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Green Supplier Selection for Wire Material Procurement in Oil and Gas Manufacturing

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ABSTRACT

This study develops a green supplier selection framework for ERNiCrMo-3 (Inconel 625) welding wire procurement at an oil and gas manufacturer in Indonesia, integrating environmental considerations with conventional operational criteria. A hybrid methodology combining the Delphi method with the Fuzzy Analytical Hierarchy Process (Fuzzy AHP) was applied between September 2024 and March 2025. Three company experts validated the evaluation criteria through a three-round Delphi process, using Coefficient of Variation (CV) and interquartile range (IQR) consensus thresholds (CV below 50%; IQR below 1.0). Fuzzy AHP with Chang's extent analysis then determined criteria weights and ranked four international suppliers from Switzerland, India, South Korea, and Austria. Sixteen sub-criteria were validated across six main categories, with Quality (30%) and Environment (20%) emerging as the most influential. Number of Non-Conformance Reports (21.8%) and Hazardous Material Control (14.2%) achieved perfect consensus (CV = 0.00%; IQR = 0.00) as the top sub-criteria. Supplier A ranked highest (0.427), reflecting balanced performance across all dimensions, while Supplier D ranked lowest (0.147) despite strong environmental performance; sensitivity analysis on the Environment weight (10%-50%) confirmed the stability of this ranking. The findings offer manufacturers a systematic approach to incorporate environmental factors into supplier selection decisions.

1. INTRODUCTION

Global market dynamics have intensified competitive pressures, compelling organizations to optimize efficiency and effectiveness across all operational aspects. As part of this optimization, supply chain management has emerged as a critical domain for achieving competitive advantage, with supplier selection representing a decisive factor that substantially influences organizational performance [1]. Concurrently with these competitive pressures, global awareness of environmentally sustainable business practices has increased substantially, leading to the emergence of green supply chain management (GSCM) as a strategic approach that integrates environmental considerations throughout the entire supply chain [2].

Within the GSCM framework, green supplier selection represents a crucial implementation component that enables organizations to understand complex trade-offs between environmental and conventional criteria, facilitating optimized supply chain decision-making [3]. Through strategic selection of environmentally responsible suppliers, organizations can substantially reduce negative environmental impacts across the supply chain, particularly regarding carbon emissions and pollution reduction [4]. The growing importance of this approach is reflected in global emissions data, where various sectors contribute significantly to greenhouse gas emissions [5], as illustrated in Figure 1.

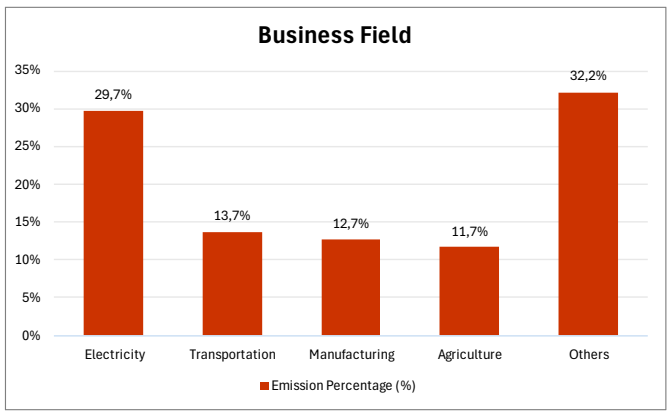


Figure 1. Global greenhouse gas emissions in 2021
Source: Adapted from [5]

Company CBM (pseudonym), an oil and gas manufacturing company in Region Y, Indonesia, specializes in weld overlay and lining for carbon steel pipes. Despite listing sustainability as one of its five core values, a significant gap exists between this commitment and its operational implementation.

Company CBM's current supplier assessments focus exclusively on conventional criteria (Delivery, Quality, problem-solving, engineering) without environmental performance metrics, which is concerning given that 82.5% of its total carbon emissions (70,576 of 85,564 metric tons CO_2e) originate from supply chain activities [6], indicating that carbon reduction strategies should prioritize supply chain management.

