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Improving Energy Efficiency through Bottleneck Analysis in Food Manufacturing: A Theory of Constraints Approach

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Abstract. *The manufacturing industry faces increasing challenges in achieving both operational efficiency and environmental sustainability. In the food sector, high energy consumption during production processes makes energy efficiency a critical concern. This study applies the Theory of Constraints (TOC) to identify production bottlenecks and evaluate their implications for energy efficiency within the framework of green manufacturing. Using a case study approach, data were collected through observation, interviews, and production performance analysis. The TOC five-step methodology was implemented to identify, exploit, subordinate, elevate, and continuously improve constraints. Findings reveal that the main bottlenecks occurred in energy-intensive stages, particularly cooling and packaging, which recorded the longest cycle times of 21.6 s/unit and 24.1 s/unit, with utilization rates above 90%. Addressing these bottlenecks led to an 18.9% increase in throughput (from 148 to 176 units/hour), a 13.9% reduction in energy consumption (from 1,255 to 1,080 kWh/shift), and an improvement of the energy efficiency index from 74.6% to 84.2%. Idle time was also reduced by 45.8%, indicating smoother production flow. The study concludes that integrating TOC with green manufacturing provides a systematic and practical approach for improving both sustainability and competitiveness in the food industry.*

Keywords: *energy efficiency; food industry; green manufacturing; theory of constraints*

I. INTRODUCTION

The manufacturing industry in the modern era is increasingly pressured to balance operational efficiency, energy consumption, and environmental sustainability. The demand for sustainable production is reinforced by global concerns regarding climate change, resource scarcity, and stricter environmental regulations. Among various sectors, the food industry plays a particularly crucial role as it directly addresses basic human needs while simultaneously being one of the largest energy consumers in the industrial supply chain. Rising energy costs and growing awareness of environmental issues make energy efficiency an urgent priority for food manufacturers. In this context, the concept of green manufacturing has emerged as an essential paradigm, focusing on integrating environmentally friendly practices into production systems without compromising productivity or competitiveness.

According to the Ministry of Energy and Mineral Resources of Indonesia (KESDM, 2024), energy demand in the industrial sector is projected to double by 2060, from 78 MTOE in 2022 to 158 MTOE. This increase will be accompanied by a significant shift in the energy mix, with renewable energy and electricity expected to contribute 39% and 34% of industrial energy consumption, respectively. The food and beverage subsector is projected to dominate industrial energy use, accounting for 26% of total demand, followed by basic metals (20%), cement (17%), and chemical fertilizers (14%). At the same time, industrial sector emissions are forecasted to reach 49 million tons of CO_2 equivalent by 2060, underscoring the importance of decarbonization strategies.

The projection in Figure 1 underscores the critical urgency for industries, particularly the food and beverage sector, to adopt energy-efficient strategies as part of their long-term operational sustainability. With energy demand forecasted to increase from 78 MTOE in 2022 to 158 MTOE by 2060, and the food industry

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expected to account for more than one quarter of this consumption, manufacturers cannot rely on business-as-usual approaches. Rising operational costs, coupled with projected emissions of 49 million tons of CO_2 equivalent, reveal that inefficiencies in production systems will not only harm competitiveness but also exacerbate environmental pressures. Unlike sectors such as cement or steel, food manufacturing faces the dual challenge of maintaining strict product quality and safety standards while simultaneously reducing its environmental footprint, given that energy-intensive processes like heating, cooling, and packaging are indispensable. This makes the sector highly vulnerable to energy cost fluctuations and increasingly stringent decarbonization regulations. At the same time, it creates an opportunity: firms that succeed in improving efficiency will reduce costs, enhance resilience, and strengthen their reputation as environmentally responsible actors, aligning with both national energy conservation policies and international sustainability frameworks. However, achieving these outcomes requires systematic methods that go beyond incremental improvements. Traditional efficiency programs often disperse resources across all processes, whereas strategic approaches should concentrate efforts on the most critical constraints that drive energy intensity. In this context, the Theory of Constraints (TOC) offers a robust framework for addressing the challenge. By identifying, exploiting, subordinating, and elevating bottlenecks—particularly those in energy-demanding stages—TOC enables manufacturers to reduce waste, improve throughput, and directly enhance energy efficiency. Thus, the projections shown in Figure 1 not only highlight the urgency of action but also justify the adoption of TOC as a practical managerial tool for transforming food industry operations into more competitive and sustainable systems.

