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BALANCING EFFICIENCY AND FLEXIBILITY – A SIMULATION OF LINE CONFIGURATIONS

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Purpose: The purpose of the study is to examine the impact of production line configurations on operational efficiency using simulation tools. Analyzing various scenarios with a variable number of production lines allows for an assessment of how infrastructure modifications affect system performance, resource management, and operational flexibility.
Design/methodology/approach: The study was conducted using FlexSim software, which enables the modeling and analysis of production processes. Key steps included: collecting operational data, developing a simulation model, validating the model, and analyzing the results for three configurations: one, two, and three production lines. Model validation was performed by comparing simulation results with real-world operational data.
Findings: The findings indicate that a single production line ensures high operational efficiency (around 98%), but its rigidity limits adaptability under changing conditions. Adding a second production line results in a moderate decrease in efficiency (approximately 1.2%), while significantly enhancing flexibility and resource management capabilities. Three production lines offer the highest flexibility; however, efficiency drops to approximately 80%, which may cause challenges related to underutilized resources and increased operational costs. The optimal solution, balancing flexibility and efficiency, is the addition of a second production line. Adding a third line may only be justified under conditions of significant demand growth.
Research limitations/implications: The study's limitations stem from the simplifications in the model, such as the assumption of constant production parameters and the exclusion of market variability. Future research should consider dynamic market conditions and a more comprehensive cost analysis.
Originality/value: The study introduces an innovative approach by applying computer simulation to evaluate the efficiency of different production line configurations. The insights provided in the article are valuable for production engineers and managers, assisting them in making informed decisions about optimizing production systems.
Keywords: Computer simulation, Production optimization, System flexibility, Resource management, Production engineering.
Category of the paper: Research paper and case study.

1. Introduction

The modern manufacturing industry faces the challenge of continuously optimizing processes to enhance operational efficiency and the flexibility of production systems. The use of advanced simulation tools, such as FlexSim, enables modeling and analysis of various production line configurations, facilitating the identification of potential improvements and better resource management (Dubaj, 2023).

Research indicates that production process simulation allows for verifying system performance before implementation or during modifications, such as expanding the product portfolio or changing production volumes (Asseco CEIT, 2024). This approach makes it possible to identify bottlenecks and optimize material flow and resource allocation, ultimately leading to increased operational efficiency (DS-Technic, 2024).

The objective of this article is to evaluate the impact of different production line configurations on operational efficiency using advanced simulation tools. The analysis encompasses scenarios with one, two, and three production lines, enabling an assessment of how infrastructure changes influence system performance, resource management, and operational flexibility. The application of computer simulations provides a detailed understanding of production processes and supports informed strategic decision-making in the optimization of production systems.

2. Theoretical background of the study

Computer simulation plays a crucial role in production management, enabling the analysis and optimization of processes without interfering with the actual system. It allows for the identification of bottlenecks, optimization of material flow, and reduction of operational costs through more effective resource utilization (Dubaj, 2023). Modern manufacturing enterprises must operate in a dynamically changing market environment, which requires flexible and efficient process management (Borshchev, Filippov, 2004). Research indicates that the use of simulation can increase production system efficiency by 10-20%, making it a key element of management strategies (Greasley, 2017).

Various tools supporting process simulation are widely used in the manufacturing industry. The most commonly utilized include FlexSim, AnyLogic, and Arena Simulation. Each of these tools offers unique features that facilitate the modeling of complex production processes and the real-time analysis of performance metrics (Borshchev, 2013; Greasley, 2017).

FlexSim is one of the most versatile tools for production simulation. It offers features such as dynamic modeling, "what-if" scenario analysis, and resource optimization (Dubaj, 2023). Its application in the food industry has demonstrated a 15% reduction in production cycle time and improved resource management (Dubaj, 2023).

AnyLogic stands out for its ability to integrate logistics and multi-aspect simulations, making it a valuable tool for analyzing complex supply chains (Borshchev, Filippov, 2004). On the other hand, Arena Simulation is widely used in the automotive industry, where it enables precise analysis of material flows and production capacity (Greasley, 2017).