The environmental challenge is exemplified by Company CBM's procurement of ERNiCrMo-3 (Inconel 625) wire, an essential consumable material for weld overlay and cladding processes that requires stringent specifications with a chemical composition of 61% nickel, 22% chromium, 9% molybdenum, and 3.5% niobium plus tantalum [7]. Its production generates substantial carbon emissions of 4,940.03 $KgCO_2eq$ per unit with energy consumption reaching 4,205.7 MJ [8]. The environmental impact is further amplified by the global nature of Company CBM's supply chain, with primary manufacturers distributed across Switzerland (Supplier A), India (Supplier B), South Korea (Supplier C), and Austria (Supplier D).

To address this complex challenge systematically, Multi-Criteria Decision Making (MCDM) methods offer effective frameworks for structuring and resolving decision problems involving multiple, often conflicting criteria [9].

Several studies have successfully applied MCDM approaches to green supplier selection across different industries, demonstrating varying priorities depending on sector characteristics and regional contexts. Research in HVAC manufacturing has shown the effectiveness of integrated Delphi–Fuzzy Analytical Hierarchy Process (Delphi–Fuzzy AHP) methodologies [10], while studies in electronics manufacturing have revealed that traditional criteria often dominate environmental factors in developing economies [11]. In upstream oil and gas operations, environmental and safety considerations have emerged as primary criteria due to the high-risk nature of these activities [12].

However, a significant research gap exists in green supplier selection for manufacturing companies in the oil and gas sector, particularly concerning specialized consumable materials with unique technical and environmental characteristics. While existing studies have addressed upstream operations or different industrial sectors, none have examined the specific challenges of procuring high-performance welding consumables that require both stringent technical specifications and comprehensive environmental considerations.

Given these challenges, this research aims to develop a contextual green supplier selection framework for Company CBM's ERNiCrMo-3 wire procurement, combining the Delphi method for expert-validated criteria identification with Fuzzy AHP for systematic evaluation and prioritization of supplier alternatives under judgment uncertainty.

2. LITERATURE REVIEW

2.1 Green supply chain management

Supply chain management represents an integrated approach to managing the flow of goods, information, and finances from suppliers to end consumers. Supply chain management can be defined as the management of upstream and downstream supplier and customer relationships to deliver superior value at lower cost across the chain [13].

Traditional supply chains facilitate raw material flows through suppliers, manufacturers, and distributors before reaching retailers and consumers [14]. Growing recognition of the limits of traditional supply chains has prompted organizations to develop more responsive and sustainable supply chain systems [15].

This evolution has led to the emergence of GSCM. GSCM is defined as the integration of environmental thinking into supply chain management, from product design to post-consumption management, elevating environmental aspects to equal importance with operational efficiency and cost [16].

GSCM incorporates environmentally friendly practices at each process stage throughout the supply chain [17]. Although implementation requires significant initial investment and organizational adaptation, GSCM practices reduce operational costs and improve service quality over the long term, strengthening competitive advantage [15].

2.2 Green supplier selection

Supplier selection represents one of the most strategic decisions in supply chain management. Supplier selection can be defined as identifying suppliers capable of providing the right quality at the right price, quantity, and time, a decision that significantly impacts a company's competitive advantage [15, 18].

Green supplier selection has become increasingly important [19]. Growing pressure to integrate environmental considerations has made green supplier selection a critical practice extending beyond conventional criteria to include environmental performance metrics.

Green supplier selection aims to identify suppliers who excel in traditional areas (Quality, Cost, Delivery) while also demonstrating strong environmental credentials. Effective green supplier selection enables companies to reduce costs and enhance both sustainability performance and customer satisfaction [19].

Recent studies (2020-2025) confirm the growing methodological maturity of green supplier selection research: interval type-2 Fuzzy AHP has been applied for a home appliance manufacturer [20], Pythagorean Fuzzy AHP has been combined with fuzzy TOPSIS [21], and a decision support system has been developed for circular-economy supplier selection [22]. In oil and gas, environmental and safety criteria have been found to dominate upstream contractor selection [12]. Applications addressing high-performance consumables such as nickel-based welding wires remain scarce, which reinforces the research gap addressed in this study.