The Theory of Constraints (TOC), introduced by Goldratt (1990), has become an influential framework for addressing operational inefficiencies by focusing managerial attention on system bottlenecks. Rather than attempting to optimize all resources equally, TOC emphasizes that system performance is determined by its most limiting constraint. Studies have applied TOC across various domains, from supply chain management Costas et al. (2015) to healthcare services (Bauer et al., 2019), consistently demonstrating its ability to enhance throughput and resource utilization.

In the context of production systems, TOC has been shown to mitigate the bullwhip effect in supply chains (Braz et al., 2018), improve workload balance (Ungern-Sternberg et al., 2020), and enhance competitiveness (Almasaeid, 2021). In food-related industries, Davididou & Frontistis (2021) demonstrated that TOC application improved production flow and reduced inefficiencies in wine processing, while Smith & Pretorius (2002) emphasized its economic value added by managing key constraints effectively. More recent studies have integrated TOC with advanced simulation models for bottleneck

Figure 1. Projected Energy Demand and Emissions in the Industrial Sector (KESDM, 2024)

identification (L. Liu et al., 2023; Xia et al., 2024) , revealing its adaptability in Industry 4.0 contexts.

While these studies highlight the versatility of TOC, most have concentrated on with relatively limited attention to energy efficiency productivity, quality, and competitiveness. Recent research linking bottlenecks with energy consumption (Ghatorha et al., 2024; Yan & Liu, 2023) suggests that constraints are strongly correlated with inefficient energy use, particularly in processes with high idle time or unbalanced workloads. However, empirical evidence focusing specifically on the food industry under a green manufacturing framework remains scarce.

This article contributes to filling the research gap by directly linking the Theory of Constraints with energy efficiency in the food industry. Unlike previous studies that primarily focused on productivity or supply chain optimization, this study emphasizes the role of bottlenecks in driving energy inefficiency and proposes TOC as a managerial tool to systematically reduce energy waste. The novelty lies in demonstrating how TOC, traditionally used for throughput improvement, can be extended to the domain of green manufacturing, where sustainability and energy conservation are equally critical outcomes.

Based on the above context and literature, this study addresses the following research questions:

1. How can TOC be applied to identify production bottlenecks in the food industry within a green manufacturing framework?
2. Which production stages represent the main constraints and how do they influence energy consumption?
3. To what extent can TOC-based improvements contribute to energy efficiency while maintaining production flow?

The objective of this article is to assess production bottlenecks and their implications for energy efficiency in the food industry using the Theory of Constraints. Specifically, it seeks to demonstrate the effectiveness of TOC in identifying energy-intensive constraints, reducing waste, and integrating green manufacturing principles to support sustainability and competitiveness.

II. RESEARCH METHOD

This study employed a case study approach to analyze production bottlenecks and their implications for energy efficiency in a food manufacturing company. The methodology was structured according to the Constraint Management Cycle of the Theory of Constraints (TOC), which consists of five stages: (1) identifying the constraint, (2) exploiting the constraint, (3) subordinating other processes, (4) elevating the constraint, and (5) repeating the cycle for continuous improvement (Horna & Chong, 2021; Puche et al., 2016)

The study was conducted on a food production line consisting of processes such as mixing, heating, cooling, and packaging. The primary materials used in the production process included:

1. Raw food ingredients (e.g., flour, sugar, vegetable oil; purity ≥ 99% for industrial grade).
2. Cooling agents (industrial water with controlled purity, ≥ 95%).
3. Packaging materials (polyethylene plastic, food-grade standard).
4. The main equipment analyzed in relation to bottlenecks and energy consumption were:
5. Industrial cooling machine (refrigeration system, electrical input 220/380V, rated power 30 kW).
6. Automatic packaging machine (servo-driven, rated power 15 kW).
7. Electric furnace for heating (capacity 200 °C, rated power 25 kW).
8. Production conveyor system (rated speed 0.5–1.5 m/s).