Computer simulation is widely used in scientific research as a tool for analyzing the efficiency of production processes and forecasting outcomes in complex systems (Borshchev, 2013). Studies by Dubaj (2023) indicate that the application of FlexSim in the electronics and food industries has delivered significant benefits, including a 20% reduction in downtime. Similar results were achieved in research by Greasley (2017), where simulations facilitated the identification of critical points in production systems, contributing to overall performance improvements (Cigolini et al., 2014).

The use of simulation tools such as FlexSim and Arena also enables integration with ERP systems, enhancing forecasting precision and supporting strategic decision-making (Borshchev, 2013). The role of simulation in the design and operation of production systems is expected to grow significantly in the future (Sobottka et al., 2017).

The manufacturing sector, as a critical component of the global economy, is becoming increasingly competitive, necessitating the adoption of modern tools to support its development (Daaboul et al., 2014). Faced with growing process complexity and the need for flexible responses to changing market conditions, enterprises are challenged to implement more advanced and efficient optimization techniques (Karwat et al., 2022).

Computer simulation, recognized as one of the most effective tools in this domain, enables better understanding and management of complex production systems (Prajapat, Tiwari, 2017). The growing significance of simulation is driven by the need to reduce operational costs, enhance efficiency, and minimize risks associated with implementing new production strategies (Kusiak, 2020).

Simultaneously, increasing digitalization and the integration of technologies such as artificial intelligence and machine learning are opening new opportunities for simulation in the industrial sector (Chen et al., 2022). Automation of processes, "what-if" modeling, and future scenario forecasting allow companies to enhance flexibility and adapt to dynamic changes in the economic environment. As a result, simulation is evolving from being merely an operational tool to becoming a strategic instrument that supports the long-term development of organizations (Lidberg et al., 2020).

3. Methods

The aim of the study was to conduct a detailed analysis of the impact of various production line configurations on key performance indicators (KPIs) and the flexibility of the production system. The use of computer simulation enabled accurate replication of real-world production processes, allowing for the testing of alternative scenarios without disrupting ongoing operational activities.

FlexSim was selected as the simulation tool due to its advanced functionalities, which were ideally suited to the needs of the study. In this case, FlexSim enabled:

- 3D Process Modeling – Accurate representation of the physical structure of the production system, including the layout of production lines, machine placement, and material flows.
- 3D Visualization – Tracking material flow and identifying potential bottlenecks through real-time visual simulations.
- Dynamic Real-Time Simulations – Analysis of material flows and resource utilization in real time, enabling the monitoring of system efficiency changes based on the number of production lines.
- "What-If" Scenario Analysis – Creation and comparison of various production system configurations, crucial for evaluating their impact on operational efficiency and flexibility. Testing different scenarios allowed for the identification of the optimal configuration.
- Generation of Operational Efficiency Indicators – Automatic generation of key performance indicators (KPIs), such as lead time, resource utilization, and idle resources, providing measurable insights into system performance.
- Reporting and Visualization of Results – The tool enabled the generation of detailed reports, including heat maps of machine utilization, material flow diagrams, and KPI charts. These reports were essential for interpreting results and presenting differences among the analyzed scenarios.

The research process was planned in several stages, each of which was crucial for achieving reliable results:

- Data Collection and Preparation – At the initial stage, detailed operational data on production processes were gathered. This included cycle times, production line structures, machine availability, and production capacities. The data were formatted appropriately for input into FlexSim.
- Development of the Simulation Model – The model was built within the FlexSim environment, replicating production processes in a virtual form. It included detailed decision variables such as the number of production lines, material flows, and resource allocation.

- Model Validation – To ensure the simulation model accurately reflected real-world operations, validation was performed. Simulation results were compared with historical operational data, confirming the model's alignment with reality.
- Scenario Simulation – Simulations were conducted for three scenarios, each analyzed based on key performance indicators and their impact on system flexibility: one production line (baseline scenario), two production lines (moderate flexibility), three production lines (maximum flexibility, potential efficiency challenges).

4. Results

The company analyzed specializes in the production of metal components with precise technical specifications, utilized across various industrial sectors. In a highly volatile market environment and amidst increasing expectations for quality and efficiency, optimizing the production system is of critical importance. To accurately replicate operational processes, a simulation model was developed based on a detailed layout of the production line. This section presents the results of the analysis conducted under three scenarios of system configuration.

