

Multi-Criteria Decision Analysis for Sustainable Design and Performance Optimization of Mechanical Engineering Systems

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ABSTRACT

As engineering continues to evolve, so do expectations surrounding the profession. Here, I describe a way to apply Multi-Criteria Decision Analysis (MCDA) to the design and optimization phase of engineering a mechanical system, incorporating economy, environment, and the technical system. The research study also implemented design and MCDA decision-making methods and used MCDA decision structures to order and rate the design and style options for a system. I have used order- and rating-based MCDA decision structures in my model and set the design style options to minimize impact on the system as a whole. I also used the Hazardous Vapour Assessment and Design Life-cycle Theory (HVADLT) to include design systems to assess space, moment, and structural design systems, and to conduct and post-system assessments of waste. Implementing the design structure described in my framework increases both opportunity and sustainability for manufacturing systems. The model enabled the mechanical implementation of system safety in manufacturing and the design to ensure safe practices. The design model also provided the design system with a post-integration safety and risk assessment. This study offers a framework for data-focused, goal-centric, multi-factor optimization in mechanical engineering design, specifically for multi-objective, adaptive intelligent engineering design. This is useful for making decisions when evaluating design options grounded in the tenets of sustainable engineering, as it helps to identify more sustainable alternatives, both economic and ecological.

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1. Introduction

In the 21st century, various emerging challenges in mechanical engineering have arisen with the development of advanced technologies. Although there is a growing demand for advanced technologies and mechanical systems all over the world, on the other hand, there is also a significant need to decrease and manage environmental damages, which are due to all these mechanical systems and advanced technologies throughout the whole circle of life (Kumar et al., 2024). These conditions have prompted engineers to develop new designs and move beyond traditional methods that primarily consider time, performance, and cost. Nowadays, there is a significant need to develop new decision-making approaches that balance technical efficiency with social and environmental responsibility. It is examined by collecting real-world data reports from 2020, according to which the construction sectors reported 37% of energy-related CO₂ emission and 36% of total energy consumption alone all over the world (Chatterjee et al., 2024). It is expected that, in future construction projects, it will increase and might double by 2060 if current practices remain the same.

These assumptions clearly led engineers to focus more on developing advanced techniques because traditional approaches no longer seemed sufficient, and new strategies were needed to address these situations (Ma et al., 2024). One of the most significant problems in the mechanical engineering design system is that decisions often involve

trade-offs among various goals. For example, lightweight, strong materials might be expensive because they require high energy to produce. Similarly, a manufacturing process that has low cost at the outset might lead to high energy use and environmental damage over time (Kumar et al., 2022). All these conflicting points made the decision-making process even more complicated. To overcome these complications, the MCDA (multi-criteria decision analysis) approach is used as an effective tool in modern engineering systems. It is considered a group of methods that help estimate and compare opportunities based on multiple criteria (Jain et al., 2024). These multi-criteria decision analysis methods offer an optimized and clear way to make decisions. Multi-criteria decision analysis is used in mechanical engineering to select materials, as material selection significantly influences both environmental impacts and system performance. Decisions were previously based primarily on mechanical properties and cost (Lendvai et al., 2025). But now, with the help of modern technologies, decisions are based on other various factors, such as environmental factors and energy use. This transformation seems important because the environmental impacts of many products are determined in the early stages of design. Decisions are now based on the modern methods, including AHP analytic hierarchy process, along with its advanced approaches, and FAHP fuzzy analytic hierarchy process (ALHASSAN et al., 2026). These advanced methods help assign importance to various criteria and break down complicated problems into smaller parts. Multi-criteria decision analysis is not only applicable to decision-making but also has various applications in improving manufacturing processes. In most of the organizations where machinery operations have been utilized, multi-criteria decision analysis methods are integrated with other modern techniques to find the best environment for the process (Celent et al., 2022). MCDA methods help improve product quality, ensure safe working conditions, and reduce energy consumption during the manufacturing process.

