decrease the cycle time and work in process, while also increasing the average production rate. Moreover, the results also suggest that with these improvements, the production system moves closer to the best-case performance region.

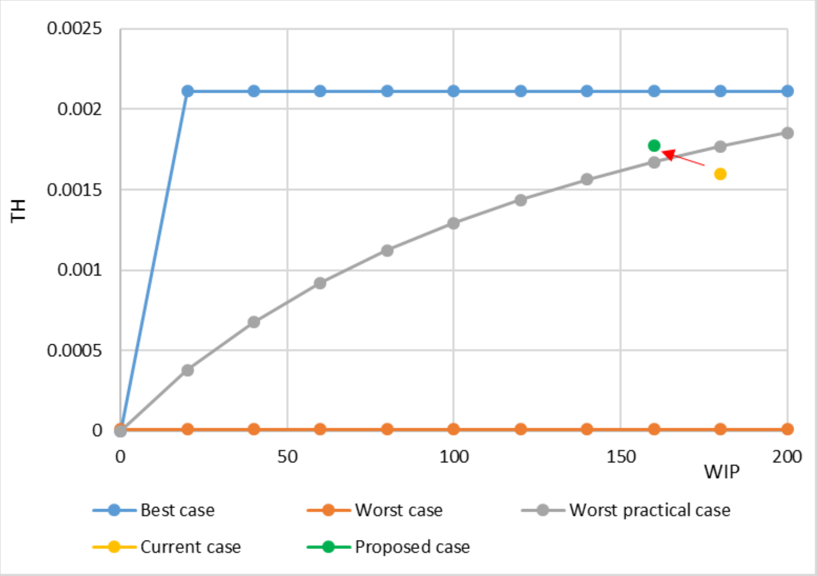

Figure 9. Internal Benchmarking of the Proposed Production System: Relationship between TH and WIP

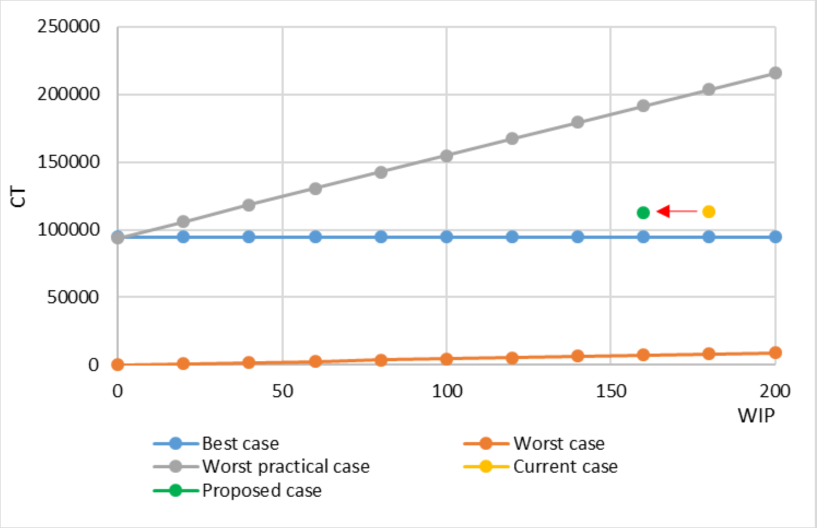

Figure 10. Internal Benchmarking of the Proposed Production System: Relationship between CT and WIP

Figure 10, shows a decrease in CT, along with a reduction in WIP. Therefore, both figures (Figure 9 and Figure 10) indicate productivity improvements, as cycle time decreases, average production increases, and WIP is reduced in both cases. This results in an overall improvement in productivity for the safety fuse manufacturing system.

