A HYBRID DECISION SUPPORT FRAMEWORK FOR SUSTAINABLE BUSINESS OPTIMIZATION

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Highlights

- Developed a hybrid AHP-regression model for promoting sustainable business optimization.
- Identified Circular Product Design and Digital Integration as key sustainability drivers.
- Achieved a model accuracy of 41.93% with robust predictive insights on sustainability.
- Applied KNIME workflow for automated, scalable decision-making in sustainability analysis.

ABSTRACT

The study introduces a decision-making framework that integrates the Analytic Hierarchy Process (AHP) with regression analysis, implemented within a KNIME workflow, to evaluate and prioritize sustainability actions. The framework utilizes AHP to analyze criteria such as resource efficiency, waste reduction, and operational transparency, and regression analysis to quantify the impact of prioritized actions on business outcomes. Applied to a manufacturing case study, the model demonstrated the ability to optimize decision-making, improve resource allocation, and accurately predict the outcomes of sustainability initiatives. The results highlight the advantages of a combined digital approach that bridges qualitative prioritization and quantitative analysis, supporting sustainability and circular economy goals.

Keywords: Business optimization, AHP, Regression analysis, KNIME workflow, Sustainability, Decision-making

1. Introduction

Businesses face growing pressure to integrate economic, environmental, and social responsibilities in their decision-making processes, particularly in resource-intensive

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industries transitioning toward sustainability and circular economy principles. Despite numerous sustainability initiatives, structured tools for prioritizing and evaluating their impacts remain limited. This study explores how the integration of the Analytic Hierarchy Process (AHP) and regression analysis, within a KNIME workflow, can provide a scalable and data-driven framework for decision-making (Saaty and Peniwati, 2007). AHP prioritizes sustainability criteria systematically, while regression analysis quantifies their impact on measurable outcomes. The research aims to answer the following questions: **(1)** How can AHP and regression analysis be integrated to support sustainability-focused decision-making? **(2)** What are the practical implications of using this framework for improving resource allocation and strategic planning? Addressing these questions is critical for industries to transition from reactive sustainability practices to proactive and optimized strategies, ensuring resilience in a competitive and rapidly evolving global landscape. By advancing decision analysis methodologies, this study contributes to a growing body of knowledge on leveraging digitalization and analytical tools for business optimization, offering a scalable solution to improve resource efficiency, operational transparency, and overall organizational performance.

2. Literature Review

The increasing emphasis on sustainable development and business optimization has driven extensive research into decision analysis methodologies that integrate sustainability into organizational strategies. Among these, Multi-Criteria Decision-Making (MCDM) methods, particularly the AHP, stand out for their ability to prioritize sustainability criteria and evaluate trade-offs among conflicting objectives. Fidanoğlu and Değirmenci (2022) demonstrate AHP's utility in evaluating the impact of sustainable product design on corporate sustainability, showcasing its practical relevance in business contexts. Similarly, Kazançoğlu et al. (2021) emphasize AHP's role in transitioning to a circular economy, illustrating its adaptability in addressing supply chain challenges by balancing sustainability, cost, and operational efficiency. To complement AHP, regression analysis provides a quantitative basis for assessing relationships between decision criteria and outcomes. Qu and Ji (2023) highlight its role in optimizing sustainable supply chain management by predicting the effects of sustainability initiatives. Trică et al. (2019) reinforce the importance of regression in evaluating the financial and environmental impacts of sustainable practices in manufacturing, demonstrating its applicability across industries. Digital platforms like KNIME workflows have revolutionized analytical methods by enhancing their scalability and adaptability. Petrović et al. (2021) highlight KNIME's ability to integrate multiple analytical techniques, making it a valuable tool for complex decision-making scenarios. However, the literature reveals limited exploration of its use in combining AHP and regression analysis for sustainability-driven business optimization. This study addresses the research gap by proposing a novel framework that integrates AHP and regression analysis within a KNIME workflow. This framework bridges the gap between qualitative prioritization and quantitative impact assessment, enabling industries to align strategies with sustainability objectives. By advancing integrated decision analysis methods, this study provides practical tools for achieving more resilient and efficient business models.

3. Objectives

This study aims to develop a decision-making framework by integrating the AHP with regression analysis for business optimization. The specific objectives are to:

1. Identify and prioritize sustainability criteria relevant to business operations using AHP.
2. Quantify the influence of prioritized criteria on organizational outcomes through regression analysis.
3. Integrate AHP and regression analysis within a scalable KNIME workflow to enhance decision-making efficiency.
4. Perform sensitivity analysis to assess the robustness of the framework and its responsiveness to input variations.
5. Provide predictive insights to support sustainable and data-driven business strategies.