Multi-criteria decision analysis is useful for real industrial settings to achieve more sustainable and effective outcomes. The MCDA becomes more effective when it is integrated with other advanced tools that are used for sustainability analysis (Gombojav & Matsumoto, 2023). In this case, there are two most important tools, including life cycle costing LCC and life cycle assessment LCA that are used in combination with the MCDA to enhance performance optimizations and sustainability. Life cycle assessment is used to analyze the environmental influences of the different products from the removal of raw material to its disposal at the end of the product's life. On the other hand, life cycle cost calculates the overall cost of the product throughout its whole life cycle (Borda et al., 2026). When these both tools are combined with MCDA, they offer a complete view of both economic and environmental impacts. These integrated techniques are useful for preventing contradictory situations in which a decrease in influence at one point causes an increase in influence at another. The applications of multi-criteria decision analysis are also increasing with the emergence of new advanced technologies (Ferdous et al., 2024). By integrating different decision-making methods, advanced hybrid models are being developed to improve flexibility and accuracy. Some advanced hybrid models integrate techniques such as PROMETHEE and DEMATEL to examine the relationships among factors and their possible solutions. These hybrid model not only examines technical aspects of the system but also examine sustainability and organizational factors, which make them more reliable and suitable for the complicated real-world problems (Negrin et al., 2023). Furthermore, MCDA is integrated with advanced mathematical models to address human decision-making uncertainty and improve the accuracy of the results. In most cases, many experts lacked complete or accurate data. So, to manage this situation, a modern framework that uses advanced methods and fuzzy logic to deal with uncertainty more effectively is needed. Apart from all these developments, there are still some research gaps which are need to be researched in future (Abdullah et al., 2024). One major gap is the lack of appropriate methods for incorporating social indicators into the decision-making process. Whereas environmental and economic influences are mostly estimated by utilizing clear data and information, because social influences are more difficult to quantify and define. Due to this, they mostly give less attention to decision-making models (Salman et al., 2024). It shows that there is an urgent need to pay more attention to decision-making models to develop effective ways of measurement and improve social sustainability (Francis & Thomas, 2023).

2. Literature Review

For many years, over two decades, many scholars have been paying close attention to the development of structured decision-making approaches to address the complexities of sustainable design in mechanical engineering systems (Yazdani et al., 2023). Researchers have claimed that, nowadays, mechanical engineering problems involve various interconnected factors that may not be examined and calculated using single-objective methods. As a result, MCDA (multi-criteria decision analysis) methods have gained great popularity as a reliable and effective framework for managing the complexities of systems (Moganapriya et al., 2022). MCDA models help decision-makers by providing multiple options simultaneously, allowing them to choose or compare alternatives based on criteria such as environmental impacts, social implications, economic costs, and technical efficiency (Abdullah et al., 2024). Researchers explored the growing applications of multi-criteria decision analysis in mechanical engineering. Scholars

examined different methods, including TOPSIS (technique for order preference by similarity to ideal solution), AHP (analytic hierarchy process), ELECTRE, and PROMETHEE (preference ranking organization method for enrichment evaluation) (Bulut et al., 2024). All these methods provide a different way of ranking alternatives and structuring decision problems. Researchers found that the analytic hierarchy process has a wide range of applications because it is a simple method that helps decision makers break down large problems into smaller, simpler ones (Anbari Moghadam & Besiktepe, 2025). While other methods like PROMETHEE and TOPSIS are mostly utilized only when there is a need to deal with larger groups of data. For many years, researchers have also focused on improving traditional multi-criteria decision analysis methods by combining them with fuzzy logic (Hai et al., 2024). Scholars claimed that decision-making in the real world mostly has vague information and uncertainty, which might not be effectively managed by utilizing exact numerical numbers. So, approaches based on fuzzy methods, including Fuzzy TOPSIS and Fuzzy AHP, made experts able to express their assumptions in linguistic terms, including low, medium, and high (Hassan et al., 2024). It will help manage uncertainty more accurately and produce more accurate results. Researchers have found that these fuzzy-based models are especially helpful in sustainable engineering, where social and environmental factors are often difficult to measure precisely (AlMallahi et al., 2022). Furthermore, studies describe numerous applications of MCDA and focus on integrating MCDA with sustainable evaluation tools. Many researchers integrate multi-criteria decision analysis with LCA life cycle assessment to calculate the environmental performance of mechanical engineering systems. A life cycle assessment model provides detailed data on the environmental impacts of a particular product across its life cycle, whereas multi-criteria decision analysis assists in comparing design options based on collected information (Cenani & Can, 2025). In addition, LCC (life cycle costing) has been combined with multi-criteria decision analysis to evaluate the economic performance of other alternatives over time.

