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SIMULATION-BASED PRODUCTION PROCESS IMPROVEMENT CONSIDERING THE QUALITY-COST TRADE-OFF

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Abstract:
Production systems are increasingly required to maintain high quality standards while simultaneously reducing operational costs and ensuring production efficiency. This study presents a simulation-based approach to production process improvement considering the quality–cost trade-off. The main objective of the research was to develop a decision-support framework enabling the analysis of how processing time and repair policies influence production system performance under varying operational conditions. A discrete-event simulation model was developed in the FlexSim environment to represent selected stages of a manufacturing process, including processing operations, quality inspection, and rework activities for nonconforming products. The proposed approach incorporates the relationship between processing time and product quality, enabling the evaluation of multiple production scenarios characterized by different operational strategies and repair limits. The study applies a multi-criteria analysis focused on balancing quality-related outcomes and operational profitability. Simulation results were evaluated using Pareto-based analysis to identify efficient production configurations characterized by different levels of product quality, production cost, and economic performance. The obtained results indicate that extending processing time may improve product conformity; however, it can simultaneously reduce operational efficiency and increase production costs. Moreover, excessive rework intensity does not necessarily generate proportional economic benefits. The proposed approach may support managerial decision-making in manufacturing systems by enabling the identification of production strategies adapted to different quality and cost priorities.

Key words: discrete-event simulation, production process optimization, quality–cost trade-off, rework strategy, decision support systems, manufacturing systems

INTRODUCTION

Contemporary manufacturing enterprises operate under conditions of increasing competitive pressure associated with the need to simultaneously improve operational efficiency, maintain high product quality, and reduce operating costs [1, 2, 3]. In industrial practice, achieving a balance between these factors constitutes a significant managerial challenge, as improving product quality is often associated with increased process costs and reduced production efficiency [4, 5, 6].

A particularly important issue is determining the trade-off between operation processing time, product quality level, and costs related to defects and rework activities [7, 8]. Excessive efforts to increase process efficiency may lead to a higher number of defective products, whereas an overly restrictive approach to quality may result in reduced economic efficiency of the enterprise [9, 10, 11].

Simulation methods are increasingly used in the analysis of such relationships, as they enable the representation of real operating conditions of production systems and the evaluation of various operational scenarios without interfering with the actual process [12, 13, 14, 15, 16]. Computer simulation constitutes an effective decision-support tool in the field of production process improvement and optimization of operational parameters [12, 13, 17].

The aim of this article is to present a simulation-based approach to production process improvement considering the trade-off between quality and operational costs. A simulation model developed in the FlexSim environment was used to analyze the impact of processing time and defective product repair strategies on the economic performance of the production system [1, 16, 18, 19].

LITERATURE REVIEW

The literature extensively discusses issues related to production process improvement, quality management, and optimization of operational costs [2, 4, 10, 20]. The influence of technological parameters on product properties has also been demonstrated in advanced surface engineering processes [21]. Particular attention is paid to the use of simulation methods as tools supporting the analysis and design of production systems [3, 13, 14, 16, 18, 22]. Computer simulation enables the representation of real production conditions and the assessment of the impact of process parameters on system efficiency without interfering with the actual production environment [12, 15, 23]. Recent reviews and decision-support studies further confirm that simulation methods and multi-criteria models are suitable for evaluating production scenarios and balancing time, cost, quality, and operational performance [7, 8, 13, 24, 25].

Numerous studies emphasize the importance of discrete-event simulation models in analyzing production flow, identifying bottlenecks, and evaluating process performance [12, 16, 23]. Simulation tools are also applied in the analysis of product quality, defect-related costs, and repair strategies [1, 11, 20]. It is indicated that increasing process efficiency may lead to deterioration in product quality and increased costs associated with complaints or the reprocessing of defective products [5, 6, 8].