Secondary supporting devices such as pumps, sensors, or auxiliary conveyors were excluded from detailed analysis, as the focus was on primary energy-intensive machines.

The procedure consisted of the following steps:

1. Observation and Data Collection
2. Direct observation of production processes was conducted to identify potential bottlenecks.

3. Data on cycle time, throughput, machine utilization, and energy consumption were recorded.

Structured interviews with operators and production managers were carried out to validate observations.

Constraint Identification and Improvement Approach

Constraint Identification.. The identification of production constraints is a fundamental step in the Theory of Constraints (TOC) methodology. In this study, bottlenecks were determined by systematically comparing the cycle times and utilization rates of each major machine in the production line. A bottleneck is defined as the process or equipment that limits the overall capacity of the system, operating at or near its maximum capacity, and preventing other processes from reaching higher throughput. By calculating the average cycle time for each stage, it was observed that cooling and packaging processes consistently exhibited the longest cycle times relative to mixing and heating stages. Additionally, their utilization rates exceeded 90%, indicating that these machines were almost continuously occupied during production shifts. This pattern strongly confirmed that cooling and packaging were the system constraints. Identifying these stages allowed the research team to focus managerial and technical interventions where they would yield the greatest impact on efficiency and energy performance.

Constraint Exploitation and Subordination. Once the constraints were identified, the next step was to exploit them effectively. Exploitation in this context means ensuring that bottleneck resources operate without interruption and with minimal downtime. Production schedules were carefully adjusted so that the cooling and packaging machines received a steady and uninterrupted flow of work. This eliminated unnecessary idle times, reduced the accumulation of semi-finished products, and maximized the output of the most critical stages.

In parallel, the principle of subordination was applied to all non-bottleneck processes. This required upstream processes such as mixing and heating, as well as downstream handling, to align their pace with the capacity of the bottlenecks. Subordination prevented excessive buildup of work-in-progress before the cooling and packaging stages, ensuring smoother flow throughout the system. Although subordination sometimes meant reducing the speed of non-bottleneck machines, it avoided energy waste and inefficiencies associated with overproduction, making the entire production line more synchronized and sustainable.

Constraint Elevation. Beyond exploitation and subordination, additional measures were introduced to elevate the capacity of the bottlenecks. Elevation refers to structural improvements designed to increase the effective throughput of the identified constraints. In this study, technical adjustments were implemented, including optimizing the cooling cycle to shorten processing time and reconfiguring the feeding system of the packaging machine to minimize changeover delays. These improvements reduced downtime and improved the energy performance of the machines. Although these measures required modest investment, they provided substantial benefits by enhancing both throughput and energy efficiency, demonstrating the long-term value of elevating bottleneck capacity.

Evaluation of Energy Efficiency. The impact of these interventions was evaluated by comparing energy consumption before and after TOC implementation. Energy usage was measured for each production stage using electricity meters, and total consumption was analyzed relative to throughput. By examining the ratio of energy input to production output, it was possible to quantify efficiency gains. The comparison revealed that addressing bottlenecks not only increased throughput but also significantly reduced idle time, which in turn lowered overall energy consumption. This confirmed that energy efficiency could be improved through targeted bottleneck management rather than system-wide overhauls.

Analytical Methods

Several analytical methods were employed to support this evaluation.

Throughput Analysis. Throughput (T) was calculated using the formula:

$$T = \frac{Q}{t} \quad \text{...(1)}$$

where Q represents the quantity of finished products (units), and t represents the total production time (hours). This measure provided insight into how many units were produced per unit of time and how throughput changed after bottleneck improvements.

