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Eliminating compressed air leaks in production process on compressor machine using TRIZ decision making – A case study in Somaliland company

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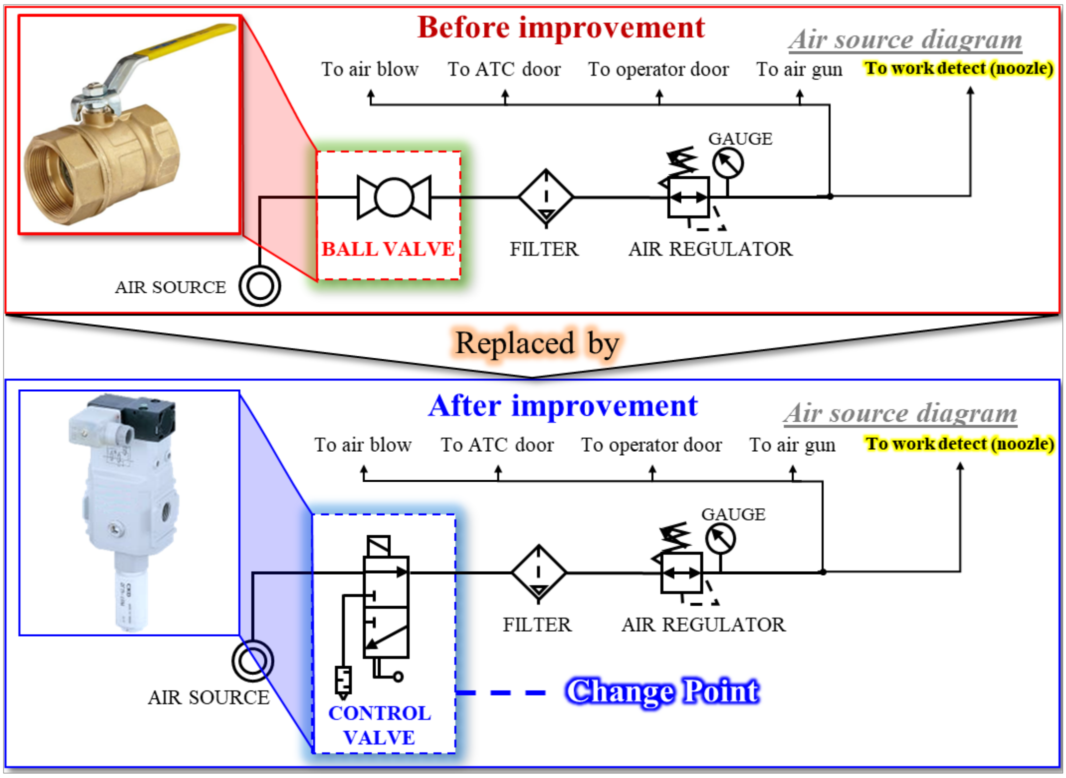

Highlights:

- TRIZ-based solution was applied to reduce energy loss from air compressor leakage in Somaliland's manufacturing sector.
- An integrated control system replaced manual ball valves with automatic air control linked to CNC emergency buttons.
- The solution led to 10.49% energy savings, reducing electricity consumption from 10,982 kWh to 9,830 kWh annually.
- Cost savings reached SOS 605,952 (USD 1,067) over 12 months, improving manufacturing energy efficiency.

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Abstract

In Somaliland, electricity is an expensive necessity. The high expense of electricity presents challenges for industrial development in Somaliland. Existing industries must operate efficiently to survive, specifically in the manufacturing sector, which relies heavily on electrical machinery. The compressor is widely used in manufacturing to provide the air supply to production machines, including CNC machines. However, in some cases, the air supply from the compressor is not supplied efficiently due to air leakage in standby mode. This research aims to solve this issue by implementing an integrated system that reduces energy waste caused by compressed air leakage during standby mode. This research is grounded in the application of the TRIZ contradiction matrix, which identified Inventive Principle #28 (Mechanics Substitution) as a potential solution. The proposed solution was subsequently implemented and evaluated using a pilot experimental method within the context of a case study conducted at a manufacturing company located in Hargeisa, Somaliland. The result led to the successful implementation and testing of a control system that integrated the operations of the compressor machine and CNC machine. Compared to the conventional ball valve components, the new system replaced it with an automatic air control valve integrated with the CNC machine emergency button. Electricity consumption on the compressor machine was observed and calculated for twelve months before improvement and twelve months after implementing the improvements. The data was collected for a total of 24 months to compare before improvements and after improvements for each 12 months in a machine. The improvements showed a significant reduction in electricity consumption, from 10,982 kWh to 9,830 kWh representing 10.49% energy savings, and reduced electricity operating costs by SOS 605,952 (USD 1,067) in 12 months.

Keywords: Air Valve; Compressor; CNC Machine; Control; Energy

1. Introduction

In Somaliland, electricity is an expensive necessity. The cost of electricity there is approximately US$ 1 per kilowatt-hour (kWh), making it one of the highest rates in the world [1]. In comparison, the cost of electricity in the United States is around US$ 0.12 per kWh [2], while in Ethiopia, Somaliland's neighboring country, it is about US$ 0.05 per kWh [3]. This highlights that electricity in Somaliland is significantly more expensive. This high cost poses challenges for the development of industries in Somaliland. The existing industries must operate efficiently to survive, specifically in the manufacturing sector which has many electrical machines.

Compressed air has become vital in modern machine production activities [4], [5]. It is primarily used as an air source for various pneumatic components [6], [7]. When compressed to a specific pressure, air can provide sufficient power to drive actuators, cylinders, valves, and other pneumatic components [8]. To provide pressurized air to the production system, a specialized machine called an air compressor is required [9], [10]. The primary responsibility of a compressor is to elevate air pressure to an appropriate level that caters to the machinery or equipment it is serving [11]. The compressor achieves this by decreasing the volume of air or gas, thereby augmenting its molecules' kinetic energy [12], [13]. Subsequently, the compressed air or gas is channeled through a piping system to various pneumatic components that necessitate it [14], [15].