An important research direction involves integrating computer simulation with quality management methods such as Lean Manufacturing, Six Sigma, and Total Quality Management [2, 10, 26]. These approaches support process efficiency analysis and the search for trade-offs between quality level, productivity, and operational costs [3, 4, 7]. Multi-criteria methods and Pareto analysis are also increasingly used to evaluate alternative production strategies while considering different efficiency indicators [3, 5, 7, 8].

In recent years, increasing attention has also been paid to the application of modern technologies supporting production process analysis, including artificial intelligence systems, risk analysis methods, and decision-support solutions for operational management [15, 27]. Research also highlights the importance of flexible resource management and work organization under conditions of varying production system workload [23, 28].

Despite numerous studies concerning simulation of production processes, relatively few works focus on the simultaneous analysis of relationships between processing time, defective product repair policies, and the economic consequences of operational decisions [5, 6, 8]. In particular, there remains a limited number of studies considering the trade-off between quality level and process costs within a single production decision-support model [7, 15].

Therefore, this study proposes a simulation-based approach enabling the analysis of relationships between process parameters, quality level, and economic efficiency of a production system. The developed model allows the evaluation of various production strategies and the identification of solutions supporting decision-making in production process improvement [1, 3, 13, 14, 28].

RESEARCH PROBLEM

Assumptions of the research model

To analyze the trade-off between quality level and operational costs, a simulation model representing selected elements of a production process was developed. The model was built in the FlexSim environment using a discrete-event simulation approach, enabling the analysis of product flow, resource utilization, and the impact of process parameters on production system efficiency [16, 18, 19].

The developed model includes product generation, processing operations performed at workstations, quality inspection, and the reprocessing of defective products [1, 28]. The system assumes the possibility of redirecting defective products for reprocessing while considering a limited number of repair attempts. Products that still failed to meet quality requirements after exceeding the permissible number of attempts were removed from the process as production waste [4, 11, 26]. Formalized error-counting systems also support the interpretation of inspection outcomes and the registration of defects in production processes [29].

An important assumption of the model was the inclusion of the relationship between processing time and product quality level. It was assumed that increasing operation processing time reduces the probability of defective products, but simultaneously increases operational costs and reduces system throughput. This relationship was described using a power function:

$$PercentageDefects = a\left(\frac{t_0}{t}\right)^b, \tag{1}$$

where:

P_d – percentage of defective products,

t – processing time,

t_0 – reference time,

a – scaling parameter.

b – coefficient determining the sensitivity of quality to changes in processing time.

The adopted relationship enables the representation of the nonlinear nature of the interaction between operation time and quality level, according to which an initial increase in processing time results in a significant improvement in quality, whereas further extension of processing time yields gradually diminishing benefits.

Figure 1 presents the structure of the developed simulation model, including processing stations, quality inspection, and product flow between successive stages of the process.

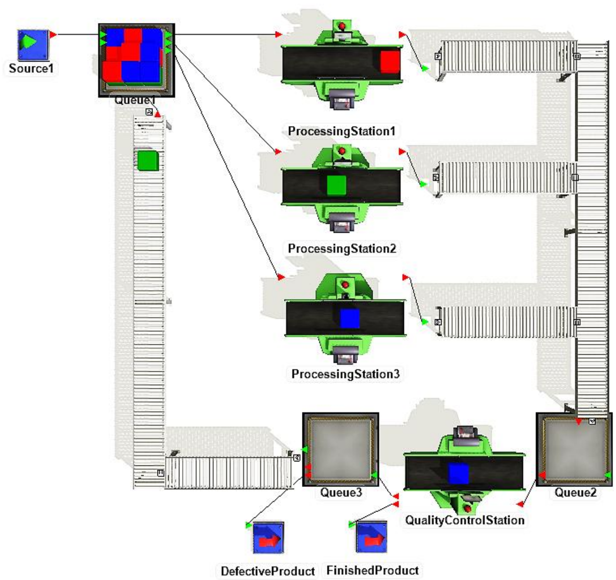

Fig. 1 Simulation model of the production process developed in the FlexSim environment

Alt text: *Simulation model of a production process in FlexSim showing three processing stations, a quality inspection station, product flow paths, and rework loops for defective products.*

Simulation experiment scenarios

The research was conducted for various configurations of production process parameters. The analysis focused on the impact of processing time and the number of allowable repairs on quality level, process costs, and economic efficiency of the production system.