Utilization Rate. The utilization rate (U) of each machine was determined as:

$$U = \frac{t_{operation}}{t_{available}} \times 100\% \quad \text{... (2)}$$

where toperationt is the actual running time of the machine, and tavailable is the total available time. A high utilization rate, particularly above 90%, indicated that the machine was operating near its maximum limit and was therefore a likely bottleneck.

Energy Efficiency Index. Energy efficiency (EE) was calculated as:

$$EE = \frac{P_{out}}{P_{in}} \times 100\% \quad \text{... (3)}$$

where P_{out} is the effective energy utilized for production (kWh), and P_{in} is the total energy input (kWh) measured from electricity meters. This index provided a clear measure of how effectively input energy was converted into productive output. Improvements in EE after TOC application confirmed that bottleneck-focused interventions directly enhanced energy performance.

Together, these analytical methods validated the positive impact of TOC on both production efficiency and energy utilization, underscoring its suitability as a tool for green manufacturing practices.

Research Framework

Production system analyzed in this study, a schematic framework of the main processes is presented. The diagram highlights the sequence of stages in the food manufacturing line, including mixing, heating, cooling, and packaging. Among these stages, the cooling machine and packaging system were identified as the most energy-intensive and critical in relation to bottleneck identification

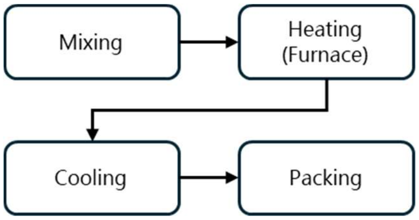

Figure 2. Main production line

After analyzing the schematic in Figure 2, it becomes evident that the production flow is sequentially dependent, meaning that a slowdown or disruption in any stage will directly affect subsequent processes. The visual representation helps clarify why the cooling and packaging stages act as the principal constraints in the system: both require significant processing time, consume high levels of energy, and thus limit the overall throughput of the line. This framework guided the subsequent analysis in identifying, exploiting, and elevating the system's bottlenecks.

III. RESULT AND DISCUSSION

Research Data

Identification of Production Bottlenecks. Field observations and production data analysis revealed that the most critical bottlenecks occurred in the cooling and packaging processes. Both processes recorded higher cycle times and utilization rates compared to other stages, significantly influencing throughput and energy usage. Table 1 presents the comparison of cycle times and utilization rates for the main machines.

The results indicate that cooling and packaging have the longest cycle times (21.6 s/unit and 24.1 s/unit, respectively) and the highest utilization rates (>90%). These processes are energy-intensive and directly limit production flow. The bottleneck machines consumed nearly 60% of total production energy, underscoring

Table 1. Cycle Time and Utilization Rate of Main Production Equipment

Process Stage	Average CT (sec/unit)	Utilization Rate (%)	Energy Consump (kWh/shift)
Mixing	8.5	68	120
Heating	12.2	74	250
Cooling	21.6	92	410
Packaging	24.1	95	380
Conveyor	7.3	61	95

Source: Field data, 2024

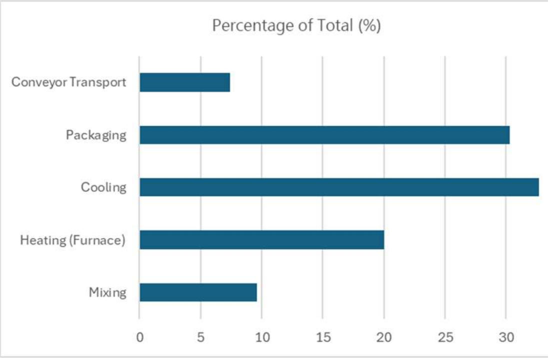

Figure 3. Energy consumption by production stage (per shift).

their dual role as throughput and energy constraints.