One of the modern production machines that makes extensive use of compressed air is the Computer Numerical Control (CNC) machine [16], [17]. CNC machines are a type of machine that is controlled by a computer system to produce products with high precision and accuracy [18], [19]. In operation, CNC machines require compressed air to move various pneumatic components, such as pneumatic cylinders used to move the spindle, pneumatic valves to control material flow, and pneumatic grippers to hold the workpiece firmly [20], [21]. This compressed air is supplied by an air compressor connected to the CNC machine via a piping system. Apart from moving pneumatic components, compressed air is also used in other production activities, such as cleaning with an air gun, lubrication, and transporting materials or products via pneumatic tubes [22].

On the other hand, the use of an air compressor can cause energy waste if there is any air leakage in the piping system or pneumatic components [23], [24]. This condition occurs when the compressor continues to pump and circulate compressed air through the pipes and nozzles, even though there is no active use or even when the engine is idle or at break time. As a result, there is a waste of energy because the compressor works without being utilized optimally [25]. The air leaks are caused by less than optimal pneumatic system design or failure of control components such as solenoid valves. High-pressure air is wasted through nozzles and air holes without being utilized for work [26]. Apart from consuming energy, air leaks also cause high noise due to the continuous blowing of compressed air from the nozzles. The long-term impact of air leaks is that compressor energy costs increase due to excessive electricity use [27]. Air leaks should be handled immediately by repairing the control system and replacing worn components, as a result, if they are not replaced, the service life of pneumatic components and device performance can also be reduced because they work continuously without stopping [28], [29]. The research aims to develop a system that may mitigate the air leakage in CNC machines and minimize wasted energy.

The problem addressed in this study concerns the development of a system capable of detecting and reducing air leakage in the CNC machine, with the aim of minimizing energy waste resulting from inefficient compressor operation. The objective of this research is to design and implement a technology-driven monitoring and control system that can effectively identify and mitigate air leakage, thereby optimizing energy consumption and prolonging the operational lifespan of the pneumatic system.

2. Literature Review

Energy efficiency has emerged as a critical concern across various industrial sectors, specifically in the utilization of compressed air through compressor systems. The compressor serve as an important component in industrial operations, and it is often integrated with production machinery. However, it operation is associated with significant energy consumption, presenting a major challenge. In response to these issues, numerous studies have been undertaken to investigate both technological and operational strategies aimed at enhancing energy efficiency, minimizing air leakage, and developing adaptive automatic control systems. This section provides a synthesis of key findings from the existing literature concerning energy consumption in compressor systems and the implementation of technology-based optimization approaches.

The utilization of compressed air contributes to approximately 10% of the world's electricity consumption. Given that compressors alone represent 15% of the industry's total electricity usage, it becomes imperative to ensure the efficient operation of compressor machines. Addressing energy-saving initiatives is the key solution to mitigating energy consumption from compressors [30]. Air leaks that occur during standby periods can also be considered leaking electricity because not only is air leakage wasted but electrical energy from equipment is also wasted. Leaking electricity refers to electrical energy that is wasted by electrical equipment when it is not in use [31]. These air leaks often occur due to the ineffectiveness of the valve system, check valves, or relief valves [32], [33].

Nowadays, many devices have conventional or traditional air valves, specifically in the residential or industrial sector. However, its system has weaknesses due to there is non-automatic method and requires human awareness. The concept of this valve needs human resources to conduct the operations [34], [35].

In several studies, valve replacement is a solution to increase energy savings in air compressors. Using an automatic system for valves in air compressors by implementing automatic solenoid valves can save energy from 5% to 35% [36]. In addition, one automobile plant in the United States installed automatic valves to replace the conventional valve, then this improvement resulted in a 40% reduction in off-shift compressed air use, saving over 10,000 kWh for a single weekend [37].

Based on the growing demand for industrial energy, the optimization of compressor systems has emerged as a strategic priority in the pursuit of energy efficiency. Numerous empirical studies have proposed innovative approaches to mitigate the high energy consumption typically associated with compressor operations. These approaches encompass integrated technological advancements, system design improvements, and refined operational strategies. Comprehensive investigations into energy optimization in compressor systems have identified several effective methods, including the implementation of high-efficiency motors (with potential energy savings of 2–8%), the installation of variable speed drive (VSD), which can achieve savings of 15–40%, and the use of ultrasonic detectors for air leakage prevention. Additional strategies include optimizing the temperature of external air intake, reducing system pressure, recovering waste heat from compressors, employing energy-efficient nozzles, utilizing variable displacement compressors, and establishing periodic maintenance schedules [32].

Another study examined the application of three stage centrifugal compressors equipped with intercoolers, identifying several key optimization strategies. These included the insulation of piping systems using rock wool to prevent increases in nitrogen inlet temperature, which contributed to an efficiency improvement of approximately 3–7%. Additional measures involved the utilization of high-temperature nitrogen to preheat liquid nitrogen, the regulation of intercooler cooling water temperature, and ambient temperature control—each of which contributed to power consumption reductions of approximately 15–20% [38]. Furthermore, the comprehensive integration of multiple optimization technologies, such as high-efficiency motors, variable speed drive (VSD), ultrasonic-based air leakage detection, inlet air temperature optimization, system pressure reduction, heat recovery systems with efficiencies reaching up to 90%, the use of efficient nozzles, variable displacement compressors, and scheduled maintenance programs has demonstrated the potential to achieve total energy savings of 20–50% compared to initial consumption levels [39].

