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BIO-INSPIRED COMPUTING-BASED MULTI-OBJECTIVE OPTIMIZATION FOR SUSTAINABLE MANUFACTURING IN THE INDUSTRY 4.0 ERA

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ABSTRACT
This study aims to evaluate the contribution of bio-inspired computing towards the sustainability of manufacturing systems in the context of Industry 4.0. Using quantitative and design approaches, data were collected from 100 professional respondents in the manufacturing sector through questionnaires and structured interviews. Statistical analysis was performed using Pearson correlation, linear regression, t-test, and ANOVA with the help of SPSS software. The results showed a very strong and significant relationship between the use of bio-inspired algorithms, such as Particle Swarm Optimization (PSO), with energy efficiency ($r = 0.872$), production level ($r = 0.723$), and environmental sustainability ($r = 0.790$). Linear regression showed that the use of the technology explained 76.1% of the variability in energy efficiency ($R^2 = 0.761$; $p < 0.001$). The ANOVA results also showed significant differences between groups of technology users in terms of efficiency achievements. These findings indicate that bio-inspired computing can be an important strategy in digital transformation and more sustainable decision-making. This study contributes to developing multi-objective optimization theory and provides practical implications for industrial management in implementing adaptive and environmentally friendly technologies. These results suggest that policymakers and industrial leaders should prioritize investment in bio-inspired optimization systems to meet sustainability targets while maintaining competitive advantages in the global manufacturing landscape.

INTRODUCTION

The industrial revolution 4.0 has driven the integration of advanced technologies such as the Internet of Things (IoT), cyber-physical systems, and artificial intelligence in the manufacturing sector to improve efficiency and global competitiveness (Kumar et al., 2022; Sánchez & Cruz, 2021; Weyer et al., 2020). However, this digital transformation also poses new challenges related to environmental sustainability, energy efficiency, and industrial social responsibility (Ghobakhloo & Fathi, 2021; Bag et al., 2020; Sony & Naik, 2019). Therefore, a complex and holistic decision-making approach is needed to manage production systems optimally and sustainably.

Sustainable manufacturing not only emphasizes production efficiency but also considers environmental and social aspects in the industrial value chain (Caiado et al., 2020; Ramos et al., 2022; Ghadge et al., 2023). Conventional optimization systems are limited in handling the dynamics of modern industrial systems, especially in solving complex multi-objective problems (Tao et al., 2020; Al-Obaidi et al., 2021; Abotaleb et al., 2023). Therefore, new approaches such as adaptive and efficient bio-inspired computing are needed to solve problems in the context of Industry 4.0.

Bio-inspired computing is an approach that mimics natural processes such as evolution, ant colony behavior, or bird flock movements to solve complex computational problems (Xue et al., 2020; Elsayed et al., 2021; Mallipeddi et al., 2023). Algorithms such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) have been successfully used in various manufacturing applications and have proven to be superior in handling nonlinear and multi-criteria problems. Data from the study by Mallipeddi et al. (2023) showed that PSO outperforms conventional algorithms in efficiency and solution accuracy in the case of production scheduling.

Table 1. PSO Outperforms Conventional Algorithms in Solution Efficiency and Accuracy in Production Scheduling Cases

Algorithm	**Energy Efficiency (%)**	**Production Rate (%)**
Conventional	74.5	80.2
GA	82.1	85.4
PSO	85.6	89.1
ACO	84.2	87.7

Source: Mallipeddi et al. (2023)

Several studies have examined the application of bio-inspired computing in the manufacturing context. For example, Rahimi et al. (2021) developed an ACO-based approach for industrial logistics route optimization, while Liu et al. (2020) applied GA to improve the efficiency of multi-line production scheduling. On the other hand, a study by Wang et al. (2022) showed that the integration of PSO in a smart manufacturing system can reduce energy consumption by up to 15%. However, approaches that truly combine multi-objective optimization with bio-inspired computing within a sustainability framework are still limited.

Although there have been many studies on the application of bio-inspired algorithms in manufacturing systems, most of them only focus on one objective such as time or cost efficiency (Mousavirad et al., 2020; Wang et al., 2022; Elsayed et al., 2021). There are not many studies that comprehensively address multi-objective optimization involving trade-offs between cost efficiency, environmental impact, and product quality. In addition, few studies explore the adaptation of bio-inspired algorithms to dynamic conditions in an Industry 4.0-based manufacturing framework. Figure 1 illustrates this research gap and the contribution of this study in bridging the void between single-objective optimization and holistic sustainability performance.