2.3 Multi-criteria decision making

MCDM is a specialized branch of operations research that focuses on methods and procedures for handling decision problems involving several conflicting criteria. MCDM is the decision-making process in conditions where various criteria must be considered simultaneously to select the best alternative from a series of available alternatives [9].

In multi-criteria decision contexts [23], multiple criteria are typically weighed simultaneously rather than sequentially. This is especially relevant for green supplier selection, where

decision-makers must concurrently evaluate Quality, Cost, Delivery time, and environmental aspects.

One of the principal advantages of MCDM is its ability to accommodate both quantitative and qualitative criteria in the decision-making process. MCDM provides a comprehensive framework for structuring complex decision problems, measuring the relative importance of each criterion, and systematically evaluating available alternatives against multiple dimensions simultaneously [9].

2.4 Fuzzy Analytical Hierarchy Process

AHP is a widely recognized multi-criteria decision-making method used to determine criteria weights and alternative priorities through pairwise comparisons [24]. Despite its effectiveness in structuring complex decisions, conventional AHP faces limitations when addressing problems involving uncertainty in human judgment.

To overcome these limitations, linguistic variables were introduced to better represent subjective assessments in decision-making processes [25].

In Fuzzy AHP implementation, pairwise comparison assessments are represented using Triangular Fuzzy Numbers (TFN) [26]. A TFN is represented as (l, m, u), where l is the lower value, m is the modal value, and u is the upper value. This approach captures the inherent ambiguity in expert judgments more effectively than conventional crisp values, thereby improving decision reliability.

A scale system for converting linguistic assessments into fuzzy numbers was developed in the study [27] and subsequently refined in the study [28], which proposed five more structured basic assessment levels. The linguistic scale and its corresponding TFN values are shown in Table 1.

Table 1. Linguistic scale membership function

Fuzzy Number	Linguistic Scale	Triangular Fuzzy Numbers (TFN)
1	Equally important	(1, 1, 3)
3	Weakly important	(1, 3, 5)
5	Essentially important	(3, 5, 7)
7	Very strongly important	(5, 7, 9)
9	Absolutely important	(7, 9, 9)

Source: Adapted from previous studies [27, 28].

The implementation of Fuzzy AHP involves the following systematic procedure:

(1) Hierarchical Structure Development

The decision problem is structured into a hierarchy with goal, criteria, and alternatives.

(2) Expert Judgment Aggregation

Expert assessments collected through pairwise comparison questionnaires are aggregated using geometric means to obtain consensus values:

$$\left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 . x_2 . x_3 \dots x_n} \quad (1)$$

where, x_1, x_2, … x_n are individual expert assessment values and n is the number of experts.

(3) Pairwise Comparison Matrix

The aggregated assessments are used to form pairwise comparison matrices, structured as illustrated in Table 2, where a_{ij} represents the relative importance of criterion i compared to criterion j. For consistent matrices: $a_{ii} = 1$ and $a_{ji} = 1/a_{ij}$.

(4) Consistency Testing

Assessment consistency is verified using the Consistency Index (CI):

$$CI = \frac{(\lambda_{max} - n)}{(n - 1)} \quad (2)$$

And the Consistency Ratio (CR):

$$CR = \frac{CI}{RI} \quad (3)$$

where, λ_{max} is the maximum eigenvalue, n is the number of criteria, and RI is the Random Consistency Index (values shown in Table 3). For reliable results, CR must be ≤ 0.1.

Table 2. Pairwise comparison

C	A_1	A_2	…..	A_n
A_1	a_{11}	a_{12}		a_{1n}
A_2	a_{21}	a_{22}		a_{2n}
A_3	a_{31}	a_{32}		a_{3n}
…..	…..	…..		…..
A_n	a_{n1}	a_{n2}	…..	a_{nn}

Table 3 Random index (RI) values

n	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41

(5) Triangular Fuzzy Number Transformation

After obtaining a consistent matrix, crisp values are converted to fuzzy numbers using the TFN scale presented in Table 1.