In the context of energy efficiency optimization, the TRIZ (Theory of Inventive Problem Solving) methodology has demonstrated its effectiveness as a systematic approach for identifying and resolving technical contradictions within complex systems. This aligns with prior research highlighting TRIZ as a valuable tool for enhancing both material and energy efficiency in industrial production processes. Empirical studies indicate that the integration of TRIZ with cleaner production strategies can lead to reductions in process energy consumption by approximately 15–25%, yielding substantial economic benefits [40]. Another notable application of TRIZ in the domain of energy management involves the optimization of unnecessary energy usage through the development of automatic motion detection systems that regulate electronic devices, such as lighting, fans, and air conditioning units, based on human occupancy. This TRIZ-based approach involves the incorporation of intelligent automation using Passive Infrared (PIR) sensors coupled with counters to detect human presence. The system activates devices when occupancy is detected and deactivates them when the space is unoccupied, thereby minimizing energy waste resulting from human oversight, promoting energy conservation, and supporting environmentally sustainable practices [41].

Based on the literature review of previous studies, it can be concluded that the use of compressed air through an air compressor machine requires quite a lot of electrical power. Air leaks can also cause more wasteful energy use, where these leaks are often associated with air valves as one of the components for distributing compressed air. Conventional valves are still widely used today, but in industry, the use of automatic valves has been proven to provide an energy saving solution that can reduce energy waste. In the context of optimizing energy efficiency, the TRIZ (Theory of Inventive Problem Solving) approach is chosen as a systematic methodology to identify and resolve technical contradictions in energy efficiency systems. Therefore, this study uses the TRIZ approach to develop an automatic valve system that can optimize energy efficiency in air compressor systems.

3. Method

This study uses experimental methods combined with the TRIZ approach. TRIZ is a problem solving methodology that uses an analytical and creative approach to identify optimal solutions [42]. The TRIZ (Theory of Inventive Problem Solving) approach can be used as a systematic method in finding innovative solutions [43], [44], especially by analyzing common failure points such as air valve inefficiency and proposing design improvements based on inventive principles. The research stages in this study are identify problems, function analysis, root cause analysis, engineering contradiction analysis, inventive principal analysis, proposed specific solution, and implementation.

3.1. Identify Problems

Based on the observed Standard of Operations (SOPs) in this study, the workers turn the CNC machine to standby mode by pressing the emergency stop button on the machine. Apart from being used for emergencies, an emergency stop is also used to prevent the machine from being used by irresponsible people when the person in charge is not operating the machine or standby mode [45].

The problem to be solved is compressed air from the compressor which continuously comes out of the nozzle on the CNC machine during standby periods such as rest time, lunch time, and dinner time. In addition, one component of the CNC machine, namely the nozzle, persists in emitting compressed air during standby periods even though the emergency button has been pressed. This is because the compressed air that comes out of the nozzle originates from a compressor air machine that continuously distributes air every time. This condition is illustrated in **Figure 1**.

The standby mode can disable all internal components present on a CNC machine. However, external components and resources cannot be disabled. In **Figure 1**, the nozzle on the CNC machine still releases the compressed air. This is because the ball valve as a conventional component that connects compressed air from the compressor machine to the CNC does not turn off automatically. In addition, the location of the compressor which is far from the CNC machine, due to it being located in a different room to reduce noise also causes the compressor cannot be turned off easily by the operator. This condition causes compressed air to continue to come out of production machines such as CNC, even though the production machine is turned off, which ultimately causes air leaks.

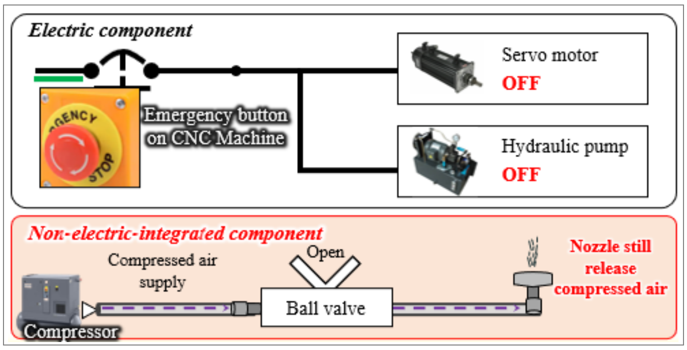

Figure 1. The standby mode condition of CNC machine

3.2. Function Analysis

Functional analysis has been conducted on a case study related to compressor machines, specifically the compressed air delivery system to CNC machines as production machines. **Figure 2** illustrates the compressed air distribution system in the case study location. Compressed air is channeled to the CNC machine continuously. Compressed air continues to flow through the pipe from the compressor machine to the nozzle in the CNC machine. The function of the noozle is to convert pressure energy into kinetic energy that can be used for production [46].