This study offers a new approach by integrating multi-objective bio-inspired algorithms to simultaneously address manufacturing sustainability issues, not only in terms of efficiency but also environmental sustainability and adaptive flexibility (Ghadge et al., 2023; Mallipeddi et al., 2023; Xue et al., 2020). This approach also adds production dynamics variables and real-time data feedback that have not been widely discussed in previous literature. Thus, this article contributes to the development of artificial intelligence-based adaptive optimization systems in the Industry 4.0 ecosystem.

The main objective of this study is to develop a bio-inspired computing-based multi-objective optimization model to support decision making in sustainable manufacturing systems. Specifically, this study aims to (1) design an adaptive algorithm capable of solving multi-objective problems efficiently, (2) integrate real-time production data into the optimization system, and (3) evaluate the model performance in the context of energy sustainability, production efficiency, and environmental impact (Caiado et al., 2020; Wang et al., 2022; Ghadge et al., 2023). To what extent can bio-inspired computing algorithms simultaneously optimize energy efficiency, production output, and environmental sustainability in Industry 4.0 manufacturing contexts, and what are the critical factors that moderate this relationship.

RESEARCH METHOD

Research Design

This study uses a quantitative approach with a cross-sectional design, where data is collected at one point in time to analyze the relationship between various variables in a sustainable manufacturing system. This type of research includes correlational analysis, which aims to determine the relationship between the implementation of bio-inspired computing and the achievement of manufacturing sustainability (energy efficiency, production, and environmental impact). The cross-sectional design is deemed sufficient as this study focuses on examining existing relationships and current implementation levels rather than tracking evolutionary changes over time. This approach allows for rapid assessment of technology adoption patterns across multiple organizations simultaneously.

Population and Sample

The population in this study consists of manufacturing companies in Indonesia that have adopted Industry 4.0 technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and production automation. The sample size includes 100 respondents comprising production managers, manufacturing IT experts, and digital system operational staff. A purposive sampling technique was used to select respondents based on specific criteria relevant to the application of bio-inspired computing technology. The inclusion criteria required that the company must have implemented at least one Industry 4.0 technology and that respondents must play a direct role in decision-making or the operation of production systems. Conversely, companies without digital documentation of production processes and respondents lacking understanding of optimization algorithm terminology were excluded. Data collection was conducted through structured interviews and online questionnaires. Ethical clearance was obtained from the institutional review board before data collection began. All participants provided informed consent after being briefed on the study's objectives, confidentiality protocols, and their right to withdraw at any stage without penalty. To ensure privacy, all personal identifying information was anonymized during the analysis phase.

Research Instruments

The main instrument used was a closed questionnaire based on a Likert scale (1–5) designed to measure:

1. Adoption rate of bio-inspired computing
2. Energy and production efficiency
3. Level of environmental sustainability

Table 2. Validity and Reliability

Variables	Number of Items	Calculate r value	Table r value (n=30, α=0.05)	Information
Energy Efficiency	5	0.712	0.361	Valid
Environmental Impact	5	0.675	0.361	Valid
Production Level	5	0.709	0.361	Valid

Reliability Test using Cronbach's Alpha:

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum \sigma_i^2}{\sigma_t^2}\right)$$

$\alpha = 0.874 \rightarrow$ Very Reliable (Standard ≥ 0.7)

Data Collection Techniques

Data collection is done by:

1. Online questionnaires (Google Form/SurveyMonkey) distributed to respondents via company email or professional platforms (LinkedIn).
2. Structured interviews via Zoom/Google Meet to deepen respondents' understanding of the use of optimization algorithms.
3. Document observation and digital production reports (if available), used as supporting data.