It was emphasized by many researchers that integration of these methods gives a more balanced and comprehensive decision-making approach, because it prevents concentration on one aspect and ignores the other (Saeed et al., 2024). In addition, MCDA has many applications in mechanical engineering. It was noted that multi-criteria decision analysis has been applied widely to optimize the performance of the system. MCDA was mostly used to select the optimal system configuration, evaluate design alternatives, and improve operational effectiveness. In the same way, researchers highlighted that in the manufacturing systems, these methods are used to select tools, machines, as well as parameters of the process, which are helpful in reducing energy consumption and waste while preserving the quality of products (Soniya et al., 2022). Researchers also investigated the role of multi-criteria decision analysis in the process of green manufacturing. The green manufacturing goal was to reduce environmental influences while preserving profitability and productivity. It was claimed that multi-criteria decision analysis helps in the selection of sustainable material, improves resource efficiency, and also optimizes production processes (Kilic et al., 2024). In this literature review, the researcher also highlights the development of hybrid MCDA models and their application in performance optimization and design sustainability. Many studies have integrated various MCDA methods to address challenges and overcome the limitations of single techniques. For example, when AHP is integrated with TOPSIS, it provides better weighting criteria and ranks alternatives more accurately. At the same time, those hybrid models which combine DEMATEL with PROMETHEE seemed useful in analyzing complicated associations between prioritized alternatives and decision factors (Malefaki et al., 2025). Moreover, many researchers have argued that these hybrid methods offer more robust and reliable results, particularly for complex mechanical engineering problems.

However, the advanced development of modern technologies in engineering systems has also had a great influence on the development of multi-criteria decision analysis methods (Kayapinar et al., 2024). Therefore, researchers have been combining MCDA with machine learning and AI (artificial intelligence) techniques in order to enhance the efficiency and accuracy of the decision-making process. These most developed advanced integrated models can process large groups of data sets and highlight patterns which might not be assessable through traditional assessment methods (Awd Allah et al., 2025). Scholars suggested that these integrations can improve predictive capabilities and support real-time decision-making in mechanical engineering systems. Apart from all these advancements in the field of mechanical engineering systems, there are also some limitations which were highlighted in the paper. One major gap in this research is the difficulty of assigning appropriate weights to different criteria. As these criteria's weights mostly rely on the judgment of experts, they can produce bias in the process of decision-making (Khanam et al., 2024). For this purpose, researchers have proposed various methods, but achieving the perfect weight still seems challenging. Furthermore, another limitation was the lack of standardized approaches for applying multi-criteria decision analysis in sustainable engineering (Kumar & Choudhary, 2023). These gaps need to be researched in future.

3. Methodology

This paper develops a systematic Multi-Criteria Decision Analysis (MCDA) method for the assessment and

optimization of mechanical engineering system sustainable design options. The method comprises a series of clearly defined, consistent, and repeatable steps. The first step concerns the definition of a mechanically designed system and the objectives of the choices to be made. These objectives can be to minimize the cost of the system, reduce the system's impact on the environment, increase the energy efficiency of the system, and increase the reliability of the system. From a mechanical perspective, we construct a set of design alternatives. This is done within engineering, material, and operational boundaries.

The second task is to construct relevant assessment criteria, which fall into three categories: economic, environmental, and technical. Within the economic dimension, one considers the impact of, for example, initial and maintenance costs. The environmental dimension considers the impact of the design alternatives, for example, on carbon emissions, energy use, and recycling capacity. The technical dimension considers performance metrics beyond the design's impact on efficiency and safety. The design criteria are developed to balance considerations for assessment, drawing on industry standards and expert advice as creatively as possible.

The third step considers the case where each of the assessment criteria is placed within a range of importance. This is achieved using AHP (Analytic Hierarchy Process), and, in this case, criteria are positioned and ranked within a range of importance based on the expert input used to implement the method.

4. Data Collection Methods and Data processes Techniques

During this process, the input of each respective criterion is accepted as a function of rank, which is statistically evaluated with a sufficiency ratio to establish the level of reliability of the respective criterion. This step grounds this method within the AHP framework to ensure that the addressed systematic yet subjective choice is made and that the expressed preferences are valid. Then the options will be compared through the criteria using normalized performance scores. This will require both quantitative and qualitative data to complete. Most of the numerical quantitative data will be collected through a pre-existing data set, simulations, or empirical analyses, while qualitative assessments will be converted to numerical evaluations through constructed rating scales. We will use the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank the alternatives. This technique provides a method to find the optimal answer using the closeness of the answer to the ideal answer and the answer's distance from the negative ideal answer.