4.8. Analysis of Results

Several improvements were observed in the distribution of operators' time. In the proposed production system, the proportion of time that operators actively work increased to 71.3%, compared to 58.9% in the current production system, a statistically significant difference ($t(29) = 914.37$; $p < 0.05$), representing a 12.4% increase. Additionally, the waiting time per part decreased significantly from 35.3% in the current production system to 23.9% in the proposed production system ($t(29) = -111.69$; $p < 0.05$), corresponding to an 11.4% reduction. Similarly, transportation time decreased significantly from 5.5% in the current production system to 4.3% in the proposed production system ($t(29) = -11.69$; $p < 0.05$), resulting in a 1.2% reduction. No significant differences were observed in the time operators spent walking between workstations.

Regarding the variables analyzed in this study, we used the Student's t-test to compare the average cycle time of the current production system with that of the improved production system. The results in Table 4 show a significant improvement, with a decrease in WIP (10.50%), an increase in TH (13.30%), and a marginal reduction in CT (0.70%).

Table 4. Statistical Comparison of Variables between the Current and Proposed Production Systems

Variable	Current	Proposed	Student's t-test	Improvement
Cycle Time	112740.41	112570.61	t (29) = -3199.79	0.70%
WIP	180.00	156	t(29) = -156.24	10.50%
TH	46.00	50.7	t(29) = 55.23	13.3%

6. Conclusion

This study examined the applicability of the Factory Physics methodology and computer-based simulation in enhancing the production system of a Bolivian explosives company to increase productivity. The study found that the system had unnecessary waiting times and non-value-added activities. These factors contributed to high CTs and high WIPs. Based on analyses, three improvements were recommended: (a) eliminating unnecessary waiting times, (b) modifying the manual packaging process, (c) optimizing the use of machinery and personnel, and (d) implementing inventory buffers.

These improvements resulted in the following outcomes in the safety fuse production system: (a) a 0.7% reduction in CT, (b) a 10.50% reduction in WIP, (c) a 13.30% increase in TH, and (d) a 0.14% increase in Bottleneck rate. Overall. These improvements increased the productivity of the safety fuse production system by 25%, due to a more efficient use of company resources (time, personnel, and machinery).

These results suggest that applying the Factory Physics methodology is an effective way to enhance productivity without incurring additional investments. By analyzing time and motion, identifying activities that add no value, and conducting internal benchmarks, it was demonstrated that better management of available resources (time, personnel, and machinery) can lead to significant gains in production capacity, shorter waiting times, and improved manual processes. Additionally, computer-based simulation proved to be the most effective tool for exploring different scenarios and system changes, as it allows observation of how key variables impact behavior and outcomes.

Although our research has a weakness in being applied to only one type of production from an explosives factory, it offers tangible outcomes for the case study organization. Also, it develops a replicable methodology for other resource-constrained industries. It affirms that operational efficiency can be realized through the optimization of internal resources, presenting a viable and sustainable alternative to enhance the competitiveness of the manufacturing sector in Bolivia and other developing nations.

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Biographies

Boris Christian Herbas-Torrico is an industrial engineer with an international background and a passion for research and education. He received his PhD in Industrial Engineering from the Tokyo Institute of Technology in Japan. and has an extensive background in the field. His research interests cover a wide range of topics. such as market research. corporate social responsibility. production and applied statistics. He has published more than 60 papers in international refereed journals. conferences and books. and has received numerous awards for his contributions to the field. including the Outstanding Professor Award 2021 from IEOM Society International (USA) or the 2013 Nikkei QC Literature Prize awarded by the Japanese Union of Scientists and Engineers. Currently. Dr. Herbas Torrico is a research professor at Tecnologico de Monterrey in the Department of Industrial Engineering at the Guadalajara Campus in Mexico.

Fernanda Hur Alvarez. She is a part-time research assistant at the Bolivian Industrial Research and Development Group. She earned her B.S. in Industrial Engineering from the Bolivian Catholic University in Cochabamba. Bolivia. Her thesis focused on the use of factory physics and product system simulation. She has experience in production management and currently works in the biggest brewing company in Bolivia (Embol S.A.).