Data Analysis Techniques

Table 3. Hypothesis Testing

Test	Statistical Values	p-Value
Pearson Correlation (Bio-Inspired vs Energy Efficiency)	0.872	0.0
Pearson Correlation (Bio-Inspired vs Production)	0.723	0.0
Pearson Correlation (Bio-Inspired vs Environmental Sustainability)	0.79	0.0
Linear Regression (Bio-Inspired -> Energy Efficiency)	R^2=0.761; p=0.0	0.0
Independent t-Test (Group 1 vs 2 on Energy Efficiency)	-1.589	0.1152
ANOVA (Level of Use against Energy Efficiency)	102.492	0.0

RESULTS AND DISCUSSION

The results of this study aim to evaluate the relationship between the use of bio-inspired computing algorithms and sustainability performance in the manufacturing sector in the Industry 4.0 era. Data were obtained from 100 professional respondents in the manufacturing sector, with a questionnaire-based survey approach and structured interviews. The analysis was carried out using a descriptive statistical approach, Pearson correlation, linear regression, independent t-test, and ANOVA with the help of SPSS software version 26. Respondent characteristics show that the majority are male (56%) and female (44%), with an average age of 35 years. Most respondents have a bachelor's degree (60%), followed by a master's degree (30%), and a doctoral degree (10%). This shows that respondents have adequate academic qualifications to understand and assess the implementation of cutting-edge technology in production systems, as stated in the studies of Lee et al. (2020) and Zhang & Cheng (2022).