To enable a realistic yet transparent analysis, the following key assumptions were adopted:

1. Operational Parameter Stability – It was assumed that operation cycle times, machine efficiency, and resource availability remain constant, reflecting average values derived from historical data.
2. No Demand Variability – The simulation model focused on optimizing the current production configuration, excluding the impact of dynamic changes in product demand.
3. Machine Performance – All machines were assumed to operate at maximum technical efficiency, with downtime occurring only due to failures or maintenance requirements, which were incorporated into the model parameters.

Model The simulation model was developed based on a detailed layout of the production line (Figure 1). The layout accounted for the placement of key production infrastructure elements, including:

- Production Machines and Equipment – The placement of machines along the production line was accurately modeled to reflect actual material flows and the operational characteristics of the system.
- Storage Buffers – The model included the location and capacity of buffers, enabling an analysis of interdependencies between production stages and identification of potential bottlenecks.
- Quality Control Points – Quality control checkpoints were defined on the factory floor layout, playing a critical role in maintaining production standards.

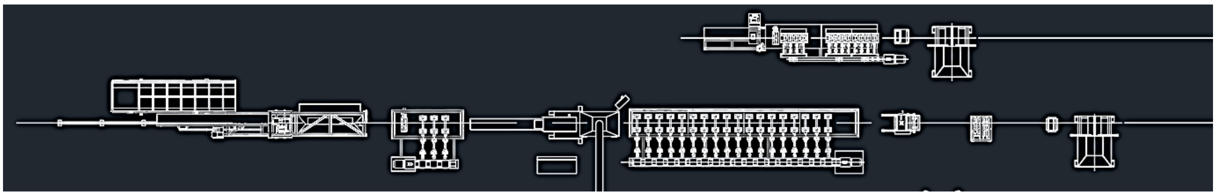

Figure 1. Production line layout.

The simulation based on the layout enabled realistic modeling of material flows, queues, and operational cycles. This facilitated a detailed analysis of the impact of changes in production line configurations on key operational performance indicators.

Subsequently, using the production line layout, a detailed resource flow process was modeled in FlexSim software. The Process Flow illustrates all key stages of the production process, including resource generation, transport, processing, and quality control (Figure 2). Additionally, each block depicted in the diagram was thoroughly discussed, considering its role in the model and the key parameters used in the simulation.

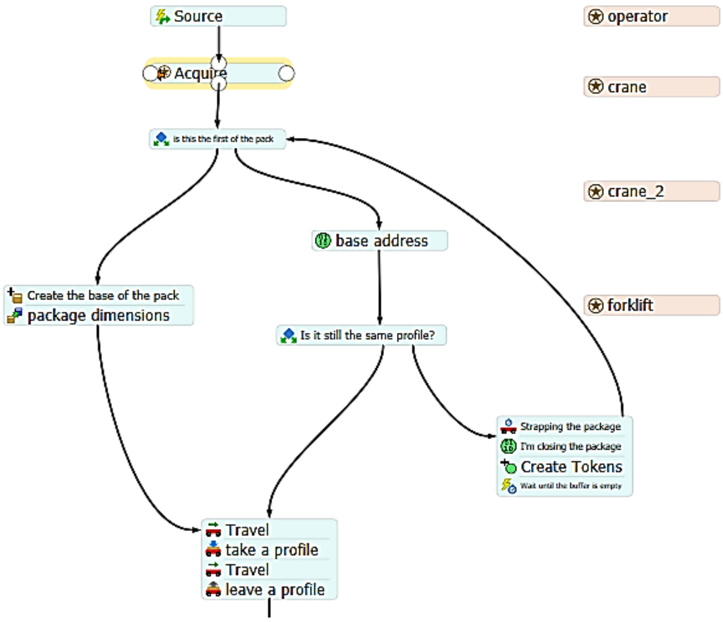

Figure 2. Production process – block diagram.

- Source block (resource generation) – This is the starting point of the process, responsible for introducing resources into the production system. At this stage, units representing input materials are generated. The block's parameters were configured to reflect real operational conditions. The number of generated units corresponds to the production batch size. A fixed resource introduction time was set to simulate a consistent material flow into the process.
- Acquire block (resource allocation) – This block handles the assignment of resources to operators or machines required for processing. At this stage, resources are allocated to the appropriate infrastructure elements. The system automatically checks the availability of the required resources. If the resources are available, they are assigned; if not, the process waits for resources to be released.