The following parameters were varied during the simulation experiments:

- processing time of technological operations,
- maximum number of allowable repairs of defective products.

For each scenario, the following key process performance indicators were recorded:

- number of finished products,
- defect level,
- number of repair operations,
- utilization of production resources,
- operational costs.
- economic performance of the process.

To increase the reliability of the results, multiple simulation replications were conducted for each variant, which allowed the influence of process randomness on the obtained results to be reduced.

Optimization approach

A multi-criteria approach was applied in the study to identify the trade-off between quality level and economic efficiency of the production process. The impact of process parameters on defect level, operational costs, and achieved economic performance was analyzed simultaneously.

The evaluation function included revenues associated with production execution and costs resulting from resource utilization and the occurrence of defective products. The objective of the analysis was to determine process parameter configurations that provide a favorable balance between product quality and system operating costs.

Pareto analysis was used to interpret the results and identify solutions effective from the perspective of multiple criteria simultaneously. This approach enabled the determination of alternative operational strategies corresponding to different production management priorities, such as quality maximization, cost reduction, or improvement of economic efficiency.

RESULTS

Simulation experiments were conducted for a single work shift covering 8 hours of production system operation. The analysis focused on the impact of processing time and the number of allowable repairs on quality level, operational costs, and economic efficiency of the process. Multiple simulation replications were performed for each variant to reduce the influence of process randomness on the obtained results.

Impact of processing time on quality level

To analyze the relationship between operation processing time and process quality level, a series of simulation experiments was carried out for different processing time values. The obtained results confirmed the existence of a nonlinear relationship between operation time and the percentage of defective products.

Figure 2 presents the relationship between processing time and the percentage share of defective products.

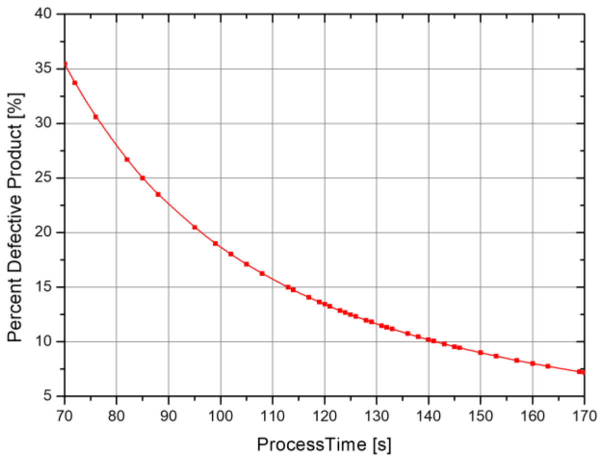

Fig. 2 Influence of processing time on the percentage of defective products
Alt text: *Line chart showing a decreasing relationship between processing time and the percentage of defective products. The defect rate drops rapidly for shorter processing times and then decreases more gradually as processing time increases.*

As processing time increased, a systematic decrease in the percentage of defective products was observed. The greatest quality improvement was obtained for short operation times, whereas further increases in processing time resulted in gradually smaller improvements in quality. This indicates the occurrence of diminishing quality-related benefits associated with extending process execution time.
The obtained relationship confirms the validity of using a power function to describe the impact of processing time on quality level. The results indicate that even a slight increase in operation time in the range of short processing times may significantly reduce the number of defective products. In contrast, for higher processing times, further quality improvement requires increasingly longer process duration, which may limit the operational efficiency of the system.