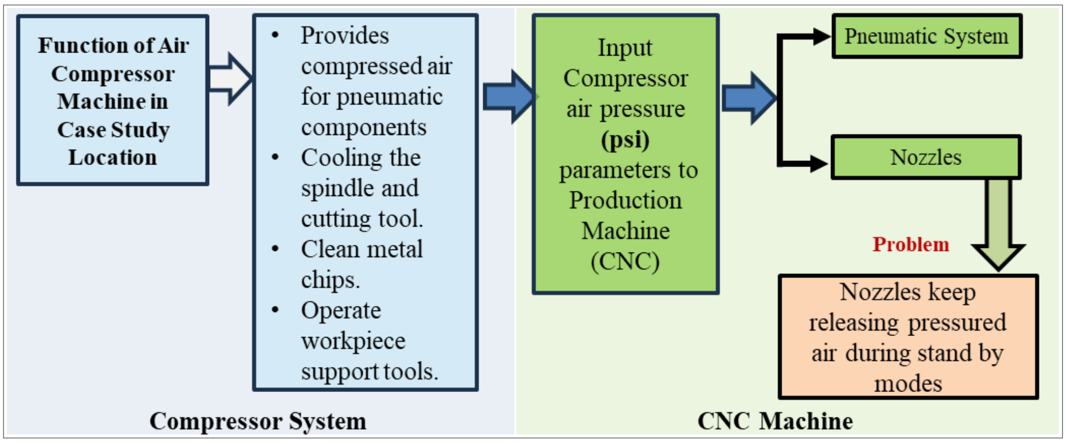

Figure 2. Function analysis of air compressor and CNC in case study

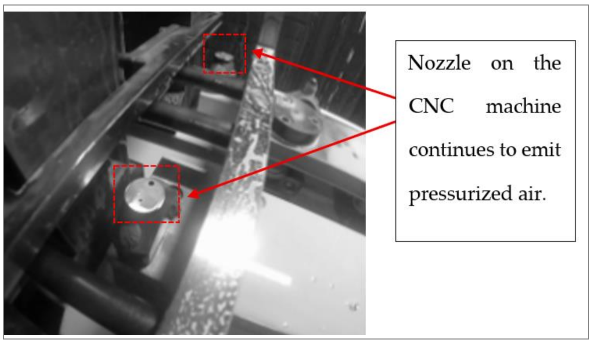

Figure 3. CNC nozzles in case study

In **Figure 3**, there is a condition where the nozzle on the CNC machine continues to release compressed air from the compressor machine during standby mode (rest time, lunch time, and dinner time). This case is an air leak due to the compressed air is distributed not for production and operational purposes. The more compressed air that is wasted, the greater the use of electrical energy for compressor operations.

3.3. Root Cause Analysis

The Root Cause Analysis (RCA) methodology employed a multi-method data collection approach to ensure a comprehensive and systematic identification of the underlying issues. Direct observations were conducted over a two-week period across multiple operational shifts to capture real-time machine behavior, particularly during standby periods. Semi-structured interviews were conducted with five CNC machine operators and two maintenance technicians to gain insights into operational practices and to identify recurring challenges. Furthermore, a systematic review of relevant documentation, including maintenance logs and energy consumption records, was undertaken to provide quantitative evidence and contextualize the extent of the problem.

After observing the actual conditions, conducting the interview, and analyzing the function analysis of the air compressor machine. **Figure 4** shows the analysis results, the main problems identified that occurred during standby mode were machine noise, the compressor machine not having integration with the production machine, and compressed air continues to be supplied at all times.

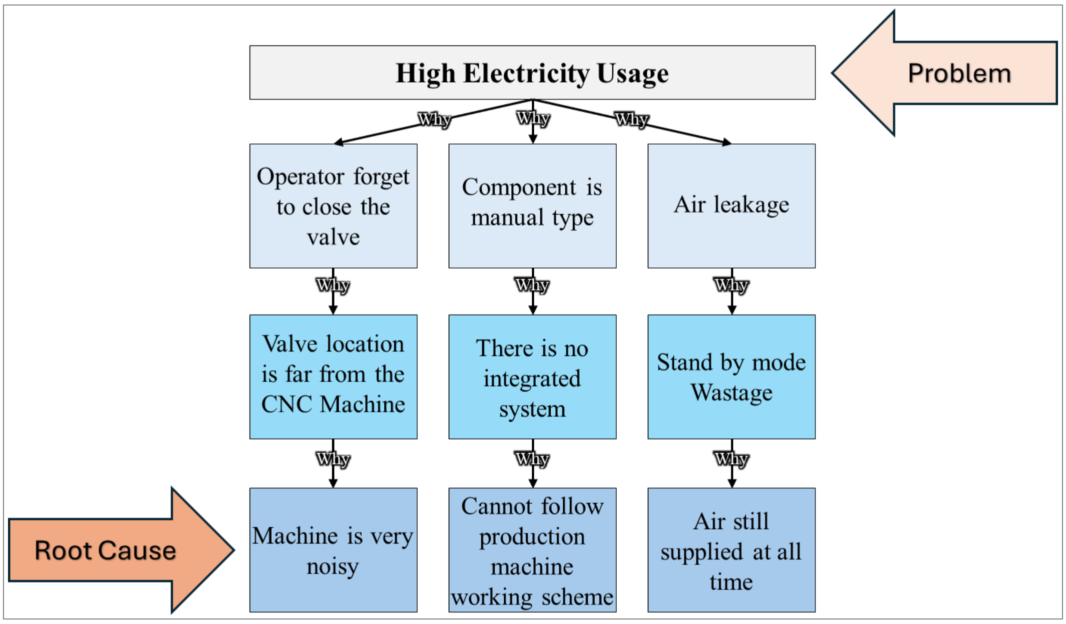

Figure 4. Root cause analysis on air compressor issues

The root cause of the machine noise is the failure of operators to close the valve, which leads to the continuous distribution of compressed air to the CNC production machine, many operators are not aware to close the valve. Furthermore, manual type component such as a conventional valve is also the root of the problem because it cause the operations of the air compressor machine and CNC machine not to be integrated into a system. Then, the root of the problem is air leaks which are caused by the compressed air supply being always active even though the machine is in standby condition.

3.4. Engineering Contradiction Analysis

Contradictions are a common occurrence in our daily lives, just like the plus and minus in engineering mathematics [47]. An engineering contradiction arises when improving one parameter of a system leads to the worsening of another parameter [48]. The TRIZ approach translates various parameters into one of the 39 engineering parameters. Its primary goal is to eliminate and solve engineering contradictions, which can be identified through several analyses. Contradictions are an integral part of solving inventive problems [49]. The Altshuller matrix, also known as the Contradiction Matrix, is used to solve these contradictions. It suggests inventive principles based on a mapping process between a good and a bad parameter [50]. **Figure 5** is the Altshuller's Contradiction Matrix for this study.