- Create the base of the pack block – This block is responsible for preparing unit packages, which serve as the primary transport units within the system. The block parameters included package dimensions and the maximum number of units that can be placed in a single package. At this stage, resources are grouped into sets, which are then passed to subsequent stages of the process.
- Base address block – This block performs a control function. At this stage, the system verifies whether the processed resources match the product defined at the beginning of the process. If the resource aligns with the specified profile, it continues in the process; otherwise, it is directed to an alternative path. This stage prevents the mixing of different types of materials, which is crucial for maintaining production quality.
- Travel block (resource transport) – Simulates the transportation of resources between successive stages of the production process. It accounts for various means of transport, such as operators, forklifts, and cranes. The block parameters included transport time and the availability of transportation resources.
- Is it still the same profile? block (product profile control) – Serves a control function by checking whether the processed resources still align with the declared profile. If the material profile changes during the process, resources are redirected to an alternative area. This mechanism prevents errors in further processing.
- Create tokens block – Generates tokens that act as indicators of operation progress within the system. These tokens represent the completion of key process stages, such as packaging or redirection. They allow for precise tracking of the status of each unit in the system.
- Auxiliary machines and operators – Their availability was included as a constraint in the model, enabling a realistic analysis of flow efficiency.

The model allowed for realistic replication of actual production operations, identification of potential bottlenecks, and evaluation of system efficiency under various operational scenarios. Based on the layout, it was also possible to configure parameters for each block, significantly enhancing the accuracy and value of the analysis.

As part of the study, simulations were conducted using the Experimenter module in FlexSim software, considering full utilization of the existing production line and the potential acquisition of one or two additional lines. The goal of the simulation was to determine the potential benefits and operational efficiency improvements resulting from the implementation of new production lines. This analysis enabled an assessment of the impact of new configurations on system performance.

For the study, three scenarios were defined:

- Scenario with one production line – The baseline system configuration, representing the current state of resource utilization.

- Scenario with two production lines – An extended configuration that includes the addition of one additional production line.
- Scenario with three production lines – The maximum system expansion, incorporating two additional production lines.

Each scenario was thoroughly analyzed using Performance Measure Tables, enabling precise determination of key indicators, such as:

- Production line efficiency – Measuring the utilization rate of available resources.
- Operator efficiency – Reflecting the workload and productivity level of operators.
- Average content of the Profile Packaging Line – Indicating the system's capacity to manage material flow.

To ensure the statistical reliability of the results, 500 replications were performed for each scenario. Setting this number of repetitions allowed for accounting for variability in production processes, eliminating the impact of random events on the final simulation outcomes, and obtaining more precise and reliable data that can serve as a basis for decisions regarding system expansion.

As part of the simulation, the impact of the number of production lines on key operational efficiency indicators and the system's adaptive capacity was examined. The analysis was conducted for three scenarios: one, two, and three production lines. The results are presented in the form of charts illustrating the average content of the packaging line (Figure 3), production line efficiency (Figure 4), and operator efficiency (Figure 5) in each of the considered scenarios.

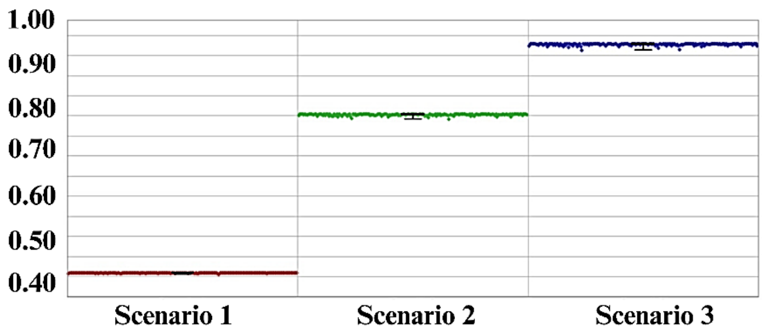

Figure 3. Analysis of the average content of the packaging line.