Impact of processing time on system efficiency
The conducted experiments demonstrated a significant impact of processing time on the economic efficiency of the production system. Reducing operation processing time increased process throughput; however, it simultaneously led to a higher percentage of defective products, generating additional quality-related costs.
Figure 3 presents the relationship between processing time and achieved economic performance for different repair strategy variants.

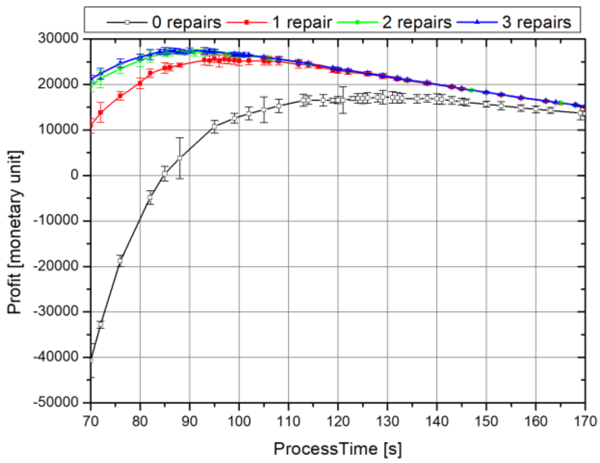

Fig. 3 Influence of processing time on the economic performance of the production process
Alt text: *Line chart presenting profit as a function of processing time for different repair strategies. Profit increases to an optimal range and then gradually decreases for longer processing times. Repair options improve economic performance, especially at shorter processing times.*

The analysis indicates that the relationship between processing time and achieved profit is nonlinear. For very short operation times, a rapid decrease in economic efficiency was observed, particularly in the variant without the possibility of repairing defective products. This resulted from the high percentage of production defects and increasing waste-related costs.
As processing time increased, production quality improved and economic performance increased until maximum values were reached. However, further extension of operation time led to a gradual decrease in profit due to reduced system throughput and increased production resource utilization costs.
The obtained results confirm the existence of a trade-off between process efficiency, quality level, and operational costs. The most favorable economic results were achieved for intermediate processing time values, which provided a balance between the number of finished products and the reduction of defect-related costs.

Economic impact of repair strategies
The analysis showed that the possibility of performing repair operations significantly affects the economic efficiency of the production system. Variants including repair activities were characterized by higher profit levels and greater system resistance to quality deterioration.
The largest differences between the analyzed strategies were observed for short processing times, where the percentage of defective products was the highest. Under such conditions, the possibility of performing repairs reduced losses associated with production defects and enabled the process to maintain a positive economic result.
As processing time increased, the differences between the variants gradually decreased. This indicates that at higher quality levels, the significance of repair strategies becomes less important from the perspective of system economic efficiency.
The obtained results also indicate that increasing the number of allowable repairs above a certain level does not lead to a proportional increase in profit. The greatest improvement in efficiency was observed after introducing one or two repairs, whereas further increases in the number of possible repair actions provided relatively limited economic benefits.

Pareto-Based Trade-Off Analysis
To identify efficient configurations of process parameters, Pareto analysis was applied to simultaneously evaluate production quality and economic performance of the system. Figure 4 presents the Pareto front illustrating the relationship between quality level and economic performance for the analyzed process variants.

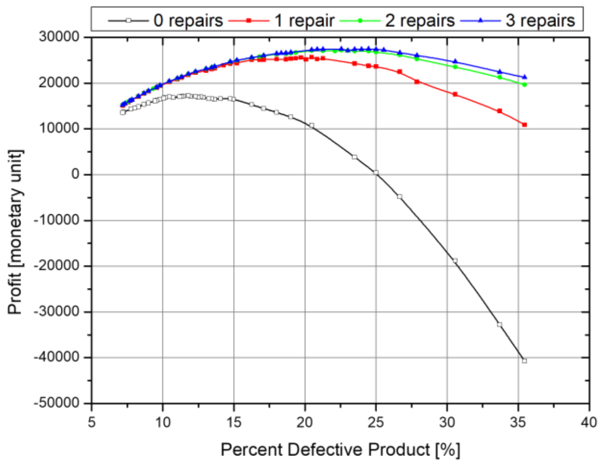

Fig. 4 Pareto front illustrating the trade-off between quality level and economic efficiency of the process
Alt text: *Scatter plot showing Pareto-optimal solutions for different repair strategies. The chart illustrates the trade-off between the percentage of defective products and profit, highlighting alternative production configurations with different quality and economic outcomes.*