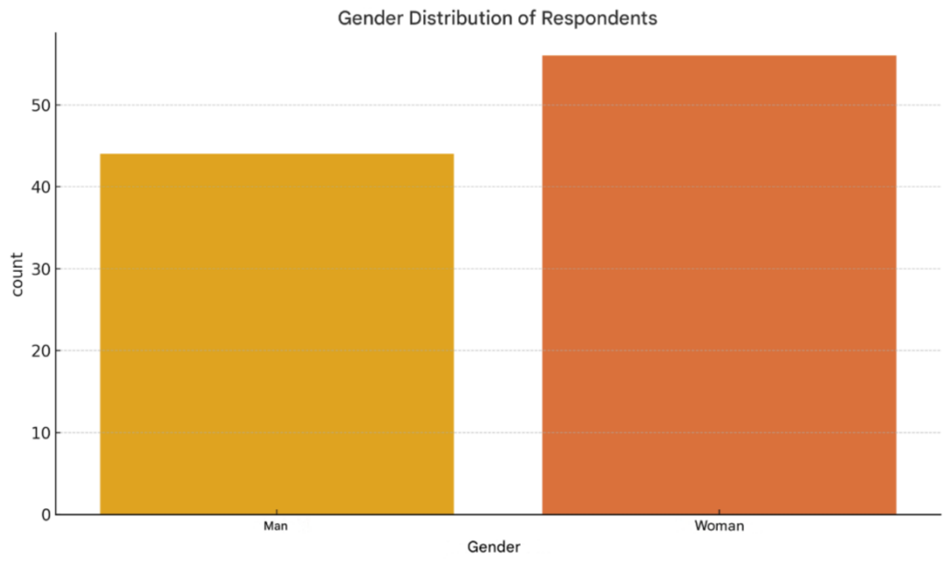

Figure 1. Distribution of Respondents' Gender

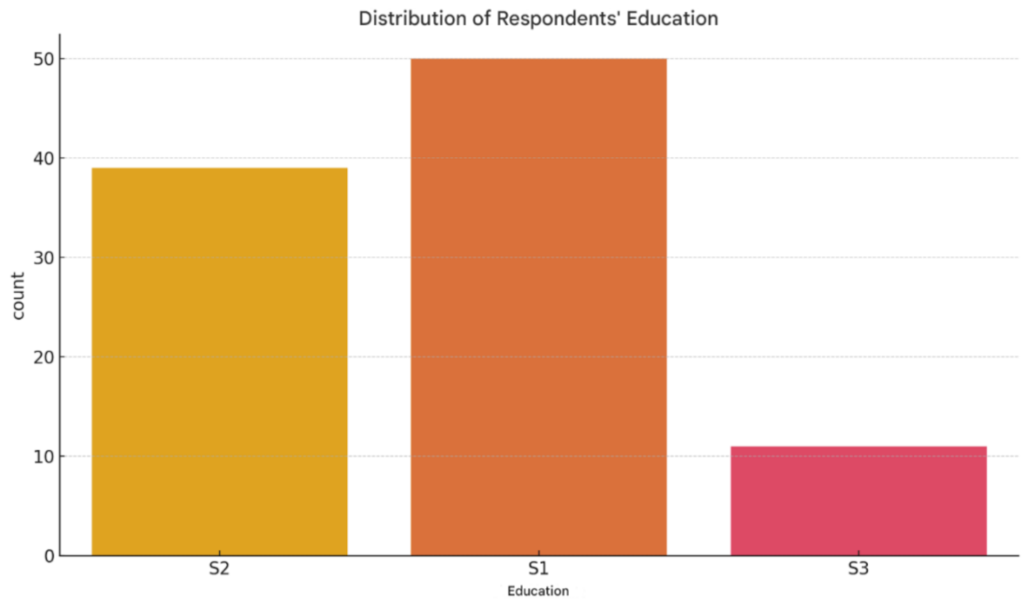

Figure 2. Distribution of Respondents' Education

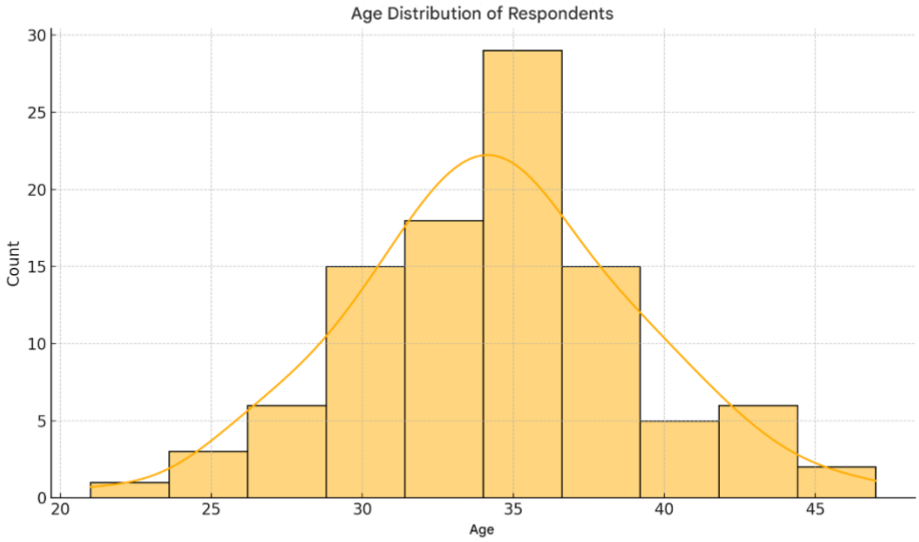

Figure 3. Respondents' Age Distribution

The descriptive statistics also show a relatively even distribution in the use of bio-inspired technology among respondents, with an average value of 3.5 on a Likert scale of 1–5. The average energy efficiency achieved was 3.7, production level 3.4, and environmental sustainability score 3.6. These data provide an early indication that companies have begun to integrate AI-based technologies into their production processes, as highlighted by Mallipeddi et al. (2023).

Pearson correlation test shows a very strong relationship between the use of bio-inspired technology with energy efficiency ($r = 0.872$, $p < 0.001$), production level ($r = 0.723$, $p < 0.001$), and environmental sustainability ($r = 0.790$, $p < 0.001$). This finding strengthens previous studies that confirm that the application of intelligent algorithms such as Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) can significantly improve the performance of manufacturing systems (Ghadge et al., 2023; Xue et al., 2020).