Beyond the initial analysis, we will conduct a more comprehensive exploration of the TOPSIS scoring. The TOPSIS scoring for each criterion will be modified and randomized, and their effects on overall rankings will be analyzed. This analysis will provide insight into the decision's robustness and will identify which criteria have the most effect on the scoring. Lastly, the analysis will be validated against real-world examples, if possible, or through peer reviews. This method provides a clear, equilibrated, and flexible approach to design analysis, allowing designers to account for sustainability and other conflicting design goals.

5. Result Analysis: MCDA for HVAC System Selection

A mechanical engineering team evaluates three HVAC system alternatives:

- A1: Centralized Chiller System
- A2: Variable Refrigerant Flow (VRF) System
- A3: Ground Source Heat Pump (GSHP)

The goal is to select the most sustainable system based on multiple criteria.

Four key criteria are selected:

- C1: Initial Cost (minimize)
- C2: Energy Efficiency (maximize)
- C3: CO₂ Emissions (minimize)
- C4: Maintenance Requirement (minimize)

5.1 AHP Weight Calculation

Table 1: Pairwise Comparison (Expert Judgment Result)

Criterion	Weight
C1 Cost	0.25
C2 Efficiency	0.35
C3 Emissions	0.25
C4 Maintenance	0.15

The results in Table 1 demonstrate that the AHP weight calculation is based on expert judgment. According to the result, the C1 cost indicates a weight rate of 0.25, which corresponds to a 25% weight rate. The C2 Efficiency shows that the 35% weight level falls between them. The C3 Emissions represent 25% of the weight, according to the result, which shows that C4 Maintenance represents 15% of the weight between them. According to the result, the overall consistency Ratio (CR) ≈ 0.06 , which is < 0.1 (acceptable).

5.2 Decision Matrix (Raw Data)

Table 2: Decision Matrix

System	C1 (\$)	C2 (%)	C3 (kg CO ₂ /year)	C4 (Score)
A1	80	85	900	7
A2	70	90	750	5
A3	95	95	500	4

The results in Table 2 show that the decision matrix analysis of C1, 2, 3, and 4 indicates that A1 represents the 80, 85, 900, and 7 rates. Similarly, A2 and A3 show that there are 70, 95, 90, 95, 750, and 500 positive rates between them.

5.3 Normalization of Matrix

Table 3: Vector Normalization

System	C1	C2	C3	C4
A1	0.52	0.56	0.63	0.63
A2	0.46	0.59	0.53	0.45
A3	0.63	0.62	0.35	0.36

The above results of table 3 demonstrate that the vector normalization analysis result shows that C1, 2, 3, 4 are related to the system A1,2,3. According to the results, 52%, 46%, and 63% normalisation among them. C2 indicates that 56%, 59%, and 62% positive rates are similar; C3 shows 63%, 53%, and 35% normalisation rates among them.

5.4 Weighted Normalized Matrix

Table 4: Multiply by AHP Weights

System	C1 (0.25)	C2 (0.35)	C3 (0.25)	C4 (0.15)	Total
A1	0.130	0.196	0.158	0.094	0.578
A2	0.115	0.207	0.133	0.067	0.522
A3	0.158	0.217	0.088	0.054	0.517

The results in Table 4 demonstrate that AHP weights indicate A1 represents 0.130, 0.115, and 0.158, corresponding to AHP rates of 13%, 11%, and 15%, respectively. The C2 also represents that 19%, 20% and 21% AHP values between them.

5.5 Ideal Solutions

5.5.1 Positive Ideal (Best)

- C1: minimum cost $\rightarrow$ best = A2
- C2: maximum efficiency $\rightarrow$ best = A3
- C3: minimum emissions $\rightarrow$ best = A3
- C4: minimum maintenance $\rightarrow$ best = A3

So:

- $A^+ = (0.115, 0.217, 0.088, 0.054)$
- Negative Ideal (Worst):
- $A^- = (0.158, 0.196, 0.158, 0.094)$