This framework seeks to bridge the gap between qualitative prioritization, quantitative impact assessment, and decision-making adaptability.

4. Research Design

The AHP model prioritizes sustainability for business optimization through a hierarchical structure of Goal, Criteria, and Alternatives. The Goal is to enhance sustainable decision-making; the Criteria "energy optimization, circular product design, eco-friendly materials, waste reduction, closed-loop supply chain, digital integration, and employee training" were driven by literature, industry standards (ISO 14001), EU guidelines, and expert input. Alternatives represent specific strategies assessed under each criterion. Pairwise comparisons of criteria were conducted with input from 10 sustainability and operations experts, using the 9-point Saaty scale (1 for equal importance, 9 for extreme importance) using Super Decisions software V3.2.0. Consistency was verified through the consistency ratio (CR), applying Saaty's 0.1 threshold; matrices exceeding this limit were revised with expert feedback to ensure reliability. The aggregated pairwise comparison matrix A=[aij], where aij represents the relative importance of criteria i and j, was used to compute the priority vector w (criteria weights) by solving the eigenvalue problem:

$$A.w = \lambda\,\text{max}.w$$

Here, λ_{max} is the maximum eigenvalue of A, and w is normalized to ensure $\sum$wi=1.
To assess consistency, the Consistency Ratio (CR) was calculated as:

$$CR = \frac{\text{CI}}{\text{RI}}$$

Where $CI = \frac{\lambda_{max-n}}{\text{n}-1}$ is the consistency index, n is the matrix size, and RI is the random index. Sensitivity analysis, introducing ±10% variations in criteria weights, confirmed the model's robustness with performance deviations limited to ±5%

Integrating Regression Analysis

Regression analysis was conducted to quantify the impact of sustainability criteria on business outcomes, using the criteria weights derived from AHP as independent variables. Dependent variables included Key Performance Indicators (KPIs), such as cost reduction (\$), energy efficiency (%), and environmental impact reduction, waste minimization (kg). The regression model is specified as:

$$Y = \beta_O + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \epsilon$$

Where:

- Y: Business outcome (e.g., cost efficiency, environmental performance).

- Xk: Sustainability criteria weights from AHP.
- βk: Regression coefficients indicating the impact of each criterion.
- ϵ: Error term.

The regression analysis was performed on a dataset of 50 sustainability-focused projects from manufacturing sectors, with performance metrics standardized to ensure comparability. Results showed strong correlations between criteria weights and outcomes, with R2 values exceeding 0.85, indicating high model fit.

Validity and Expert Aggregation

To enhance face validity, expert opinions were validated through iterative feedback loops. The combination of expert judgment and data-driven regression analysis ensures that the framework aligns with real-world scenarios. Expert judgments were aggregated using the geometric mean method:

$$aij = \sum_{k=0}^{n} \binom{n}{k} x^k a^{n-k}$$

where m is the number of experts. This approach ensured a consensus-based evaluation. Moreover, KNIME's workflow structure enables reproducibility and transparency in the decision-making process to optimize sustainability practices and achieve measurable improvements in business performance.

5. Model Analysis

The AHP model results highlight Environmental Impact as the most critical criterion (45.29%), followed by Resource Efficiency (27.5%), emphasizing their central roles in sustainable decision-making (Figure 1), as detailed in Table 1. Other criteria, including Regulatory Compliance (9.55%) and Cost and Profitability (7.9%), show moderate importance, while Technological Feasibility (6.98%) and Skill Development (2.77%) hold lesser influence. Among alternatives, Circular Product Design ranks highest (normalized priority: 0.3006), followed by Energy Optimization (0.1704) and Eco-Friendly Materials (0.1669), underscoring their strategic importance as shown in Table 2. The model demonstrates strong alignment between Environmental Impact and Eco-Friendly Materials (55.51%) as well as between Resource Efficiency and Energy Optimization (56.69). These results validate the AHP framework as a practical tool for prioritizing sustainability goals and optimizing resource use.