(6) Criteria Weights Determination

Final criteria weights are determined using Chang's extent analysis method through calculation of fuzzy synthetic extent values, comparison of fuzzy numbers, determination of priority vectors, and normalization of weight vectors [29].

2.5 Delphi method

The Delphi method is a structured approach for facilitating group communication, allowing experts to address complex problems through a systematic process of consensus building [30]. Developed by the RAND Corporation in the early 1950s, this technique was designed to obtain reliable consensus from expert panels through sequential questionnaires with controlled feedback between rounds [31].

Research indicates that while the Delphi process can theoretically extend to multiple iterations, three rounds typically provide optimal results [30]. The procedure follows a distinct progression: the first round explores the topic through open-ended inquiries; the second round develops collective understanding through structured feedback; and the third round focuses on refining positions to either achieve consensus or clearly delineate persistent differences.

For quantifying consensus in Delphi studies, the literature identifies two particularly effective statistical measures: the interquartile range (IQR) and Coefficient of Variation (CV) [32]. This review establishes that criteria with IQR < 1.0 and CV < 50% demonstrate strong consensus among experts. When these values approach zero while maintaining high mean ratings, they indicate both high relevance and strong agreement among expert participants.

3. RESEARCH METHOD

This study employed a mixed-methods research design to develop a contextual green supplier selection framework for ERNiCrMo-3 wire material procurement at Company CBM. Conducted from September 2024 to March 2025 in Region Y (pseudonym), Indonesia, the research integrated qualitative case study using Delphi method for expert consensus building, and descriptive quantitative using Fuzzy AHP for mathematical analysis and supplier ranking.

Expert selection employed purposive sampling technique based on expertise criteria and direct involvement in procurement processes, supply chain management, and corporate sustainability aspects. Three key experts were purposively selected from Company CBM: a Supplier Quality Assistant Manager, a Procurement Engineering Specialist, and an ESG Specialist, ensuring comprehensive coverage of technical, operational, and environmental aspects critical to green supplier selection decision-making.

The experts were selected according to three predefined criteria: (i) a minimum of five years of professional experience in the relevant field; (ii) direct involvement in ERNiCrMo-3 wire procurement, supplier evaluation, or corporate sustainability activities at Company CBM; and (iii) willingness to participate in all three Delphi rounds and the subsequent pairwise comparison stage. The profiles of the three experts and the justification for their selection are summarized in Table 4.

Data collection employed a multi-method strategy combining semi-structured interviews, document analysis of company procurement records and supplier evaluation documentation, Delphi method questionnaires, and pairwise comparison questionnaires. Supplier performance data was gathered through company historical records, supplier documentation, and expert assessments based on direct procurement experience.

Table 4. Expert panel profile and selection justification

Expert	Position	Experience (Years)	Field of Expertise	Perspective Contributed
E1	Supplier Quality Assistant Manager	12	Supplier quality management and audit	Technical and quality
E2	Procurement Engineering Specialist	9	Procurement of welding consumables	Operational procurement
E3	ESG Specialist	7	Corporate sustainability and ESG reporting	Environmental and sustainability

All Delphi consensus statistics and Fuzzy AHP computations were performed in Microsoft Excel (Microsoft 365) on a notebook computer equipped with an Intel Core i5 processor (2.40 GHz) and 8 GB of RAM running Windows 11. Owing to the limited matrix dimensions (a maximum of 6 × 6), each complete computation cycle, covering consistency testing, fuzzy transformation, extent analysis, and sensitivity recalculation, required less than one minute of runtime, and no specialized hardware or software is needed to reproduce the results.