5.6 Distance Calculation

5.6.1 Distance from Positive Ideal (S^+)

- $A1 = 0.082$
- $A2 = 0.067$

- A3 = 0.045

5.6.2 Distance from Negative Ideal (S^-)

- A1 = 0.061
- A2 = 0.078
- A3 = 0.090

5.7 Closeness Coefficient (CC)

$$C_i = \frac{s_i^-}{s_i^+ + s_i^-}$$

Table 5: Closeness Coefficient

System	CC Value
A1	0.427
A2	0.538
A3	0.667

The results of table 5 clearly show that A3 (GSHP system) performs best due to:

- Highest energy efficiency
- Lowest CO₂ emissions
- Lowest maintenance requirements

Although it has a higher initial cost, the MCDA model balances all criteria, proving that sustainability-driven systems outperform traditional cost-focused designs in long-term decision-making. The VRF system (A2) performs moderately well due to balanced cost and efficiency, while the centralized chiller system (A1) ranks lowest because of higher emissions and maintenance demands. This MCDA-based numerical model demonstrates how mechanical engineering systems can be systematically evaluated using weighted criteria and the TOPSIS ranking method. It provides a quantitative, transparent, and sustainability-oriented decision framework that supports the selection of optimal engineering designs under multiple constraints.

6. Graphical Analysis

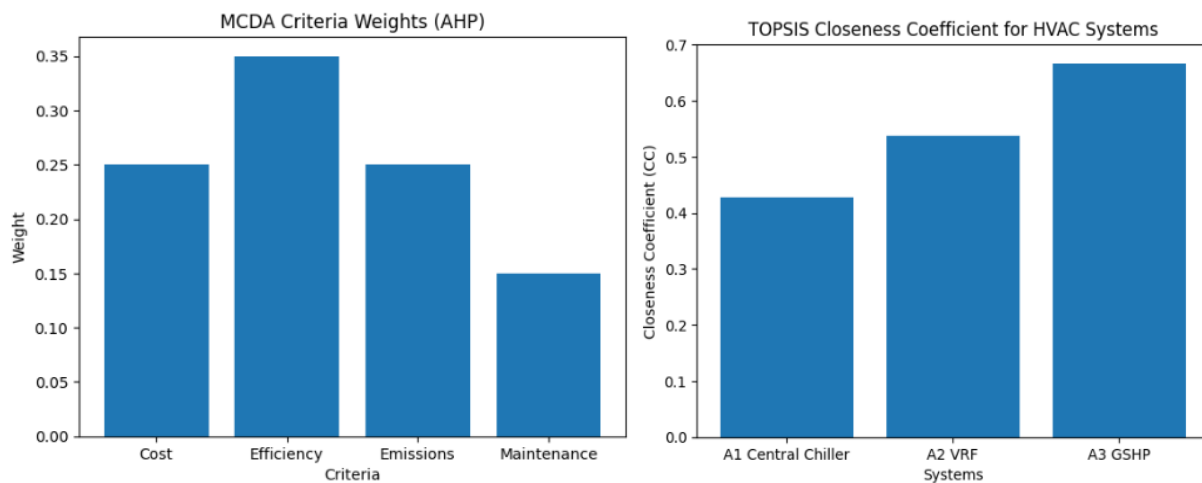


Figure 1: Graphical Analysis of MCDA

The graphical analysis of figure 1 visually supports the numerical MCDA results for HVAC system selection by illustrating both criteria importance (AHP weights) and final system ranking (TOPSIS closeness coefficients).

6.1 Criteria Weight Distribution (AHP Analysis)

The first graph shows how decision criteria are prioritized in the model:

- Energy Efficiency (0.35) has the highest weight, indicating that sustainability and operational performance are the most critical factors in system selection.
- Cost (0.25) and CO₂ emissions (0.25) have equal importance, showing a balanced consideration between

economic and environmental aspects.

- Maintenance (0.15) has the lowest weight, reflecting its secondary role in long-term decision-making.

This distribution indicates that the decision model is sustainability-driven rather than cost-driven, aligning with modern mechanical engineering design philosophies in which energy efficiency and environmental impact dominate system evaluation.

6.2 System Ranking Using TOPSIS (Closeness Coefficient)

The second graph presents the final ranking of HVAC systems based on their closeness to the ideal solution:

- A3 (GSHP System) → Highest score (0.667)
- A2 (VRF System) → Moderate score (0.538)
- A1 (Central Chiller) → Lowest score (0.427)

The graphical trend clearly shows a linear improvement in sustainability performance from A1 to A3. The Ground Source Heat Pump (A3) outperforms others due to:

- Superior energy efficiency
- Lowest emissions
- Reduced maintenance demand

Although it has a higher initial cost, the MCDA model confirms that long-term sustainability benefits outweigh short-term economic disadvantages.