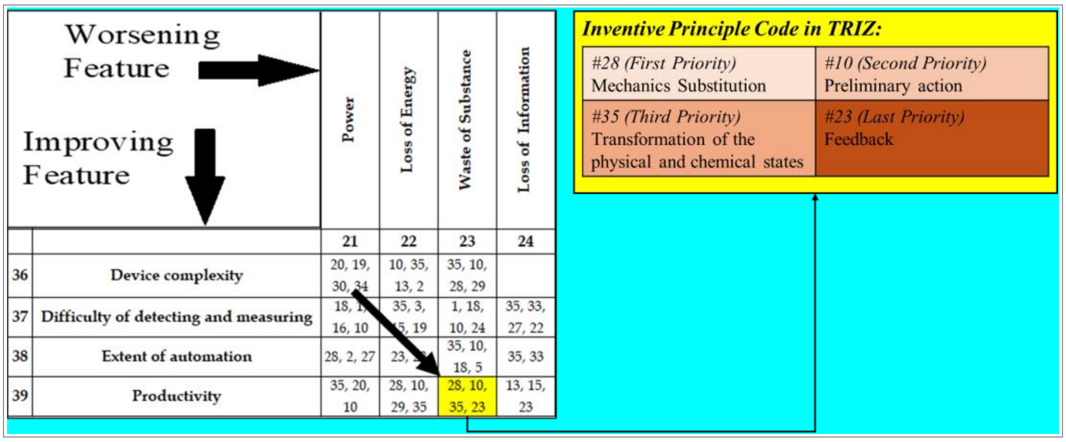

Figure 5. Altshuller's contradiction matrix for this study

For this energy efficiency issue, the selection of engineering parameters requires careful consideration of the main objectives of the system. The parameter to be improved is identified as '39: Productivity', because the excessive air productivity needs to be improved to be more optimal according to the needs of the CNC machine.

Meanwhile, the worsening parameter is '23: Waste of Substance', it specifically refers to the consumption of compressed air wasted during the standby period. This parameter is justified because the main concern is the continuous release of compressed air from the nozzle when the CNC machine is not actively producing, resulting in material waste (compressed air) and energy waste (compressor operation). A detailed contradiction analysis reveals that increasing the response speed of air delivery (faster shutdown during standby) has the potential to worsen the waste of substance if the system becomes too sensitive and causes frequent on-off cycles. However, this contradiction is acceptable because the main goal is to eliminate continuous waste during extended standby periods.

Based on the analysis results above, the improving parameter considered in this study is 'productivity', researchers tried to streamline the productivity of compressed air for its use and distribution to production machines. Then, the worsening parameter considered in this study is 'waste of substance', Waste of substance occurs when compressed air continues to escape from the pneumatic system when the machine is not operating, causing significant energy losses and operating costs for the manufacturing industry. Researchers wanted to reduce wasted substances, which was compressed air that comes out of the nozzle during standby mode.

3.5. Inventive Principle

In the inventive principles obtained from the contradiction matrix, 4 inventive principles were obtained from the 40 available inventive principles. All potential inventive principles were derived from the results of the contradiction matrix analysis, as utilized within the TRIZ methodology and presented in **Figure 5**. The principle identified as the highest priority is Principle #28 (Mechanics Substitution), followed by Principle #10 (Preliminary Action) as the second priority, Principle #35 (Transformation of Physical and Chemical States) as the third priority, and Principle #23 (Feedback) as the last priority. A comprehensive explanation of these selected inventive principles and their relevance to the problem context is provided in **Table 1**.

Table 1. Inventive principles

Altshuller's contradiction matrix	Inventive principles	Suitable inventive principle
Improving Parameter: Reduce productivity on air supply *(#39 Productivity)* Worsening Parameter: The air substance supplied is not utilized optimally for the production process *(#23 Waste of Substance)*	*#28 (First Priority)* Mechanics Substitution #10 *(Second Priority)* Preliminary action #35 *(Third Priority)* Transformation of the physical and chemical states #23 *(Last Priority)* Feedback	*#28* Mechanics Substitution

The selection of Inventive Principle #28 (Mechanics Substitution) was made based on its designation as the top priority in this case study, as determined through the TRIZ contradiction matrix analysis. This principle was subsequently tested through a structured process involving planning, implementation, and evaluation within a one-week trial period. If the application of this principle proved to be effective in addressing the identified problem, it would be adopted as the final solution. Meanwhile, if the outcome was unsatisfactory or failed, the improvement would proceed to the next prioritized inventive principle. The successful implementation of Principle #28 during the trial phase would render further application of other alternative inventive principles unnecessary.

Furthermore, the researchers conducted preliminary assessments of the alternative inventive principles ranked second to fourth in priority to ensure. Principle #10 (Preliminary Action) would necessitate the initial regulation of air pressure levels, however this inventive principle would likely fail to resolve the core issue of continuous compressed air supply during non-operational periods. Then, Principle #35 (Transformation of Physical and Chemical States) would involve altering the physical state of the air, thereby introducing unnecessary system complexity without guaranteeing proportional benefits. Meanwhile, Principle #23 (Feedback) would require the implementation of a continuous monitoring system, which would significantly increase system costs due to the need for additional sensors and control components. Otherwise, Principle #28 (Mechanics Substitution) was deemed the most appropriate, as it directly targets the root cause of the problem by replacing the passive mechanical ball valve with an active automatic control system. This solution enables an immediate and reliable response to changes in machine status without the added complexity of real-time monitoring or physical state transformation.

The inventive principles offered by TRIZ place mechanics substitution as the first priority as a solution to this problem. By implementing mechanics substitution, the change in the mechanical concept of distributing compressed air from a compressor machine to a CNC machine will be changed from conventional to automatic as shown in **Figure 6**. The substitution planned is to replace the ball valve with an automatic control valve.