Energy Implications of Bottlenecks. Energy consumption is a critical performance indicator in food manufacturing, where processes such as heating, cooling, and packaging are inherently energy-intensive. Bottlenecks, by definition, operate near or at full capacity, making them disproportionately responsible for high energy use compared to other stages. Identifying these points is therefore essential not only for improving throughput but also for reducing unnecessary energy waste. By linking bottleneck analysis with energy monitoring, this study highlights how TOC provides a focused approach to enhance both production performance and energy efficiency simultaneously.

The figure confirms that cooling and packaging are the most energy-demanding processes, consuming 410 kWh and 380 kWh per shift, respectively. Together, they account for approximately 65% of total energy usage. The analysis supports the argument by J. Liu et al. (2021) that bottlenecks are strongly correlated with inefficient energy use, particularly when they operate continuously at or beyond capacity.

Application of TOC Five-Step Approach

The TOC five-step methodology was systematically applied to address the identified bottlenecks:

1. Identify – Cooling and packaging stages were confirmed as the primary constraints.
2. Exploit – Operating schedules were modified to ensure maximum utilization of bottleneck machines, reducing idle time.
3. Subordinate – Upstream and downstream processes were synchronized to match the capacity of bottlenecks, preventing excessive accumulation or waiting.
4. Elevate – Technical adjustments were made, including reconfiguration of packaging machine feeding systems and optimization of cooling cycles.
5. Repeat – Continuous monitoring revealed potential new constraints in raw material preparation, indicating the cyclical nature of constraint management.

To evaluate the effectiveness of TOC interventions, it is essential to compare production performance indicators before and after implementation. Such a comparison provides quantitative evidence of whether improvements were achieved and how they translated into operational and energy-related benefits. The focus is not only on throughput, which represents the system's ability to produce more units within the same time frame, but also on supporting indicators such as cycle time, energy consumption, efficiency index, and idle time. Throughput is a traditional measure of productivity, while cycle time highlights process speed and stability. Energy consumption reflects resource intensity, and the energy efficiency index combines both productivity and sustainability perspectives. Idle time, meanwhile, indicates the extent of synchronization across processes. Collectively, these metrics offer a holistic picture of performance and enable an assessment of whether TOC has successfully addressed bottlenecks and improved both operational and environmental outcomes. The summary is presented in Table 2.

Table 2. Performance Indicators Before and After TOC Implementation

Indicator	Before TOC	After TOC	Improvement (%)
Throughput (units/hour)	148	176	+18.9
Average Cycle Time (sec/unit)	15.1	12.7	-15.9
Energy Consumption (kWh/shift)	1,255	1,080	-13.9
Energy Efficiency (EE, %)	74.6	84.2	+12.9
Idle Time (minutes/shift)	48	26	-45.8

Source: Field data, 2024

Results presented in Table 2 confirm that the implementation of TOC had a positive impact on multiple dimensions of production performance. Throughput increased from 148 to 176 units per hour, representing an improvement of 18.9%, while average cycle time decreased by 15.9%, demonstrating smoother and faster process flows. Importantly, these gains were achieved alongside significant energy savings, with consumption reduced from 1,255 kWh to 1,080 kWh per shift (a 13.9% reduction). This directly improved the energy efficiency index from 74.6% to 84.2%, reinforcing that productivity gains were not achieved at the expense of higher resource use. On the contrary, the dual benefits of higher throughput and lower energy intensity emphasize the strength of TOC as a green manufacturing tool. Furthermore, idle time was nearly halved, declining by 45.8%, which indicates successful synchronization of production stages and reduced waste. Overall, these findings highlight the integrated benefits of TOC.

Discussion

The findings are consistent with Kikolski (2016) and Edirisinghe & Karunarathne (2023), who showed that bottleneck analysis identifies critical stages limiting system performance. However, this study extends their conclusions by showing that bottlenecks not only affect throughput but also directly increase energy intensity.

Compared to Davididou & Frontistis (2021), who applied TOC to wine processing, this research demonstrates similar outcomes in food manufacturing, but with a stronger emphasis on energy efficiency under green manufacturing. Almasaeid (2021) highlighted that TOC enhances competitiveness by focusing on constraints, and the present findings validate t his claim by linking constraint management with measurable reductions in energy consumption.