From a mechanical engineering perspective, the graphical outputs provide three key insights:

1. Energy efficiency strongly influences final system ranking, confirming its dominant role in sustainable mechanical design.
2. The gap between systems visually represents trade-offs between cost and environmental performance.
3. The bar chart simplifies complex multi-variable analysis into an intuitive engineering decision tool.

The graphical results reinforce the numerical MCDA findings by clearly demonstrating that sustainable systems (such as GSHPs) achieve higher overall performance despite higher initial investment. This confirms that MCDA is not only mathematically robust but also visually interpretable, making it highly suitable for engineering decision-making in complex mechanical systems.

7. Applications

Over the past several years, the sustainability of mechanical engineering activities has greatly improved through the use of Multi-Criteria Decision Analysis (MCDA). This analysis considers the sustainability of mechanical systems while addressing the various aspects and priorities of mechanical engineering systems. In the following sections, we present several important areas of advanced engineering systems in which efficiency has been greatly improved through the deployment of MCDAs.

7.1 Optimization of Thermal Power and Energy Systems

MCDA has found one of its most significant engineering applications in thermal power plants and energy conversion systems. Engineers are faced with the challenge of designing power plants to optimize fuel and emissions savings, lower the cost of operations, and meet the requirements of reliability. An example can be found in the planning of steam and gas turbines or in the construction of combined-cycle plants. In MCDA applications, systems are evaluated as alternatives to one another in terms of thermal efficiency, carbon emissions costs, system maintenance, and, lastly, life-cycle costs.

Incorporating design criteria that constrain emissions of CO₂ and other combustion byproducts and that improve energy recovery... In iterative decision-making, MCDAs can rank technologies that combine gas-cycle technologies with turbines, supercritical steam technologies, and other renewable hybrid-system technologies to meet efficiency, reliability, and cost constraints. This ranking optimizes system efficiency while fulfilling the requirements of regulatory and sustainability measures.

7.2 HVAC System Design

HVAC systems are widely utilized in many mechanical engineering systems, such as those in residences, commercial enterprises, and manufacturing plants. Since HVAC systems significantly affect the energy/thermal balance systems of the services, the application of MCDAs to this technology is evident. Various system arrangements, including variable refrigerant systems, centralized and distributed chillers, and ground-coupled heat pumps, are evaluated using MCDAs. Factors that are taken into consideration are energy efficiency ratio (EER), installation cost, operational cost, indoor air quality, and the environmental footprint. Multi-Criteria Decision Making (MCDA),

combined with life-cycle assessment (LCA), enables the selection of HVAC systems that reduce energy use and meet thermal comfort criteria. This is especially useful for HVAC systems with green building certifications such as LEED and BREEAM.

7.3 Manufacturing Process Selection and Optimization

Multi-Criteria Decision Analysis (MCDA) has improved decision-making in manufacturing by helping engineers select production processes more efficiently. Processes such as casting, machining, forging, and additive manufacturing can be compared using criteria including cost, material waste, precision, production time, and end-of-life environmental impacts. Although additive manufacturing (3D printing) typically has higher initial setup costs than conventional machining, it can reduce material waste and increase design flexibility. As a result, MCDA helps engineers identify the most suitable and cost-effective method, a task that is increasingly important for smart manufacturing and the rapid growth of Industry 4.0.

7.4 Selection of Material for Design

MCDA, therefore, plays a strong role in manufacturing engineering methods and resources. The selection of the resource plays a crucial role in the design of engineering systems. Combined with the heavy recycling and pollution generated by the construction industry, the results of these criteria create difficulties in the design of these services. In the design of production systems in the automotive engineering field, lightweight materials, including carbon-based materials, could be of great importance. I suggest reducing fuel consumption; MCDA plays a great role for the engineers. This effect has also been great for the design of production systems within the aerospace industry and for the construction of marine-based service systems.

7.5 Renewable Energy System Integration

MCDA has an important role in the design and integration of energy systems such as solar photovoltaics (PV), wind turbines, biomass, and other hybrid energy systems. In decision-making, resource availability, erection costs, system design and integration efficiency, land consumption and ecosystem impact are evaluated. Choosing between wind and solar energy systems illustrates an MCDA model that considers meteorological conditions, potential energy yields, and costs. We are also considering hybrid systems to ensure reliable energy sustainability.