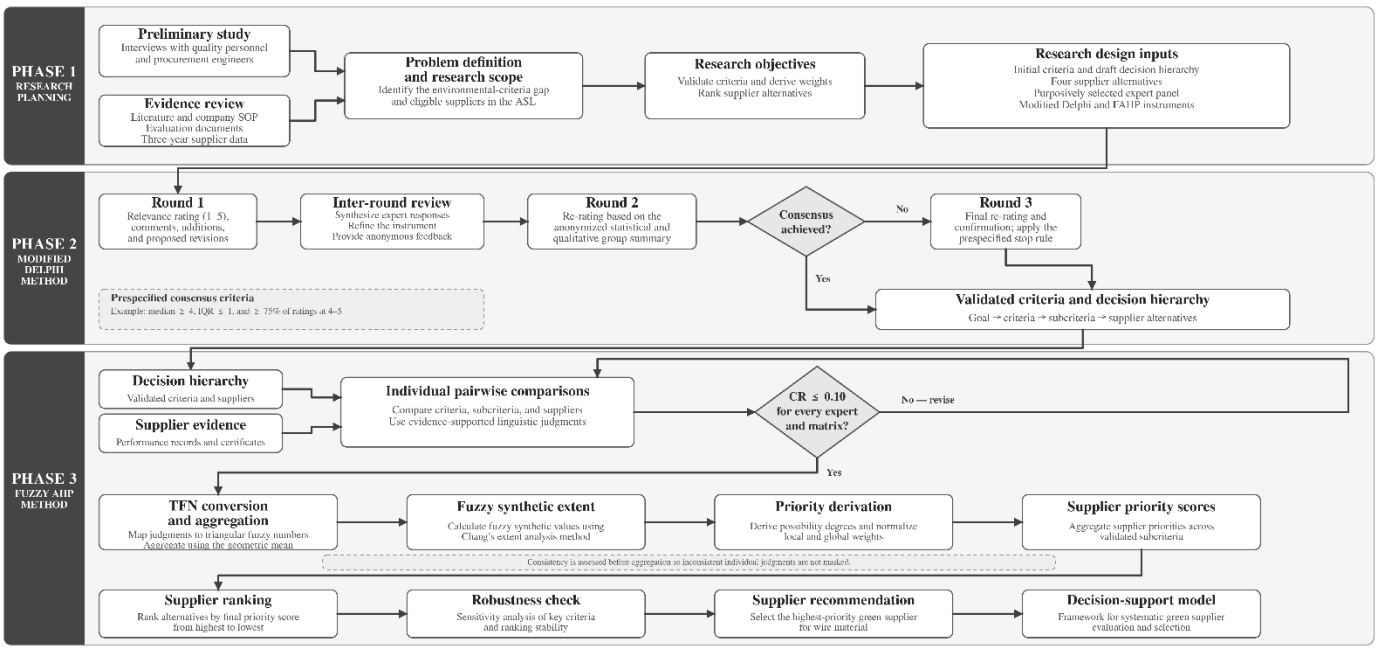


Figure 2. Research framework

The research framework, illustrated in Figure 2, follows a systematic three-phase methodology comprising planning, data collection and validation, and analysis and decision-making. The first phase encompassed preliminary study and problem identification through literature review and initial interviews, revealing the gap between the company's

sustainability commitments and existing supplier evaluation practices. The second phase implemented a three-round Delphi method to validate and refine green supplier selection criteria through expert consensus. Starting with an initial set of criteria derived from literature and company procurement documentation, the process refined these through iterative expert feedback until consensus was achieved on the final criteria set.

The third phase applied Fuzzy AHP to determine criteria weights and evaluate alternative suppliers. Four wire material suppliers; Supplier A (Switzerland), Supplier B (India), Supplier C (South Korea), and Supplier D (Austria), were evaluated against the established criteria framework. Through this structured approach, environmental considerations were integrated into the supplier selection process, and the suppliers were ranked according to overall performance scores that balance conventional operational metrics with environmental indicators.

To complement the narrative description of the methodology, Figure 3 presents a simplified flowchart of the integrated Delphi–Fuzzy AHP procedure, showing the inputs, the expert assessment nodes, and the outputs of each stage.

