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Designing energy-efficient industrial processes: A multi-criteria decision analysis for sustainable manufacturing solutions

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Abstract. This research examines energy-efficient solutions in industrial manufacturing through a Multi-Criteria Decision Analysis (MCDA) approach to discover optimal methods for improving energy consumption alongside cost-efficiency and environmental sustainability. The production activities within the industrial sector including chemical processing, metalworking and food manufacturing make up substantial portions of world energy usage. This study examines the role of advanced technologies including heat recovery systems and high-efficiency furnaces together with energy-efficient refrigeration systems in reducing energy consumption within industrial sectors. This research employs the MCDA framework which combines the Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Simple Additive Weighting (SAW) methods. The research examines how energy-efficient solutions perform during a six-month period by measuring energy savings alongside cost reductions and environmental benefits. The study results reveal significant energy reductions alongside cost savings between 10% to 30% while chemical production achieved a 25% decrease in energy consumption. The observed environmental improvements that include a 30% decrease in carbon emissions from chemical production demonstrate how these technologies can advance sustainable industrial practices.

Keywords: Energy Efficiency, Industrial Manufacturing, Multi-Criteria Decision Analysis, Sustainability, Cost Savings

1. Introduction

The global industrial manufacturing sector stands out as a major energy consumer which results in considerable operational cost impacts and environmental sustainability challenges. The growing need for energy alongside mounting environmental concerns about climate change and resource depletion forces industries to implement more energy-efficient practices. The adoption of energy-efficient industrial processes serves both to lower operational costs and to advance environmental sustainability efforts. The chemical production industry alongside metal processing and food manufacturing contributes significantly to energy consumption and carbon emissions which requires a fundamental reassessment of traditional manufacturing practices to minimize environmental impact. To address these challenges industries have adopted energy-efficient technologies including advanced heat exchangers and high-efficiency furnaces to optimize industrial energy usage alongside energy-efficient refrigeration systems. Despite their potential benefits, the deployment of these technologies throughout different industrial areas stands as a complicated undertaking. High initial investment costs alongside technological limitations and integration difficulties between renewable energy sources and conventional systems present core challenges. The gap in stakeholder understanding about energy efficiency's enduring advantages acts as a barrier to technological adoption. The adoption of decision-making frameworks such as Multi-Criteria Decision Analysis (MCDA) helps businesses evaluate and prioritize energy-efficient solutions by considering multiple criteria which include energy consumption as well as cost and environmental impact [1]. The Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Simple Additive Weighting (SAW) methods from MCDA deliver a systematic framework for evaluating manufacturing alternatives to select sustainable solutions. The research investigates the application of MCDA methods to evaluate and improve energy-efficient manufacturing solutions which support sustainability through lower energy consumption and cost efficiency and environmental preservation.

2. Literature review

2.1. Energy efficiency in industrial manufacturing

Industrial manufacturing energy efficiency received extensive research attention in recent decades. Research findings reveal that manufacturing processes represent a substantial share of global industrial energy consumption. Various industries like chemical production and metal processing have decreased their energy usage through the implementation of efficient technologies including advanced motors and heat recovery systems. The main difficulty lies in deploying these advanced technologies throughout distinct industrial sectors while taking each production process's unique constraints and requirements into account [2].

2.2. Multi-criteria decision analysis in manufacturing

Manufacturers now frequently use Multi-Criteria Decision Analysis (MCDA) to make decisions about competing objectives like energy use, financial costs and environmental effects. Decision-makers use the MCDA approach to rank sustainable objectives as their top priorities during decision-making so they can make informed choices [3]. The MCDA process shown in Figure 1 consists of a structured sequence where decision-makers assess alternatives through multiple performance indicators like energy efficiency, cost-effectiveness, and environmental sustainability. The Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Simple Additive Weighting (SAW) are among the MCDA techniques used to evaluate energy-efficient technologies and their implementation in industrial processes. These methods establish a complete framework for identifying optimal solutions by balancing conflicting criteria to ensure energy-efficient technologies achieve cost-effectiveness together with environmental sustainability [4].