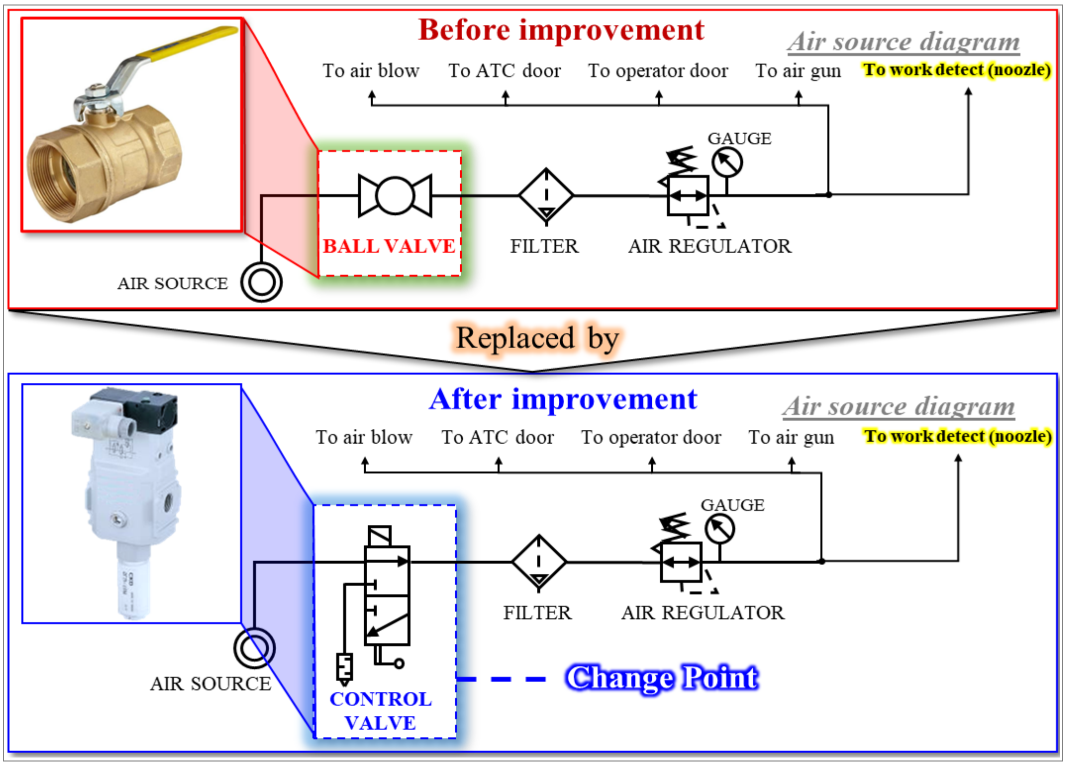

Figure 6. Mechanics substitution implementation in improvement

3.6. Proposed Specific Solution

This was a stage in the case study that could be customized to meet the specific needs of researchers at earlier stages, with the primary objective of designing and testing the experiment. In **Figure 7**, an improvement plan was presented through the implementation of an automatic air control valve. The concept involved integrating an emergency stop, which was typically pressed by the operator during standby mode or standby periods, with an automatic control valve. This concept allowed the air valve to close automatically when the CNC machine was deactivated.

The technical implementation involved the installation of an automatic control valve (24V DC, 3/4" NPT connection) in series with the existing ball valve connection. The solenoid valve was electrically connected to the CNC machine's emergency button circuit via normally open relay contacts. When the emergency button was pressed, the relay contacts opened, de-energizing the solenoid valve and causing it to close, thereby stopping the flow of compressed air. The control circuit included a time delay relay (5-second delay) to prevent rapid cycling and ensure stable operation. Additionally, a manual override switch was incorporated to allow maintenance personnel to independently control the air supply when necessary. The electrical connection utilized the 24V DC control voltage available at the CNC control panel and required only low-voltage wiring in compliance with industry safety standards.

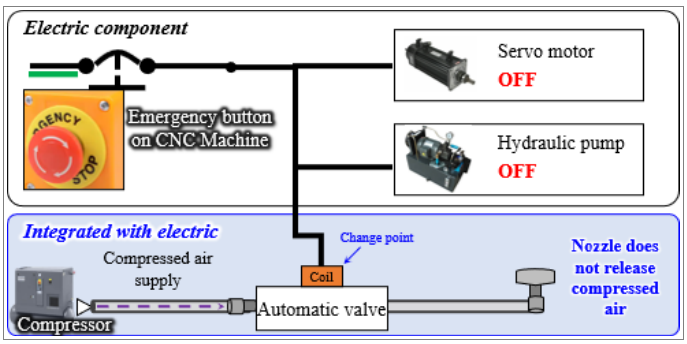

Figure 7. Improvement plan

3.7. Implementation

In Figure 8, the improvement has been conducted and implemented in systematic changes. Before improvements were made, when the emergency stop on the CNC machine was pressed it would not have any effect on the compressor machine's air valve and compressed air continued to be distributed continuously. However, after improvement is implemented, when the emergency stop on the CNC machine is pressed, the air valve on the compressor machine will close by itself and stop distributing compressed air.

Furthermore, the implementation of this improvement will be compared with the situation before the implementation of the improvement. The method used is to make a comparison regarding energy consumption before and after the implementation of the improvement. In this study, the data taken is energy consumption data from the compressor for 12 months before and 12 months after the improvement implementation.

The energy consumption data collection methodology employed a digital power meter (Schneider Electric PM2130), which was installed on the main electrical panel of the compressor to record kilowatt-hour (kWh) consumption at 15-minute logging intervals. Data collection spanned a 24-month period, comprising 12 months prior to the implementation of the improvements (January 2023 to December 2023) and 12 months following the implementation (January 2024 to December 2024).