Table 1. Overall synthesized priorities for all alternatives

Name	Ideals	Normals	Raw
Circular Product Design	1	0.300595	0.150297
Eco-friendly Materials	0.555108	0.166863	0.083431
Energy Optimization	0.566914	0.170411	0.085206
Closed-loop Supply Chain	0.400118	0.120273	0.060137
Digital Integration for Traceability	0.324801	0.097633	0.048817
Waste Reduction Programs	0.253308	0.076143	0.038072
Employee Training	0.226489	0.068081	0.034041

Table 2. Prioritization of decision criteria with normalized and limiting weights

Name	Normalized By Cluster	Limiting

Environmental Impact	0.45299	0.226494
Resource Efficiency	0.275	0.137498
Regulatory Compliance	0.09551	0.047756
Cost and Profitability	0.07904	0.03952
Technological Feasibility	0.0698	0.034902
Skill Development	0.02766	0.013829
Circular Product Design	0.30059	0.150297
Eco-friendly Materials	0.16686	0.083431
Energy Optimization	0.17041	0.085206
Closed-loop Supply Chain	0.12027	0.060137
Digital Integration for Traceability	0.09763	0.048817
Waste Reduction Programs	0.07614	0.038072
Employee Training	0.06808	0.034041

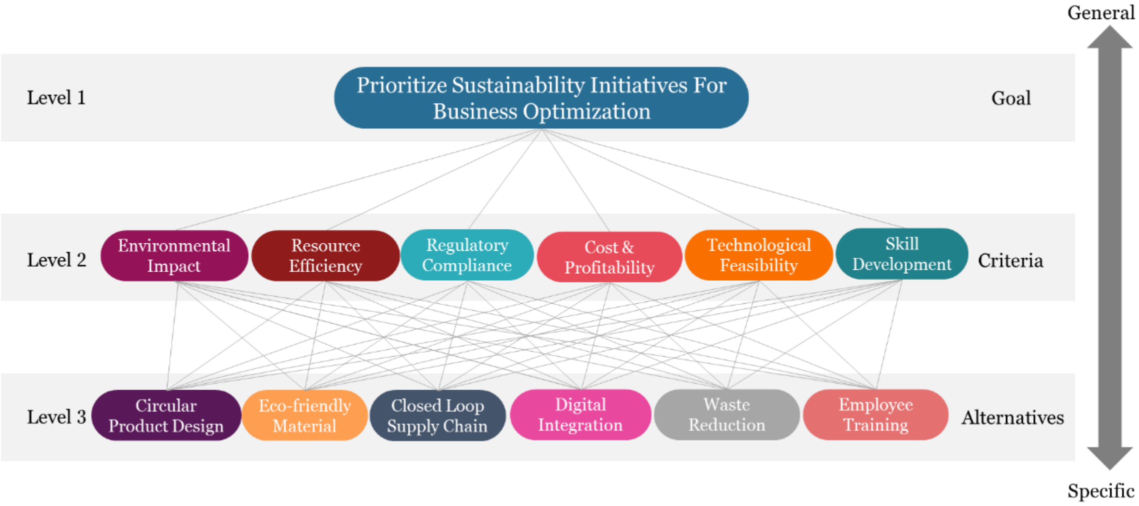
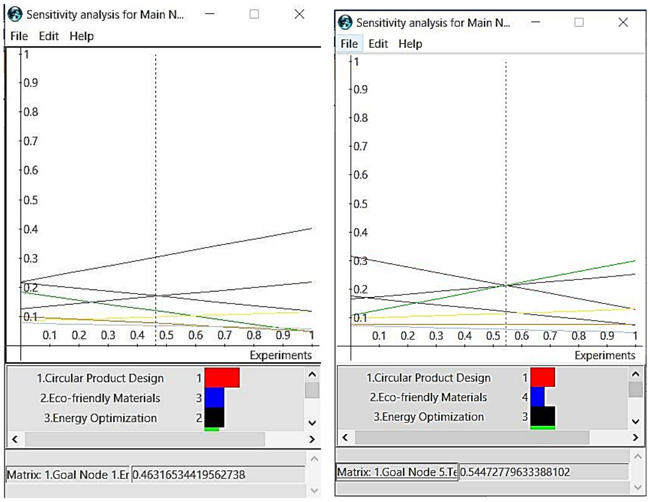


Figure 1. Representation of AHP hierarchy

Sensitivity Analysis for AHP Prioritization

Sensitivity analysis in the AHP reveals the robustness and dynamics of alternative rankings under varying criterion weights as depicted in Figure 2. For Environmental Impact, a rank reversal occurs at a weight of 46%, shifting the top alternative from Eco-Friendly Materials to Circular Product Design. Similarly, for Technological Feasibility, two rank reversals are observed: at 54%, Energy Optimization and Circular Product Design take precedence, while at 59%, the second-best option shifts to Closed-Loop Supply Chain. These results highlight the model's sensitivity to criterion weight changes and the critical thresholds influencing decision priorities.