The obtained Pareto fronts represent a set of non-dominated solutions for which improvement in one criterion leads to deterioration in another criterion.

The analysis demonstrated that solutions ensuring the highest quality level do not always guarantee the highest economic efficiency of the process. In many cases, a moderate level of defective products allowed higher profits to be achieved due to increased system throughput and reduced operation processing time.

At the same time, the results show that an excessive increase in the percentage of defective products leads to a rapid deterioration in economic performance, particularly in the variant without repair possibilities. The introduction of repair strategies increased the system's resistance to quality deterioration and shifted the Pareto fronts toward more economically favorable solutions.

DISCUSSION

The obtained results confirm the existence of a significant relationship between processing time, quality level, and economic efficiency of the production system. The conducted research indicates that both excessive shortening of operation times and an overly restrictive approach to quality may lead to deterioration in the economic performance of the process [5, 6, 8].

The results are consistent with research trends presented in the literature concerning production process optimization and quality management, which emphasize the necessity of balancing productivity and quality-related costs [2, 4, 10]. The usefulness of simulation methods in analyzing relationships between operational parameters and production system efficiency was also confirmed [3, 5, 13, 16].

The conducted analysis demonstrated that the possibility of performing repair operations can significantly reduce losses associated with defective products; however, increasing the number of allowable repairs does not always lead to proportional economic benefits. This indicates the nonlinear nature of the relationship between the intensity of repair activities and system efficiency [1, 11, 28].

An important element of the study was also the Pareto analysis, which confirmed the validity of applying a multi-criteria approach to the evaluation of production processes. The obtained results show that the selection of optimal process parameter configurations depends on enterprise priorities and the adopted operational strategy [3, 7, 8].

It should be emphasized that the developed model constitutes a simplified representation of a real production process. The study did not consider factors such as machine failures, logistics disruptions, or variability of material parameters. Furthermore, the relationship between processing time and quality level was described using a theoretical function that may be verified in future studies using data obtained from real industrial processes [16, 18, 19].

CONCLUSION

This article presented a simulation-based approach to production process improvement considering the trade-off between quality level and operational costs. The developed simulation model enabled the analysis of the impact of processing time and defective product repair strategies on the economic efficiency of the production system.

The conducted research confirmed that operational parameters of the production process significantly affect both product quality level and the economic performance of the enterprise. It was demonstrated that reducing processing time increases system throughput; however, it may simultaneously lead to a higher number of defective products and increased quality-related costs. In contrast, extending operation time improves production quality but limits operational efficiency and increases process execution costs.

The obtained results also indicate that the possibility of performing repair operations may significantly reduce losses associated with production defects and improve the economic efficiency of the system. At the same time, it was found that increasing the number of allowable repairs does not always lead to proportional economic benefits, confirming the necessity of seeking an optimal trade-off between process costs and quality level.

The application of Pareto analysis enabled the identification of efficient configurations of production process parameters and the evaluation of alternative operational strategies. The obtained results confirm the usefulness of simulation methods as decision-support tools in production process management and manufacturing system optimization.

The presented approach may be applied in manufacturing enterprises seeking solutions that enable balancing product quality, operational costs, and process efficiency. Future research may involve extending the model by including additional factors related to real industrial environments, such as machine failures, variability of material supplies, or the application of artificial intelligence methods supporting dynamic optimization of process parameters.

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