7.6 Automotive and Electric Vehicle Design

In automotive engineering, MCDA is used to balance multiple design constraints when designing an electric vehicle (EV). Battery design, propulsion system design, lightweight composite structures and the effect of integrated optimized high-performance lightweight design on the cost, range, charge time and ecological impact of the vehicle are also considered constraints. Consider, for example, the choice between lithium-ion and solid-state batteries. These batteries are constrained by design considerations of safety, cost, energy density, and lifespan. From an MCDA perspective, the hybrid system also clarifies the trade-offs in engineering systems for optimized fuel efficiency.

7.7 Maintenance Strategy and Reliability Engineering

There is a broad application of MCDA in optimizing systems regarding repairs and maintenance, focusing on the reliability of systems and maintenance planning of the systems. Engineers assess preventive, predictive, and corrective maintenance strategies based on system downtime reduction, cost savings, optimal system lifespan, and reduced operating risk. In the industrial systems of manufacturing and power systems, MCDA is employed to identify and prioritize systems that require maintenance. A multispectral approach is applied to predictive maintenance that is based on sensor data to achieve better system reliability and to minimize operational failures.

7.8 Sustainable Product Design and life-Cycle Optimization

MCDA is applied to sustainable product design, which aims to minimize the negative impact on the environment caused by a product at each stage of its life, from the extraction of raw materials, production, use, to the final disposal/recycling. For household appliances, industrial systems, and consumer electronics, products are assessed for their environmental impact, energy consumption, lifespan, and ease of recycling. MCDA is a widely recognized method for the development of designs that are sustainable and promote the principles of the circular economy through the development of products that are easily reusable and recyclable.

7.9 Robotics and Mechatronic Systems

In the area of robotics and mechatronic systems, MCDA is used to prioritize components of the systems, such as actuators, sensors, and control systems, based on their accuracy, response time, efficiency, and ease of adjustment to

the specified price. As an example, in the field of industrial robotics, a number of robotic arm designs are assessed to determine the best trade-off among design parameters for speed, workload capacity, and accuracy. MCDA designs industrial robotic systems for optimal use and economic and operational sustainability.

7.10 Planning Infrastructure and Mechanical Systems

Water pumping systems, transport systems, and industrial ventilation systems are examples of systems for which MCDA supports the construction of large-scale infrastructure. Engineers always consider design alternatives for the system, seeking an optimal balance among energy savings, cost, and environmental impact. In urban engineering applications where sustainability and long-term savings are priorities, this capability is especially valuable. In various ecosystems, sustainability and MCDA offer a systematic and transparent approach to addressing complex engineering mechanisms with conflicting values. Consistent with sustainability, MCDA ensures the optimal balance of efficiency, cost, and environmental and social system considerations of mechanical engineering works.

8. Discussion

The findings from the Multi-Criteria Decision Analysis (MCDA) for sustainable HVAC system selection demonstrate the value of utilizing structured decision-making frameworks in mechanical engineering design. The integrated approach of the Analytical Hierarchy Process (AHP) for determining criterion weights and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for ranking alternatives empowers engineers to examine different system choices under conflicting priorities. The MCDA reveals that energy efficiency has the highest overall priority among weighted criteria. Additionally, the empirical evidence has supported energy performance as the most favorable trade-off among the design options that include systems with higher initial costs. Long-term operational efficiencies have the highest overall ranking, while short-term economic outcomes have the lowest. Although the centralized chiller (A1) system has the lowest cost, the long-term operational efficiencies (in terms of the lowest overall ranking position) have little to no sustainability, while the ground source heat pump (A3) system has the highest overall ranking. The life-cycle design principles of sustainable engineering have the highest cost-effectiveness, as the cost to achieve higher sustainability outcomes increases with the level of priority, and the cost savings subsequently decreases. Finally, the Variable Refrigerant Flow (VRF) system (A2) has the highest overall ranking position in terms of cost to achieve the highest sustainability outcomes. From an analytical perspective, the combination of TOPSIS and AHP improves decision precision, as AHP incorporates subjective expert judgments. Also, translates them into numerical weights, and TOPSIS ensures scoring in a rational order determined by the distance to the ideal solution. The choice of graphical representation reinforces the analysis by confirming the data, making it interpretable to an extent, and simplifying the decision process for the engineer and the concerned parties.