Moreover, the improvements observed in this study align with recent work by Ghatorha et al. (2024), which emphasized the role of Energy Footprint and Bottleneck Analysis (EFBA) in reducing carbon emissions. By integrating TOC with energy analysis, this article contributes a novel empirical perspective to the body of literature.

Contribution to Green Manufacturing. The integration of TOC with green manufacturing offers a structured and systematic approach for industries aiming to meet sustainability targets without sacrificing productivity. One of the key challenges for manufacturers is achieving efficiency improvements that deliver both economic and environmental benefits simultaneously. Conventional methods often focus either on cost reduction or environmental compliance, but rarely on both dimensions at once. By contrast, TOC focuses resources on bottlenecks that are typically the most energy-intensive points in the production line, ensuring that improvements generate the maximum impact. This makes TOC particularly valuable for food manufacturing, where processes such as cooling and packaging dominate energy use. Importantly, the results of this study show that energy savings were realized without reducing production capacity, proving that productivity and sustainability can be complementary goals rather than trade-offs. This synergy is further illustrated in Figure 4, which highlights the relationship between throughput and energy efficiency before and after TOC implementation.

As illustrated in Figure 4, the implementation of TOC shifted the production system into a more favorable performance zone, where higher throughput coincides with greater energy

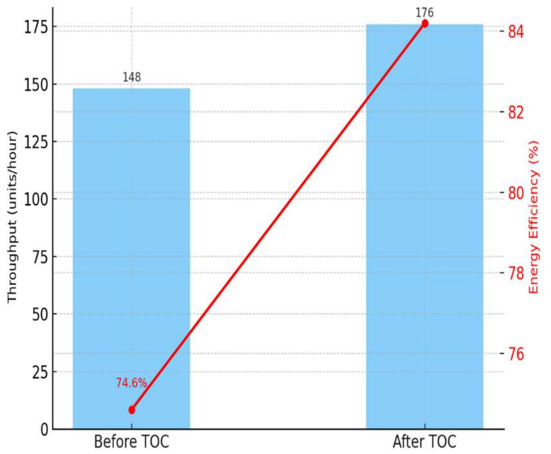

Figure 4. Relationship between throughput and energy efficiency before and after TOC implementation

efficiency. This outcome challenges the conventional assumption that improving productivity typically increases energy consumption. Instead, the results indicate that when bottlenecks are effectively managed, both throughput and efficiency can improve simultaneously. Specifically, throughput increased by nearly 19%, while energy efficiency rose by more than 12%, showing a strong dual benefit. These findings reinforce the argument by Mason-Jones et al. (2022) that TOC is compatible with broader sustainability strategies and can be integrated into green manufacturing practices without requiring substantial capital investment. The improvement trajectory depicted in the figure suggests that bottleneck-focused interventions are not only operationally effective but also strategically aligned with long-term environmental goals, positioning TOC as a powerful tool for industries seeking to balance competitiveness with sustainability.

Cost and Environmental Impact Analysis. The application of the Theory of Constraints (TOC) not only improved operational efficiency but also brought measurable economic and environmental benefits. Energy efficiency is closely tied to production costs, and in the context of food manufacturing, electricity is one of the largest operational expenditures. Therefore, quantifying the financial implications of reduced energy consumption provides a clearer understanding of the practical value of TOC.

Economic Benefits. Before TOC implementation, the total energy consumption per production shift was measured at approximately 1,255 kWh. After applying the TOC five-step methodology, this value decreased to 1,080 kWh, reflecting a reduction of 175 kWh per shift. Assuming the plant operates two shifts per day, the daily energy savings amount to 350 kWh. With the average industrial electricity tariff in Indonesia set at IDR 1,400 per kWh, this reduction translates into a daily saving of IDR 490,000.