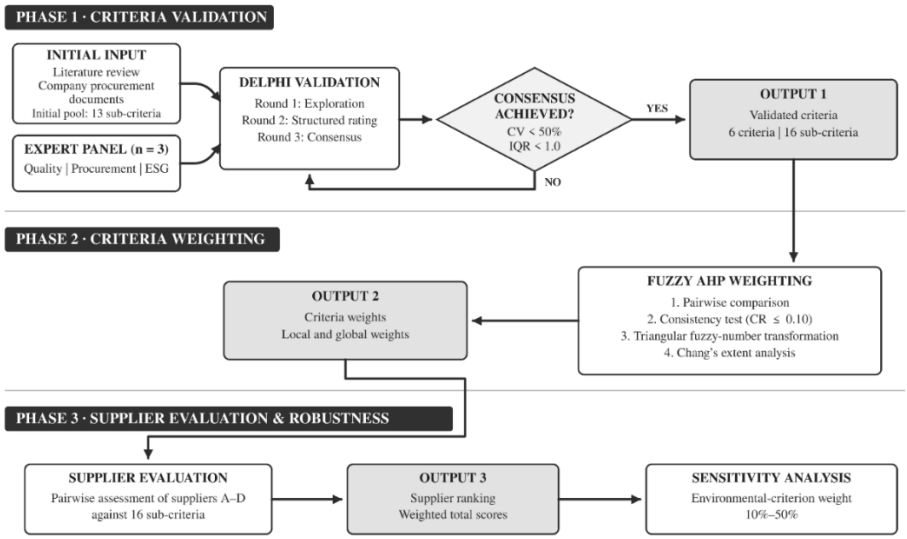


Figure 1. Integrated Delphi–Fuzzy AHP procedure

4. RESULTS AND DISCUSSION

4.1 Initial criteria identification

Table 4. Initial green supplier selection criteria

Criteria	Sub-Criteria	Source
Quality	Number of Non-Conformance Reports (NCR)	CBM's Procurement
	Response Time to NCR	CBM's Procurement
	Quality Certification	[12]
Cost	Product Cost	CBM's Procurement
	Payment Terms	[26]
Delivery	On-Time Delivery	CBM's Procurement
	Accuracy	CBM's Procurement
	Lead Time	[10]
Problem Solving	Response Time to Problem	CBM's Procurement
	Problem Resolution Time	CBM's Procurement
	Technical Support	[33]
Environment	Environmental Certification	[34]
	Hazardous Material Control	[11]

Initial criteria were identified through literature review and analysis of Company CBM's internal documentation. As shown in Table 5, these were organized across five main categories spanning operational and environmental considerations. Within Quality, the Number of Non-Conformance Reports (NCR) denotes the count of formal reports issued when delivered material deviates from specification.

4.2 Delphi results

The Delphi process ran over three rounds with three Company CBM experts (a Supplier Quality Assistant Manager, a Procurement Engineering Specialist, and an ESG Specialist), who iteratively evaluated, refined, and validated the initial criteria set.

(1) Criteria exploration and expansion

The first round used open-ended inquiries to gather expert input on ERNiCrMo-3 wire procurement, leading to contextual adjustments. Based on their feedback, the framework expanded from 13 to 16 sub-criteria across six main categories. This included a new main criterion, Technical Requirements (with sub-criteria: Chemical Composition and Packaging Conditions), and an added sub-criterion, Environmental Product Declaration, under the Environment category.

(2) Structured evaluation and refinement

The second round developed collective understanding through structured feedback using rating questionnaires, where experts evaluated the refined 16-criteria framework and provided justifications for their assessments using structured evaluation scales.

(3) Consensus achievement

The third round focused on refining positions to achieve

consensus through final validation ratings, with experts reconsidering their assessments based on group feedback from previous rounds. Final results are shown in Table 6.

The statistical analysis demonstrated consensus achievement for all criteria, as evidenced by low CV values (all below 12%) and IQR values (all < 1.0). The “Number of NCR" and "Hazardous Material Control" achieved perfect consensus (CV = 0.00%, IQR = 0.00), highlighting the equal weight experts placed on quality control and environmental safety.