1.Circular Product Design 1
2.Eco-friendly Materials 3
3.Energy Optimization 2
Matrix: 1.Goal Node 1.Er 0.46316534419562738

1.Circular Product Design 1
2.Eco-friendly Materials 4
3.Energy Optimization 3
Matrix: 1.Goal Node 5.Te 0.54472779633388102

Figure 2. AHP sensitivity analysis for priority fluctuations due to weight variations.

KNIME Workflow Analysis

The results of KNIME regression analysis provide insights into the distribution, variability, and importance of sustainability-related priorities and metrics and its workflow is shown in Figure 3.

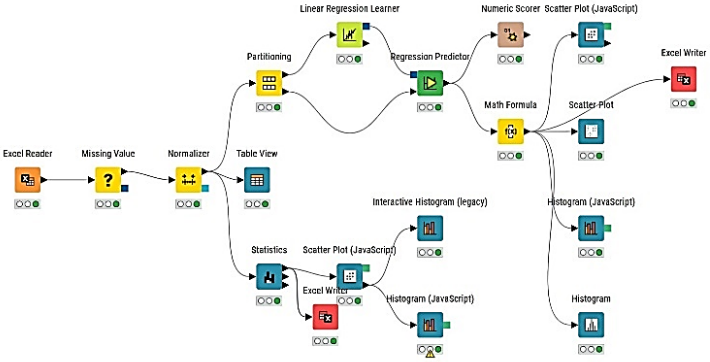


Figure 3. KNIME liner regression model

Among the analyzed attributes, `AHP_Priority_ClosedLoopSupplyChain` (mean = 0.631) received the highest emphasis, while `AHP_Priority_EnergyOptimization` (mean = 0.290) was the least prioritized, indicating areas requiring greater focus. Variability across attributes is evident, with “AHP_Priority_Digital Integration” showing the highest standard deviation (0.316), suggesting diverse responses, while “AHP_Priority_ClosedLoopSupplyChain” exhibited the lowest variability (0.224). Skewness and kurtosis reveal the asymmetry and presence of outliers in certain distributions, such as the right-skewed `AHP_Priority_EnergyOptimization` (skewness = 1.29) and the left-skewed `AHP_Priority_ClosedLoopSupplyChain` (skewness = -0.97) as depicted in Figure 4.

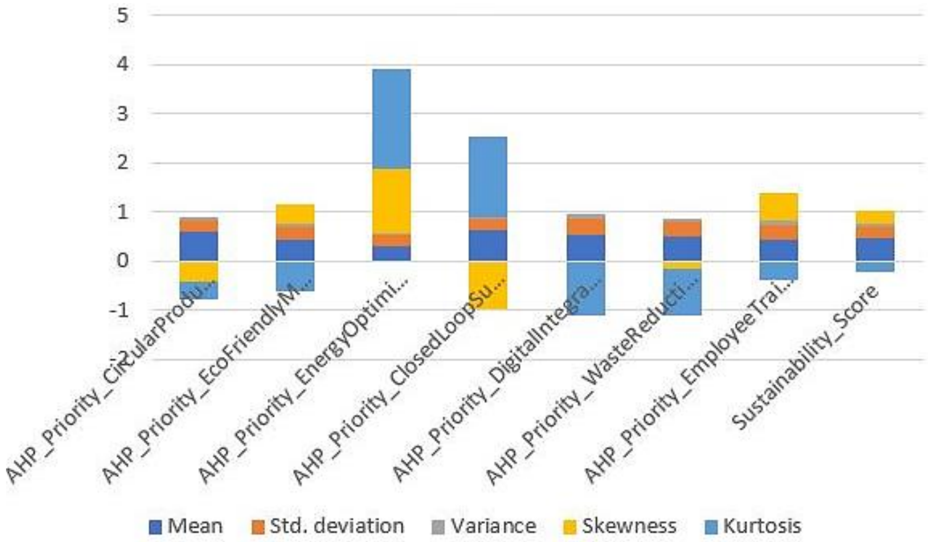


Figure 4. Bar chart of mean priority values for sustainability attributes

The sustainability scores ranged from 0.083 to 1, with higher scores aligning with strong priorities in key areas like energy optimization and closed-loop supply chains. Residual analysis highlights under-prediction (e.g., residual = 0.384) and over-prediction (e.g., residual = -0.186) in specific observations as can be seen in Figure 5. The regression model demonstrated moderate predictive power, explaining 59.7% of the variability in sustainability scores ($R^2 = 0.597$), with low mean absolute error (0.171) and root mean squared error (0.201) indicating reasonable accuracy as described in Table 3. However, variability in predictions (MAPE = 57.78%) suggests room for improvement. These findings underscore the importance of attributes like closed-loop supply chains and circular product design in driving sustainability while highlighting opportunities to enhance predictive modeling and emphasize less prioritized factors like energy optimization.