When extrapolated to a full year of operations (assuming 300 working days), the total annual energy savings reach 105,000 kWh, equivalent to approximately IDR 147 million in electricity cost reduction. This level of savings has a direct impact on company profitability, allowing resources to be reallocated for machine upgrades, staff training, or other strategic investments. Moreover, these savings help reduce vulnerability to rising electricity tariffs, which have been a recurrent issue in developing economies.

From a broader perspective, energy efficiency also improves the cost-competitiveness of the firm in the food market. Lower production costs can either enhance profit margins or allow the company to offer more competitive pricing to consumers. In industries characterized by tight margins and high competition, such as food and beverage manufacturing, this competitive edge can be crucial for long-term sustainability.

Environmental Benefits. The environmental implications of reduced energy consumption are equally significant. Using Indonesia's average electricity emission factor of 0.82 kg CO_2 per kWh (based on grid intensity data), the reduction of 105,000 kWh annually results in an approximate decrease of 86 metric tons of CO_2 emissions per year. This amount is equivalent to the annual carbon absorption of more than 3,500 mature trees or the emissions from approximately 19 passenger vehicles operating for one year.

Such reductions contribute directly to Indonesia's national energy conservation and decarbonization strategies as outlined in the Rencana Umum Energi Nasional (RUEN). The results of this study align with government targets to lower greenhouse gas emissions in the industrial sector and highlight how practical managerial tools such as TOC can complement broader policy initiatives. By focusing on bottleneck machines, companies can achieve environmental improvements without requiring costly investments in renewable energy infrastructure or new technologies.

Beyond direct financial and environmental benefits, the integration of TOC-driven efficiency improvements offers strategic advantages for firms. *First*, it positions the company as a more sustainable and environmentally responsible actor, which is increasingly demanded by global supply chains and export markets. Many multinational corporations now require their suppliers to comply with carbon reduction or energy efficiency standards, and proactive efforts in this area can enhance access to international markets.

Second, the linkage between energy efficiency and corporate reputation cannot be overlooked. Consumers are becoming more aware of sustainability issues, and companies that can demonstrate tangible energy and carbon savings gain reputational value, which can influence brand loyalty and market preference.

Third, the savings achieved through reduced energy consumption can be reinvested into further process optimization or adoption of Industry 4.0 technologies such as IoT-based energy monitoring, predictive maintenance, and real-time bottleneck detection. In this way, TOC serves not only as a short-term cost-saving tool but also as a stepping stone toward long-term digital transformation.

The economic and environmental impact observed in this study reinforces findings from previous research while extending their applicability to the food industry. Ghatorha et al. (2024) demonstrated through the Energy Footprint and Bottleneck Analysis (EFBA) method that targeting energy-intensive bottlenecks in heavy machinery reduced both carbon emissions and operational costs, a perspective validated here in a different sector using simpler TOC interventions. Similarly, Mason-Jones et al. (2022) showed that TOC improved sustainability outcomes in renewable energy supply chains at a macro level, whereas this study highlights comparable benefits at the micro level of production lines. In the wine industry, Kikolski (2016) emphasized the use of simulation to identify bottlenecks for productivity improvement, yet without considering energy performance; this study adds that dimension by showing how bottleneck management reduces energy waste. Finally, Almasaeid (2021) concluded that TOC enhances competitiveness by focusing on constraints, but competitiveness was measured in purely economic terms, whereas here it is expanded to include sustainability through reduced energy costs and carbon emissions. Together, these comparisons underscore the novelty of this study, which demonstrates that TOC can simultaneously increase throughput, reduce energy consumption, and support green manufacturing in the food industry.

The cost and environmental impact analysis reveals that TOC provides a dual advantage: reducing operational costs while simultaneously supporting environmental sustainability. The financial savings of more than IDR 147 million annually and the reduction of 86 tons of CO_2 emissions underscore the practical importance of TOC as a management tool. Importantly, these benefits were achieved without major capital investment, relying instead on process optimization and strategic alignment of production activities. This demonstrates the unique value of TOC in helping companies balance competitiveness with sustainability in an increasingly resource-constrained global economy.