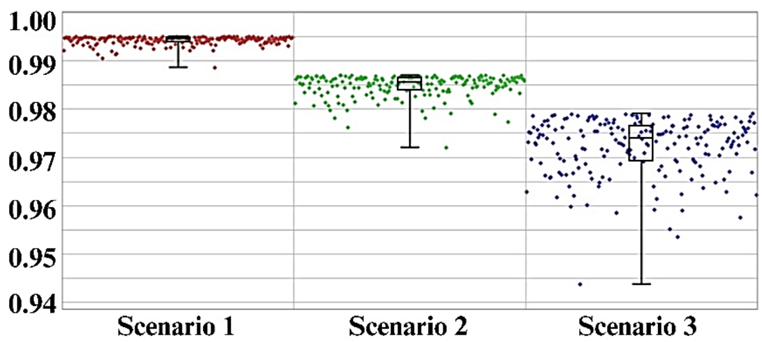

Figure 4. Analysis of production line efficiency.

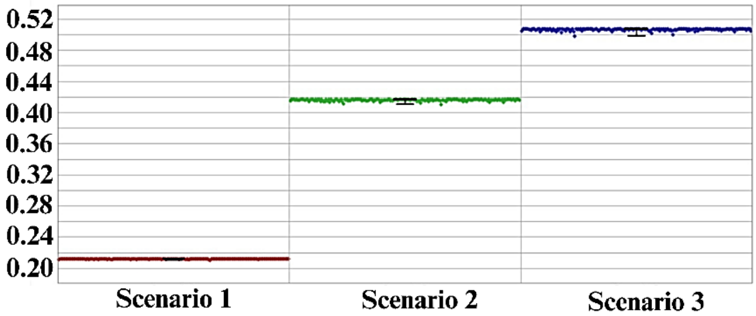

Figure 5. Analysis of operator efficiency.

Average Content of the Packaging Line (Figure 3):

- Scenario 1 – An average content of approximately 0.4 indicates limited flow management capabilities with a single production line.
- Scenario 2 – The value increases to approximately 0.75, reflecting more efficient resource utilization with two production lines.
- Scenario 3 – A maximum value of 0.95 indicates the highest flow management capabilities, though with a potential risk of excessive idle resources.

Production Line Efficiency (Figure 4):

- Scenario 1 – An efficiency level of 1.0 (100%) indicates maximum utilization of a single production line.4
- Scenario 2 – A decrease to approximately 0.98 shows that distributing work across two lines reduces the intensity of utilization for each line but increases system flexibility.
- Scenario 3 – Efficiency drops to approximately 0.95, suggesting underutilization of the full capacity of three production lines.

Operator Efficiency (Figure 5):

- Scenario 1 – Efficiency is approximately 0.2, indicating insufficient engagement of operators with a single production line.
- Scenario 2 – An increase to 0.45 reflects better utilization of operators in the two-line configuration.
- Scenario 3 – A value of approximately 0.52 indicates full operator engagement with three lines, though this requires more coordinated workforce management.

Based on the analysis, it was determined that the optimal solution for the studied system is the addition of one additional production line (the two-line scenario). This configuration achieves a balance between operational efficiency and system flexibility, ensuring the ability to handle higher demand while maintaining a high level of productivity. The introduction of a third line may only be justified in the case of a significant increase in demand or a reduction in the risk associated with resource underutilization.

To gain a more precise understanding of the efficiency differences between the analyzed scenarios, a detailed statistical analysis was conducted. The results are presented in Table 1, which highlights the differences in production efficiency between Scenario 1 and Scenarios 2 and 3, along with 95% confidence intervals.

Table 1.
Statistical Analysis of Differences in Production Line Efficiency Between Scenarios

j	Line 1 i = Scenario 1 μ_j - μ_i (95% Confidence Interval)	Statistically Significant
Scenario 1	-	-
Scenario 2	-0.009602 ± 0.000263	Yes
Scenario 3	-0.189022 ± 0.000220	Yes

The difference between Scenario 1 and Scenario 2 is -0.009602 ± 0.000263, indicating that the efficiency of the production line in Scenario 2 is slightly lower than in Scenario 1. Despite the small difference, the analysis shows that the result is statistically significant, confirming the impact of adding a second line on system load.

The difference between Scenario 1 and Scenario 3 is -0.189022 ± 0.000220, which indicates a significant decrease in efficiency when the system is expanded with a third production line. This result is also statistically significant, confirming that an additional line leads to an excess of unused resources.