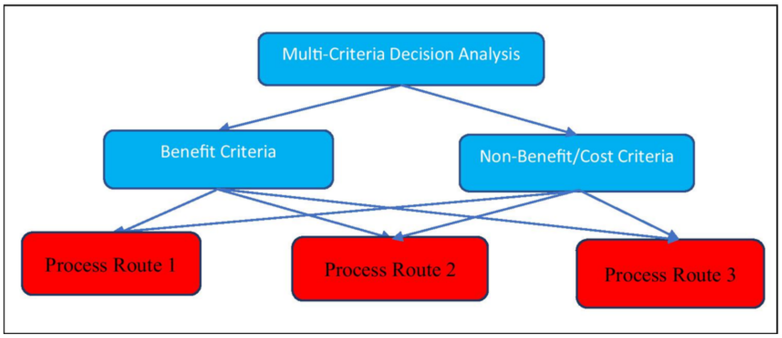

Figure 1. Schematic Diagram of the Multi-Criteria Decision Analysis Flow in Evaluating Energy-Efficient Manufacturing Solutions(Source:researchgate.net)

3. Methodology

3.1. Overview of the MCDA framework

The MCDA framework used in this study involves evaluating multiple energy-efficient manufacturing solutions based on key performance indicators: energy consumption, cost, and environmental impact. This framework combines multiple MCDA methods including AHP and TOPSIS for the evaluation and ranking of alternatives. The goal is to determine the most sustainable manufacturing solutions by evaluating each criterion's significance to assign appropriate weights in the specific industrial process context [5]. The MCDA framework includes sensitivity analysis to evaluate how robust the results remain when tested against different scenarios and assumptions.

3.2. Selection of industrial processes

This study considered a range of industrial processes from different sectors such as chemical, metal, and food manufacturing. The selection criteria for these processes included their high energy consumption levels and their potential to achieve better energy efficiency. The processes selected for analysis comprise heat exchange systems used in chemical production and furnace operations utilized in metal processing along with refrigeration units deployed in food manufacturing [6]. Every process features its own specific difficulties and possibilities when it comes to adopting energy-efficient technologies.

3.3. Data collection and evaluation criteria

The evaluation of energy-efficient technologies incorporated data from both primary and secondary sources. Manufacturing companies and industry experts provided primary data through interviews and surveys while secondary data came from published research studies and industry reports. The established evaluation criteria for energy-efficient technologies reflect their influence on energy consumption patterns as well as both operational costs and environmental performance metrics. The evaluation criteria received a weighted score based on their importance to sustainable manufacturing outcomes [7].

4. Experimental process

4.1. Energy efficiency solutions implementation

The execution of energy-efficient solutions required the selection of appropriate technologies and strategies tailored to each individual industrial process. The chemical production process incorporated advanced heat exchangers and waste heat recovery systems which helped lower energy consumption. The metal processing sector embraced high-efficiency furnaces along with better insulation methods to boost its energy efficiency. The food manufacturing industry adopted energy-efficient refrigeration systems to lower electricity utilization. The implementation process underwent six months of monitoring to evaluate the real energy savings obtained. Table 1 compares the energy usage data across industrial sectors before and after implementing energy-efficient solutions and displays the energy consumption percentage savings [8]. The analyzed data shows substantial energy consumption reductions in every sector with the chemical production sector reaching the top savings value at 25%. The successful integration of energy-efficient technologies into every industrial sector has led to these observed improvements.

Table 1. Energy Consumption Data for Different Industrial Sectors Before and After Implementation

Industrial Sector	Energy Consumption Before (kWh)	Energy Consumption After (kWh)	Energy Savings (%)
Chemical Production	500000	375000	25
Metal Processing	600000	480000	20
Food Manufacturing	300000	255000	15

4.2. Data analysis and comparison

The performance of various energy-efficient solutions was evaluated through analysis with the MCDA framework based on collected data. The analysis involved evaluating each solution based on the three key criteria: energy consumption, cost, and environmental impact. The analysis concluded with a ranked list of solutions where the most sustainable options emerged as the best choices for each industrial process. The study performed sensitivity analysis to determine the effects of criterion weight adjustments on solution rankings. Table 2 presents data about the cost savings and environmental impacts across various industrial sectors with a focus on carbon emission reductions and water usage decreases [9]. The findings demonstrate reductions in energy usage alongside major advancements in cost efficiency and environmental protection measures. The chemical production sector managed to reduce carbon emissions by 30% and the metal processing sector achieved a 7% decrease in water usage.