Managerial Implications. From a managerial perspective, the findings suggest that:

1. Bottleneck management should prioritize energy-intensive processes. These stages not only limit throughput but also significantly affect energy bills and carbon footprints.
2. TOC provides a structured approach to direct improvement efforts where they matter most, avoiding unnecessary investments in non-constraint areas.

3. Sustainability can be achieved without sacrificing productivity. By synchronizing processes and optimizing bottleneck machines, companies gain dual benefits of efficiency and competitiveness.

Discussions

This study set out to explore how bottleneck analysis, when framed within the Theory of Constraints (TOC), can serve as a practical approach to improving energy efficiency in the food manufacturing sector. The findings provide strong evidence that production bottlenecks are not only operational constraints that limit throughput but also critical determinants of energy inefficiency. By identifying and addressing these constraints, particularly in cooling and packaging processes, significant improvements were achieved in both productivity and sustainability outcomes.

Quantitative analysis confirmed the effectiveness of this approach. Throughput increased from 148 to 176 units per hour, representing an improvement of 18.9%, while average cycle time was reduced by 15.9%. At the same time, energy consumption per shift decreased from 1,255 to 1,080 kWh, a 13.9% reduction. These improvements elevated the energy efficiency index from 74.6% to 84.2%. Moreover, idle time was reduced by nearly half, decreasing by 45.8%, indicating that the production system operated in a more synchronized and balanced manner. Such outcomes demonstrate that TOC-driven bottleneck analysis yields dual benefits: higher throughput and lower energy intensity.

From an economic perspective, the reduction in energy consumption translated into annual savings of approximately 105,000 kWh, equivalent to about IDR 147 million. These savings provide companies with opportunities to reinvest in production technologies, workforce development, or further efficiency initiatives. On the environmental side, the reduced energy usage corresponded to an estimated 86 metric tons of CO_2 emission reductions annually. This not only strengthens the company's alignment with national decarbonization targets but also enhances its competitiveness in a global market that increasingly values sustainable practices.

Theoretically, this study extends the application of TOC beyond its traditional role in throughput optimization by demonstrating its value as a tool for energy efficiency improvement. Previous studies have largely focused on productivity, competitiveness, or supply chain performance; the novelty of this research lies in empirically showing that TOC can also contribute to sustainability goals. By linking bottleneck management directly to energy outcomes, the study provides a new dimension to TOC literature and bridges a gap between operations management theory and sustainability-oriented practices.

For managers and practitioners, the implications are clear. Efforts to reduce energy costs and carbon emissions should prioritize bottleneck processes, which are often the most energy-intensive stages in production. Unlike generalized energy-saving initiatives that may spread resources thinly across multiple processes, TOC ensures that improvements are targeted where they yield the highest impact. Importantly, this research also demonstrates that meaningful improvements can be achieved without substantial capital investments, relying instead on process optimization, scheduling adjustments, and technical fine-tuning of existing machines.

Nevertheless, the study has limitations. As a single case study, the findings may not be fully generalizable across all food manufacturing contexts or other industrial sectors. Energy analysis was based on electricity consumption in kilowatt-hours, without a more detailed assessment of process-level carbon intensity. Future research could incorporate real-time energy monitoring systems, simulation models, or Internet of Things (IoT)-based analytics to provide deeper insights into bottleneck behavior and energy use. Comparative studies across industries such as cement, steel, and chemicals would also strengthen the external validity of this approach.

IV. CONCLUSION

In conclusion, this research has demonstrated that improving energy efficiency through bottleneck analysis is both feasible and impactful when guided by the Theory of Constraints. The empirical evidence confirms that TOC interventions can simultaneously enhance throughput, reduce energy consumption, and strengthen environmental sustainability in food manufacturing. By aligning operational performance with sustainability goals, TOC provides managers with a strategic framework that is not only economically beneficial but also environmentally responsible. As energy costs and sustainability pressures continue to rise, the adoption of TOC as a green manufacturing tool becomes increasingly relevant for companies seeking to secure long-term competitiveness in the global market.

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