4.3 Fuzzy AHP results

After Delphi validation, Fuzzy AHP was used to weight the criteria and evaluate supplier performance within a consistent methodological framework.

(1) Decision Hierarchy

A hierarchical decision structure was constructed as shown in Figure 4, organizing the validated 16 sub-criteria across six main categories.

(2) Pairwise Comparison

The same three experts performed pairwise comparisons at both main-criteria and sub-criteria levels, using linguistic terms such as "Equally Important," "Weakly Important," or "Essentially Important."

Individual expert assessments were converted to crisp values and aggregated using geometric means to obtain group consensus while maintaining mathematical consistency. The consolidated main criteria pairwise comparisons are presented in Table 7.

Table 5. Final validated criteria from Delphi process

Criteria	Sub-Criteria	Coefficient of Variation (CV)	Interquartile Range (IQR)	Consensus
Quality	Number of Non-Conformance Reports (NCR)	0.00%	0.00	Achieved
	Response Time to NCR	9.12%	0.25	Achieved
	Quality Certification	9.12%	0.25	Achieved
Cost	Price	10.19%	0.25	Achieved
	Payment Terms	11.55%	0.25	Achieved
Delivery	On-Time Delivery	9.12%	0.25	Achieved
	Accuracy	9.12%	0.25	Achieved
	Lead Time	9.12%	0.25	Achieved
Problem Solving	Response Time to Problem	9.12%	0.25	Achieved
	Problem Resolution Time	9.12%	0.25	Achieved
	Technical Support	11.11%	1.00	Achieved
Environment	Environmental Certification	11.11%	1.00	Achieved
	Hazardous Material Control	0.00%	0.00	Achieved
	Environmental Product Declaration	11.11%	1.00	Achieved
Technical Requirements	Chemical Composition	9.12%	0.25	Achieved
	Packaging Conditions	10.19%	0.25	Achieved