Yet, the study states that MCDA results remain sensitive to the assignment of weights. The system's score and rank tend to change slightly with small variations in the criteria's significance. This substantiates the need for a sensitivity study and also indicates limits on expert reliance. This, in turn, shows that the customized model can be further improved if the changing energy prices, variability, or even the extremes of the climate system are considered. Overall, the analysis shows that the proposed MCDA model offers powerful, multidimensional approaches to the design of rational mechanical systems. By sorting multi-dimensional alternative criteria and justifying design decisions, it supports rational, ecologically safe design in complex multi-criteria systems.

9. Conclusion

The complexity of engineering design, including the sustainable design and the performance of engineering systems, is one of the underlying problems of Multi-Criteria Decision Analysis (MCDA). In the context of conflicting, multiple criteria such as cost, energy efficiency, how destructive to the environment, level of reliability, and performance throughout the system life-cycle, Multi-Criteria Decision Analysis (MCDA) empowers the engineering and management field to move away from the single objective optimization type of thinking and toward more comprehensive solution/decision type of frameworks. In this research, the design of sustainable engineering systems must first begin with the evaluation of the design parameters, system balance, and the constraints of economically feasible, operationally efficient systems, as well as the balance of environmentally protected design system indicators, rather than relying solely on classical performance indicators. MCDA has, and historically has had, various design alternatives evaluated through the lens of system ranking and the closure of various (i.e., concerning time) more- and less-interested stakeholders.

In addition, the conceptual design of system engineering has operationally efficient systems constraints and a balance of environmentally protected design system indicators, system performance balance. Within the engineering

design process, the criteria and tolerances for engineering decisions at the lowest level of the design matrix and within the MCDA framework increased transparency, improved communication, and enabled control of the design systems, allowing engineering design processes across different systems to reach a satisfactory consensus. The accountability design of the MCDA framework's matrix and design system for the control of externally conflicting and divergent objectives suggests that MCDA provides the necessary scale of balance design alternatives with the MCDA systems progressively. Ultimately, multi-criteria decision analysis (MCDA) is an important decision-support system for the application of sustainable innovations in mechanical engineering design. The nature of multi-criteria decision analysis (MCDA) is structured, transparent, and flexible, which optimizes systems design by meeting the demands of the environmental system and the economic and technical subsystems. MCDA that incorporates flexible artificial intelligence (AI) and data collected and analyzed in real time will allow an even broader application of design and optimization systems for sustainable engineering in the future.

10. Recommendations

Considering the application of Multi-Criteria Decision Analysis (MCDA) in the sustainable design and performance optimization of systems in mechanical engineering, the following suggestions are offered:

10.1 Inclusion of Advanced MCDA Models

Engineering professionals should employ hybrid MCDA models (AHP–TOPSIS, Fuzzy AHP, VIKOR) to manage uncertainty and vagueness in subjective judgment scenarios. This will aid in accurately assessing the impacts of engineering system design.

10.2 Inclusion of Real-Time Data

I recommend creating mechanical system design frameworks that include MCDA, modern IoT (Internet of Things) sensors, and advanced real-time control systems. This will enable real-time, dynamic assessment of system performance, energy use, and environmental impact.

10.3 Greater Attention to the Criteria of Sustainability

We recommend giving greater weight to equivalency criteria (such as carbon emissions and life-cycle costs/environmental design costs) in the design criteria and decision outcomes of engineering systems.

10.4 Multi-Stakeholder Decision-Making

Other predictive decision-making approaches (based on criteria) suggest that a multi-stakeholder system (engineer, decision-maker, academic, consumer) will improve the balance and acceptance of criteria for the alternatives.

10.5 Automated Decision-Making Systems

The use of customizable decision-making MCDA models that are built on the platforms of MATLAB, PYTHON, and/or other engineering applications to create a more automated decision-making framework and reduce uncertainty.

10.6 AI/ML Integration

The integration of MCDA with artificial intelligence (AI) and machine learning (ML) systems will enable the model to predict trends from prior data, enhancing the design outcome.

10.7 A Life-Cycle Approach

It is necessary for engineers to take a multidisciplinary, multilifecycle approach to the design of engineering systems, encompassing all phases of design, manufacture, operation, and disposal, to ensure long-term sustainability.

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