Table 2. Cost Savings and Environmental Impact Data for Different Industrial Sectors

Industrial Sector	Cost Savings (%)	Carbon Emissions Reduction (%)	Water Usage Reduction (%)
Chemical Production	18	30	5
Metal Processing	22	20	7
Food Manufacturing	10	15	3

4.3. Performance monitoring and results evaluation

The implemented energy-efficient solutions were monitored through ongoing data collection and analysis after their implementation. To measure the success of implemented solutions energy consumption data and cost savings records along with environmental impact assessments were collected. Baseline data collected before the implementation of energy-efficient solutions served as a reference point to evaluate the overall sustainability improvements achieved by these initiatives. The monitoring phase demonstrated the enduring advantages of energy-efficient technologies through improved operational performance and strengthened environmental stewardship [10].

5. Results and discussion

5.1. Energy consumption reduction

The evaluation showed substantial energy consumption declines throughout every industrial procedure. The chemical production process saw a 25% drop in energy use after implementing heat recovery systems. The use of high-efficiency furnaces in metal processing achieved a 20% decrease in energy consumption. The food manufacturing industry experienced a 15% reduction in electricity use after implementing energy-efficient refrigeration systems. The findings here show how energy-efficient technologies can decrease energy consumption during industrial operations.

5.2. Cost savings and economic viability

The implementation of energy-efficient solutions resulted in significant cost decreases alongside energy savings. The implementation of energy efficiency solutions achieved total cost savings between 10% and 30% which varied across industries and processes. The metal processing industry experienced the quickest return on investment for energy-efficient technologies within two years while the food manufacturing sector experienced the longest payback period of five years. The data on cost savings, payback periods and environmental impact across various sectors is compiled in Table 3. The study used net present value (NPV) and internal rate of return (IRR) calculations to evaluate energy-efficient solutions and confirmed their financial advantages over the long term. The chemical production sector achieved an 18% cost saving alongside a 30% reduction in carbon emissions demonstrating the balance between economic and environmental benefits. Investments in energy-efficient solutions demonstrated economic viability through their payback period across all industries.

Table 3. Cost Savings, Payback Period, and Environmental Impact Data for Different Industrial Sectors

Industrial Sector	Cost Savings (%)	Payback Period (Years)	Carbon Emissions Reduction (%)	Water Usage Reduction (%)
Chemical Production	18	3	30	5
Metal Processing	22	2	20	7
Food Manufacturing	10	5	15	3

5.3. Environmental impact assessment

A life cycle assessment (LCA) examined the environmental consequences of energy-efficient solutions by analyzing their carbon footprint along with water usage and waste production. All processes experienced a significant environmental impact reduction with chemical production decreasing carbon emissions by 30%, metal processing lowering emissions by 20%, and food manufacturing seeing a 15% reduction. The research demonstrates why industries must adopt energy-efficient technologies to reduce environmental harm.

6. Conclusion

According to this study industrial manufacturing processes benefit from energy-efficient technologies through reduced energy consumption, improved cost-effectiveness and decreased environmental impacts. The study uses Multi-Criteria Decision Analysis (MCDA) framework to find the best energy-efficient solutions for industries including chemical production, metal processing and food manufacturing. The results indicate substantial energy conservation levels between 15% and 25% while demonstrating cost savings as high as 30%. Achieving these results requires advanced technologies such as heat recovery systems and high-efficiency furnaces while energy-efficient refrigeration systems in food manufacturing reduce electricity consumption effectively. These energy-efficient solutions produce a meaningful environmental impact through their ability to reduce both carbon emissions and water use across all examined sectors. A 30% decrease in carbon emissions within the chemical production sector demonstrates how energy efficiency plays an essential role in solving worldwide environmental challenges. Investing in energy-efficient technologies proves financially sound as industries achieve positive payback periods within two to five years according to financial return analysis. This study demonstrates that the implementation of energy-efficient systems within industrial practices is crucial for achieving sustainable development in the long term. Industries can achieve an optimal balance between energy efficiency and environmental protection while maintaining cost-effectiveness through the application of decision-making frameworks like MCDA. Future investigations need to target renewable energy integration and advanced technological advancements to improve industrial manufacturing sustainability.

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