Several control measures were applied to ensure data validity and to account for potential variations in machine utilization. Production schedule records were maintained to normalize energy consumption data based on actual operating hours. Monthly production output data were collected to identify any significant fluctuations in machine utilization that could influence energy consumption. Seasonal variability was considered by conducting month-to-month comparisons across both years. Furthermore, compressor maintenance schedules and any equipment modifications were documented to ensure that observed differences in energy consumption could be accurately attributed to the implemented improvements rather than to external factors. Statistical analysis using paired t-tests was conducted to determine the significance of the energy consumption reductions, with confidence intervals calculated to validate the effectiveness of the intervention.

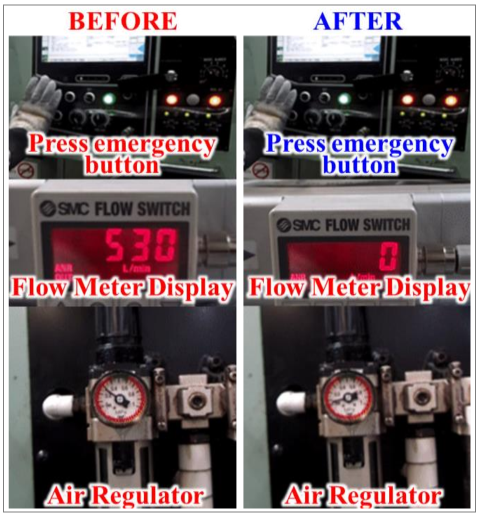

Figure 8. Comparison of conditions before and after improvement

As seen in Figure 8, it shows that there was a persistent issue before improvement with compressed air continuing to flow through the nozzle of the production CNC machine, even after the emergency stop button was pressed. The flow meter and air regulator confirmed that the compressor was still supplying compressed air to the CNC machine due to the conventional ball valve not shutting off automatically. Then, the issue was resolved by implementing an improvement that automatically deactivated the compressed air supply from the compressor to the CNC machine when the emergency stop button was pressed. This was accomplished by replacing a conventional ball valve with a new automatic air control valve. This improvement prevented the compressor from providing compressed air to the CNC machine, effectively eliminating any air leaks.

4. Results

This study uses experimental methods combined with the TRIZ approach. TRIZ is a problem solving methodology that uses an analytical and creative approach to identify optimal solutions [42]. The research stages in this study are identify problems, function analysis, root cause analysis, engineering contradiction analysis, inventive principle analysis, proposed specific solution, and implementation.

4.1. Energy Consumption Analysis

The results of a 12 months testing are used to compare data from before and after an improvement has been implemented. Specifically, data from January 2023 to December 2023 (before improvement) will be compared to data from January 2024 to December 2024 (after improvement) to demonstrate the effectiveness of the improvement.

Based on data in **Table 2**, the improvement can reduce electrical energy consumption by 1,152 kWh (-10.49%). This is due to the replacement of a conventional ball valve with an automatic air control valve, which has had a direct positive impact on the energy efficiency of the compressor machine and can eliminate air leaks.

Table 2. Analysis of energy consumption

Condition	Energy Consumption / 12 Months
Before Improvement	10,982 kWh
After Improvement	9,830 kWh
Energy Reduction	1,152 kWh (Decrease remains 10.49%)

4.2. Carbon Dioxide (CO_2) Emission Analysis

After the implementation of the improvement, there has been a reduction in CO_2 emissions as an indirect benefit. The reduction in energy consumption can positively impact the reduction of CO_2 emissions [51], [52], this is in accordance with SDGs development goal point 7 which is clean and affordable energy [53]. As per the Indonesian Government Regulation mentioned in the Letter of the ESDM Minister (Ministry of Energy and Mineral Resources of the Republic of Indonesia) No. 3783/21/600.5/2008 [54], the energy conversion factor is 0.891 kg/kWh. Based on this standard, we can calculate CO_2 emissions using Eq. (1).

$$CO_2\ Emissions = Energy\ (kWh) \times 0.891 \tag{1}$$

According to calculations based on equation (1), the improvement can reduce carbon dioxide (CO_2) emissions. As shown in **Table 3**, the improvement can reduce CO2 emissions by 1.02 tons for twelve months.

Table 3. Analysis of CO_2 reduction after improvement

Condition	CO_2 Emission / 12 Months
Before Improvement	9.78 Ton
After Improvement	8.76 Ton
CO_2 Reduction	1.02 Ton

4.3. Financial Analysis

The implementation of improved mechanics substitution by replacing conventional ball valves with automatic air valves significantly increases electrical energy efficiency in air compressor machines. After calculating electricity rates in Somaliland and converting the Somali Shilling (SOS) exchange rate to United States Dollars (USD), this improvement resulted in savings of USD 1,067 over twelve months. Detailed calculations can be seen in **Table 4**.

Table 4. Operation cost calculation in 12 months per machine

Cost / 12 Months	Energy Consumption	Cost (SOS)	Cost (USD)
Before Improvement	10,982 kWh	SOS 5,776,532	USD 10,170
After Improvement	9,830 kWh	SOS 5,170,580	USD 9,103
Cost Reduction	**1,152 kWh**	**SOS 605,952**	**USD 1,067**
Note: 1. Electricity power tariff is charged at SOS 526/kWH in Somaliland (2024). 2. United States Dollar (USD) 1 = Somali Shilling (SOS) 568 (January 6th 2025).			

Figure 9 below presents the results of the analysis of the implementation of TRIZ-based improvements to energy consumption, carbon dioxide (CO_2) emissions, and financial impacts. The evaluation was conducted by comparing data for 12 months before and after the improvements.