Both Scenarios 2 and 3 show statistically significant differences, indicating that changes in the number of production lines have a measurable impact on system efficiency, which must be considered when making decisions about production expansion. The statistical analysis confirms that the introduction of a second production line (Scenario 2) causes a slight decrease in efficiency compared to the baseline scenario. However, the difference is small enough that the benefits of increased system flexibility may offset it. On the other hand, the introduction of a third line (Scenario 3) results in a substantial drop in operational efficiency, suggesting that the decision to add a third line should only be made in the context of a forecasted significant increase in demand.

5. Discussion

The aim of the study was to analyze the impact of various production line configurations on operational efficiency and system flexibility using advanced simulation tools. The results provide valuable insights into the trade-offs between efficiency, resource utilization, and the system's adaptability. By simulating three different scenarios—one, two, and three production lines—it was possible to quantitatively assess operational performance under different conditions and identify optimal configurations.

The findings clearly indicate that increasing the number of production lines improves system flexibility, but at the expense of operational efficiency. The scenarios with two and three lines allowed for better resource allocation and shorter order fulfillment times under increased demand conditions. However, the lower resource utilization in these scenarios highlights the risk of underutilized production capacity and increased operational costs. The scenario with two production lines proved to be the most balanced solution, providing high efficiency (approximately 98%) while increasing system flexibility. This configuration helps reduce bottlenecks observed with one line while avoiding the resource surplus issues seen with three lines. Operator efficiency significantly improved with the addition of more production lines, reaching its highest value in the three-line scenario. This increase resulted from better workload distribution and reduced operator downtime. However, such a rise in system complexity requires more advanced workforce management and investment in training.

The results are consistent with previous research on the optimization of production systems, which emphasize the importance of balancing efficiency and flexibility (Mandolla et al., 2022). Previous studies have shown that increasing production capacity reduces the risk of system overload but introduces challenges such as underutilized resources and higher fixed costs (Lee, 2023). In this study, the application of FlexSim software confirmed its usefulness as a tool for analyzing these complex trade-offs, similar to findings in other studies on production system expansion.

The findings of this study provide specific recommendations for manufacturing enterprises planning production system expansion. Decision-makers should carefully evaluate the trade-offs between flexibility and efficiency to select the optimal number of production lines based on projected demand and budget constraints. The study highlights the importance of dynamic resource management, which enables adaptation to fluctuating demand. Tools like FlexSim allow for testing various configurations without the risk of losses in real production environments. The expansion of production lines necessitates attention to workforce management. Appropriate training and optimization of work schedules can increase operator efficiency while minimizing costs associated with overstaffing.

6. Summary

The study conducted within this article provides valuable insights into the optimization of production systems using simulation tools. The analysis of three scenarios—one, two, and three production lines—enabled an understanding of the key relationships between operational efficiency and system flexibility. The results clearly indicate that increasing the number of production lines improves the system's adaptive capacity but leads to reduced efficiency in cases of resource surplus.

The most balanced solution was the introduction of two production lines, which reduced bottlenecks and increased operational flexibility while maintaining high efficiency at approximately 98%. Expanding the system to three production lines offered maximum flexibility but involved the risk of underutilized resources and a reduction in efficiency to 95%. These findings suggest that decisions regarding the expansion of production systems should consider projected demand and potential operational costs associated with maintaining unused resources.

The application of simulation tools, such as FlexSim, proved highly valuable in evaluating various configurations of production systems. By realistically replicating processes and enabling the analysis of different scenarios, this tool allows enterprises to make data-driven decisions, minimizing the risks associated with actual changes in production processes.

The study also highlights the importance of operator management in expanded production systems. Optimal employee utilization is critical to the effective functioning of the system, and increasing the number of production lines requires advanced schedule planning and appropriate training.

The limitations of the study, such as the assumption of constant production parameters and the exclusion of cost analysis, point to directions for future research. Introducing dynamic parameters, such as demand variability or cost analysis, would provide a more comprehensive view of the impacts of system expansion. Additionally, extending the research to other industrial sectors could contribute to generalizing the results and identifying universal relationships in production management.

In conclusion, the study confirmed that optimizing production systems using computer simulation is an essential component supporting the decision-making process in a dynamically changing industrial environment. The results can serve as a valuable resource for managers and production engineers, assisting them in making strategic decisions regarding the expansion and optimization of systems.

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