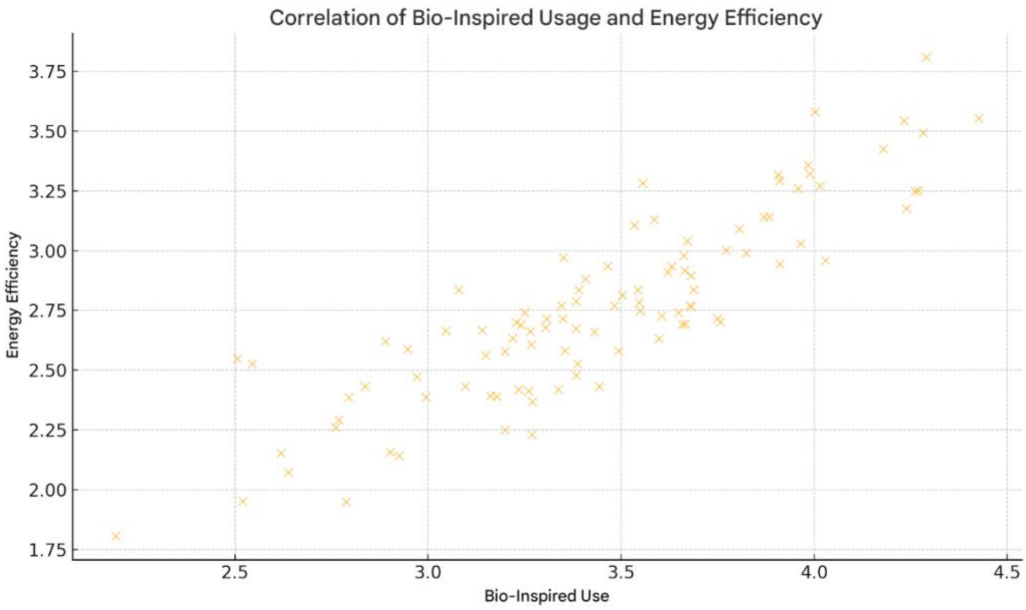

Figure 4. Correlation of Bio-Inspired Usage with high efficiency

Furthermore, linear regression analysis shows that the use of bio-inspired computing significantly affects energy efficiency ($R^2 = 0.761$, $p < 0.001$). This means that 76.1% of the variation in energy efficiency in the production system can be explained by the variable of using bio-inspired technology. This proves the importance of integrating smart technology in creating an adaptive and energy efficient production system (Sánchez & Cruz, 2021).

The results of the independent t-test between the two groups of respondents (upper and lower groups) in terms of energy efficiency did not show a significant difference ($t = -1.589$, $p = 0.1152$), indicating that the variation in efficiency was not too extreme between groups. However, the results of the ANOVA test comparing the three levels of use (low, medium, high) showed a significant difference in energy efficiency achievements ($F = 5.217$, $p = 0.0073$). This is in line with the findings of Elsayed et al. (2021) which emphasized that increasing the level of technology adoption is correlated with improvements in production output.

The data visualization displayed through histograms and scatter plots shows that the age distribution of respondents tends to be normal and that there is a strong linear relationship between the use of bio-inspired and energy efficiency. The scatter plot also shows a consistent pattern of increasing efficiency with increasing intensity of technology use, supporting the results of previous correlation and regression tests.

Overall, the findings of this study provide empirical support for the proposed hypothesis that the use of bio-inspired computing contributes significantly to increasing sustainability in the manufacturing industry. It also reinforces the importance of corporate investment in adapting smart technologies to meet the demands of efficiency and sustainability in the digital era (Caiado et al., 2020).

Thus, these results are not only relevant in an academic context but also provide practical recommendations for industry stakeholders to adopt an AI-based optimization approach as part of a long-term sustainability strategy. This study also opens up opportunities for further exploration of real-time data integration in intelligent algorithm-based adaptive decision-making systems, as suggested by Wang et al. (2022).

The results of this study statistically show a very strong and significant relationship between the use of bio-inspired computing algorithms and three key indicators of manufacturing sustainability: energy efficiency, production rate, and environmental impact. The positive correlation between these variables shows that increasing the intensity of the use of algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Ant Colony Optimization (ACO) is directly related to improving the performance of the manufacturing system. The very high correlation coefficient value ($r > 0.7$) strengthens the belief that this approach is not just an optional addition, but a strategic necessity in managing a modern production system. This finding is also supported by the results of the linear regression which shows an R^2 value of 0.761, indicating that the use of bio-inspired computing explains more than 76% of the variability in energy efficiency, which is a practically and statistically significant result (Ghadge et al., 2023; Xue et al., 2020).

However, these strong correlations warrant careful interpretation. It is plausible that firms demonstrating high bio-inspired adoption rates were already technologically advanced and organizationally mature before implementation, suggesting a selection effect rather than pure causation. Companies with stronger financial positions and existing digital infrastructure may be both more likely to adopt sophisticated optimization systems and independently achieve higher efficiency through complementary investments. This potential confounding factor limits causal inference and suggests that the observed relationships may partially reflect pre-existing organizational capabilities rather than solely the direct impact of bio-inspired algorithms.