As illustrated in **Figure 9**, the observed reduction in electricity consumption by 10.49%, equivalent to 1,152 kWh in 12 months, represents a substantial improvement in operational efficiency. This reduction is directly reflected in the decrease in electricity expenditures and was achieved through the replacement of conventional ball valves with automatic air control valves, which effectively eliminated air leakage and optimized compressor performance. Within the framework of industrial energy management, even single-digit energy savings are regarded as highly valuable due to their cumulative impact on cost reduction, process efficiency, and environmental sustainability. Furthermore, a double-digit energy saving of 10.49% is not only technically significant but also strategically impactful, especially if applied sustainably and to more than one machine unit. These findings make a meaningful contribution to energy conservation initiatives and align with broader sustainability goals, including the reduction of CO_2 emissions and long-term operational cost efficiency.

Moreover, the initial capital investment required for the proposed improvements is relatively modest, involving only three additional components as detailed in **Table 5**, with a total cost of USD 93 (equivalent to 52,731 SOS). When compared to the projected annual energy savings of USD 1,067 (605,952 SOS) resulting from the implementation of these improvements, the intervention represents a cost-effective and economically viable long-term investment. The primary challenge associated with these components lies in their procurement, as all items are imported and subject to a delivery lead time of approximately 3 to 4 weeks.

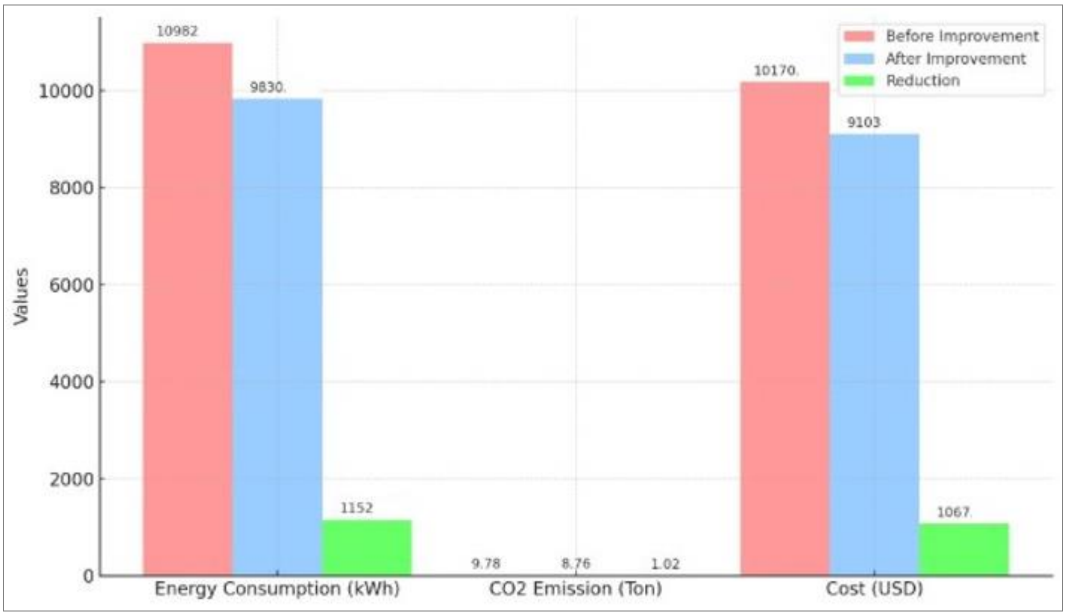

Figure 9. Energy consumption, CO_2 emission, and financial comparison

Table 5. Total cost for additional components

Additional Components	Cost (SOS)	Cost (USD)
Automatic Control Valve (1 unit)	34,020 SOS	USD 60
Relay 24V DC (1 unit)	5,670 SOS	USD 10
Power Supply (1 unit)	13,041 SOS	USD 23
Total Cost of Additional Components	**52,731 SOS**	**USD 93**

Note:
1. United States Dollar (USD) 1 = Somali Shilling (SOS) 567 (November 4^{th}, 2023).
2. All components are imported

On the other hand, the energy efficiency solution developed in this study also included an important step in the form of reprogramming the PLC (Programmable Logic Controller) system on the CNC machine. However, the implementation of this reprogramming did not require additional costs. This was because the programming process was included in the scope of the company's routine maintenance activities, which could be conducted internally by factory technicians who already had the relevant competencies. Thus, there were no additional costs charged in this programming aspect.

Based on the financial analysis that has been described, the low improvement costs but still resulting in high efficiency show that energy efficiency does not always depend on large capital investments, but can also be achieved through appropriate solutions with adequate internal human resource support.

5. Conclusion

This study provides an alternative idea for industries in Somaliland that use compressor machines in production activities. The TRIZ method is useful for researchers to identify the appropriate steps for corrective action, specifically in contradictory situations. In a case study that involved an air compressor, it was discovered that energy was being wasted during standby mode such as rest time, lunchtime, and dinner time because of air leaks. By applying the inventive principle of mechanics substitution through the TRIZ method, a specific solution was derived. This solution involved replacing the conventional ball valve, which had long been used, with an automatic air valve integrated with an emergency stop on CNC as a production machine. By implementing this improvement, the air valve from the compressor would close automatically following the production machine. The results were measured for twelve months before and after the implementation of these improvements. As a result, there was a reduction in electrical energy consumption by 10.49% and a decrease in CO_2 emissions by 1.02 tons. Additionally, there was a decrease in operational costs of USD 1,067 for a machine in twelve months. This study proves that implementing an automatic air valve is more efficient than using a conventional air valve.

Authors' Declaration

Authors' contributions and responsibilities - Conceived and designed the experiments (N.I.A, M.A, R.J.S, K.M); Performed the experiments (N.I.A, M.A, K.A.M); Analyzed and interpreted the data (M.A, N.I.A); Wrote the original paper (K.A.M, R.J.S, K.M), and Wrote the revised manuscript (R.J.S, K.M, K.A.M).

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