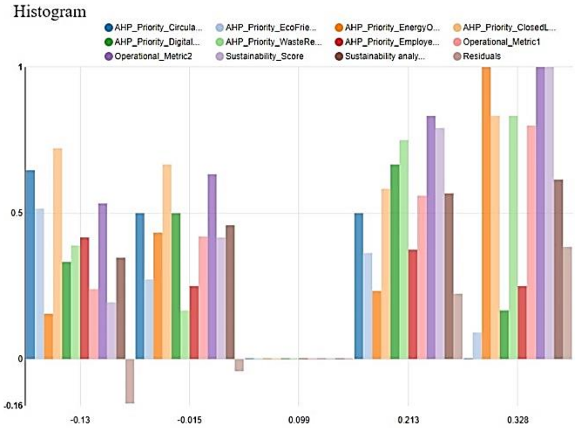


Figure 5. Distribution of differences between actual and predicted sustainability attribute values

Table 3. Eigen analysis for the Covariance Matrix

Factors	Sustainability Analysis
R^2	0.597022
mean absolute error	0.171826
mean squared error	0.040578
root mean squared error	0.201439
mean signed difference	-0.03645
mean absolute percentage error	0.577842
adjusted R^2	2.410424

6. Conclusions

This research develops a hybrid decision-support model that combines AHP with regression analysis to promote sustainable business optimization practices. The model systematically prioritizes key sustainability dimensions, such as Circular Product Design, Eco-Friendly Materials, and Digital Integration, through AHP. The quantitative influence of these factors on an overall Sustainability Score is assessed using regression analysis, providing a comprehensive approach to sustainability evaluation.

The results indicate that Digital Integration ($\beta = 65.9$) and Closed-Loop Supply Chain practices ($\beta = 42.3$) are the most significant predictors of sustainability outcomes, with an adjusted R^2 of 41.93% and a Mean Signed Difference of -0.036. Descriptive statistics show moderate variability in the AHP criteria, with Eco-Friendly Materials having a mean of 0.2373 and a standard deviation of 0.0296. Principal component analysis identifies Environmental Impact and Resource Efficiency as the main drivers of sustainability, together explaining 52.3% of the variance.

This study contributes both theoretically and practically by integrating AHP with regression analysis for sustainability decision-making. It extends the current scholarship by providing a scalable and data-driven decision-support framework that bridges qualitative prioritization and quantitative assessment, addressing a gap where MCDM methods are often isolated from predictive analysis. The inclusion of regression models enhances the predictive power of the framework, offering actionable insights into sustainability optimization. The model has been implemented using the KNIME workflow, demonstrating its practical utility and scalability for real-world applications. The results provide actionable recommendations for businesses aiming to optimize sustainability strategies in alignment with circular economy principles, especially in the European regulatory context.

Future studies will focus on expanding datasets, incorporating advanced predictive analytics, and evaluating the feasibility of proposed systems. Future research will explore the application of this model in different industries to validate its generalizability and further refine the integration of AHP with other analytical methods, such as machine learning or simulation-based optimization. Additionally, studies can focus on enhancing the sensitivity analysis by incorporating more dynamic and real-time data, further improving the robustness and predictive power of the model. This research integrates data-driven tools with sustainability priorities, providing a scalable pathway to operationalize eco-friendly practices and meet evolving global standards, while contributing to decision-support systems for sustainable business optimization through multi-criteria and predictive decision-making frameworks.

7. Limitations

This study's limitations include reliance on a limited dataset, which might not fully capture real-world variability across industries or regions. The assumption of linear relationships in the AHP-regression framework does not fully reflect the complexities of sustainability dynamics, suggesting that non-linear methods or machine learning can improve predictive accuracy. Moreover, qualitative factors like organizational culture and employee engagement were not directly measured, potentially limiting the generalizability of the findings. The model's robustness can be enhanced with real-time data in sensitivity analysis. Future work should focus on expanding the dataset, incorporating advanced techniques like simulation-based optimization or deep learning, and testing the model in diverse industry contexts particularly beyond the European regulatory context.

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