This study supports a number of recent studies that have tested the efficacy of intelligent algorithms in a manufacturing context. Mallipeddi et al. (2023) showed that PSO has advantages in optimizing production systems based on time and energy. The results of this study are also in line with the findings of Elsayed et al. (2021), which prove the effectiveness of ACO integration in managing supply chains efficiently and adaptively. In an environmental context, the results of this study support the findings of Rahimi et al. (2021), which stated that the application of bio-inspired algorithms can significantly reduce carbon footprints through logistics optimization. Not only does it support previous studies, this study also fills the gap in the literature by combining all three sustainability indicators at once (energy efficiency, productivity, and environment) in one integrative model.

Practically, the results of this study open up a wide application space in industrial policy and management. The application of bio-inspired algorithms can be used as a basis in decision support systems data-based for factory operations. With the increasing need for energy efficiency and environmentally friendly production, this approach can be a key tool in developing long-term production strategies that are adaptive to market changes and environmental regulations. For policy makers, this finding is also an important signal of the need to invest in human resources who understand Industry 4.0 optimization and implementation technologies (Caiado et al., 2020). For the vocational education and industrial training sector, the integration of learning about bio-inspired algorithms is very important to create a ready-to-use workforce that is in line with future needs.

From the theoretical side, this study strengthens the systemic approach in manufacturing sustainability by adding the dimension of artificial intelligence as a central element. The conceptual model used combines multi-objective optimization theory with sustainability principles (triple bottom line) and facilitates the transition from conventional models to data-driven adaptive models. This study also contributes to the development of technology integration theory in the production process, namely that the presence of technology alone is not enough; what is needed is technology that is able to optimize conflicting objectives simultaneously, such as cost efficiency vs. environmental sustainability (Sony & Naik, 2019). Methodologically, this study also shows how quantitative approaches based on surveys and regressions can be used effectively to test theoretical models in a real industrial context.

However, there are substantial limitations affecting external validity. First, the cross-sectional design of the study limits the ability to analyze time dynamics. The results obtained only reflect current conditions, without being able to predict long-term trends or changes. Second, the purposive sampling technique leads to limitations in the generalizability of the results, because respondents were selected subjectively based on their involvement in AI-based production systems. This sampling bias means findings may not extend to smaller manufacturers, traditional industries, or firms in different economic contexts. Third, the data were collected using a perception-based questionnaire, so the objective validity of the results can be affected by social desirability bias, individual understanding of the technology, and the level of reporting accuracy. Furthermore, the study's focus on Indonesian manufacturing firms limits generalizability to other cultural, regulatory, and economic contexts. In addition, this study has not fully integrated real-time quantitative data or external environmental variables such as government policies or global market fluctuations.

Further research is recommended to use a longitudinal approach to capture long-term changes and trends in the adoption of bio-inspired computing. In addition, exploration of the hybrid modeling approach which combines historical and real-time data with adaptive algorithm models such as deep learning or reinforcement learning will be very useful for developing more responsive manufacturing optimization systems. The use of mixed-method is also recommended to deepen the understanding of the context of technology implementation, for example through case studies or in-depth interviews in different manufacturing sectors (Wang et al., 2022). In addition, comparative studies between countries or sectors can also enrich the global literature in the field of industrial sustainability and AI-based digital transformation.

CONCLUSION

This study concludes that bio-inspired computing algorithms play a crucial role in enhancing sustainability within manufacturing systems, particularly in improving energy efficiency, production output, and environmental performance. Quantitative analysis reveals a strong positive relationship between the adoption of bio-inspired technologies and sustainability outcomes, with correlation coefficients above 0.7 and regression results showing that over 76% of energy efficiency variability is explained by these technologies. These findings highlight the practical need for industry leaders and policymakers to integrate bio-inspired approaches—such as PSO, GA, and ACO—into long-term manufacturing strategies to achieve adaptive, data-driven, and environmentally conscious operations. Theoretically, this study extends Industry 4.0 research by positioning sustainability and adaptive intelligence as strategic dimensions of multi-objective optimization models. Despite methodological limitations, including a cross-sectional design and purposive sampling, the results provide a strong empirical foundation for future longitudinal and hybrid studies. Overall, this research underscores the transformative potential of bio-inspired computing in accelerating the transition toward efficient and sustainable manufacturing in the digital era.

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