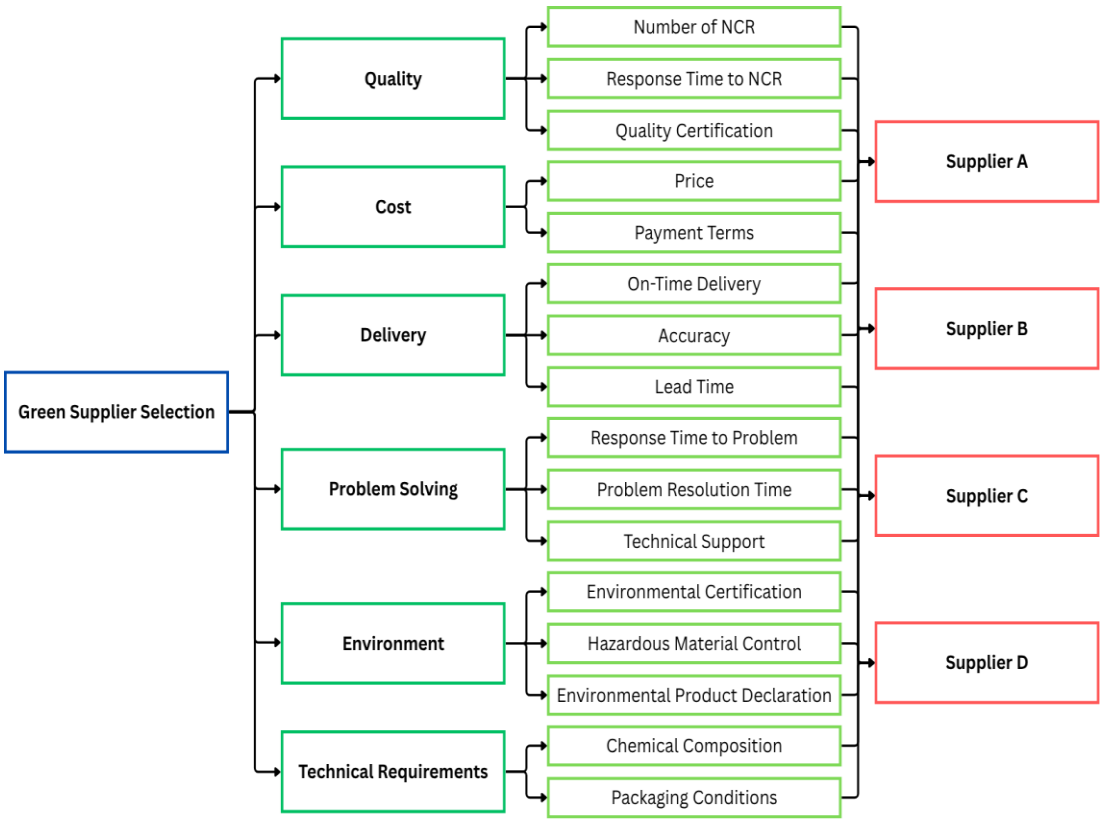


Figure 4. Hierarchical decision structure

Table 6. Pairwise comparison: Main criteria

Criteria	Quality	Cost	Delivery	Problem Solving	Environment	Technical Requirements
Quality	1.00	4.33	3.56	1.75	2.76	1.57
Cost	0.23	1.00	1.44	0.43	0.48	0.48
Delivery	0.28	0.69	1.00	0.82	0.69	0.82
Problem Solving	0.57	2.33	1.22	1.00	0.69	1.19
Environment	0.36	2.08	1.44	1.44	1.00	3.27
Technical Requirements	0.64	2.08	1.22	0.84	0.31	1.00

Note: Values are the geometric means of the three expert judgements, rounded to two decimals for presentation. The consistency statistics in Table 8 were computed from the unrounded matrix.

(3) Consistency Validation

To ensure the reliability and validity of expert judgments, consistency ratios were calculated for each comparison matrix using the standard AHP consistency testing procedure. The consistency validation results across all comparison matrices are summarized in Table 8.

Table 7. Consistency ratio (CR) testing results

Comparison Matrix	λ_{max}	CI	CR	Result
Main Criteria	6.299	0.060	0.048	Consistent
Quality	3.003	0.002	0.003	Consistent
Cost	2.000	0.000	0.000	Consistent
Delivery	3.020	0.010	0.017	Consistent
Problem Solving	3.015	0.007	0.013	Consistent
Environment	3.025	0.013	0.022	Consistent
Technical Requirements	2.000	0.000	0.000	Consistent

All comparison matrices showed acceptable consistency ratios (CR < 0.1), confirming the validity of expert judgments; the CR = 0.000 for Cost and Technical Requirements reflects the inherent consistency of 2 × 2 matrices. Assessments were thus sufficiently consistent to proceed with fuzzy transformation.

(4) Fuzzy Transformation

With validated matrices, aggregated crisp values were transformed into TFN using the linguistic scale from Table 1, capturing judgment uncertainty while preserving relative importance. Prior to this conversion, each aggregated value was first mapped to the nearest point of the fundamental AHP scale (for example, 4.33 was mapped to 5), so that the linguistic scale in Table 1 could be applied. Representative examples of the crisp-to-TFN transformation process are illustrated in Table 9.

Table 8. Examples of Triangular Fuzzy Numbers (TFN) transformation

Comparison	Crisp Value	TFN Value
Quality vs Cost	5.00	(3,5,7)
Quality vs Environment	3.00	(1,3,5)
Delivery vs Cost	1.00	(1,1,3)

Note: These examples represent the systematic transformation applied to all pairwise comparison values.

(5) Weight Calculation

Final criteria weights were determined using Chang's extent analysis, which processes TFN values through fuzzy synthetic extent calculation, fuzzy-number comparison, priority-vector determination, and weight normalization, yielding crisp weights from fuzzy inputs. The main criteria are shown in Table 10.

The weight distribution shows Quality (30%) as the highest priority, followed by Environment (20%), reflecting a balanced integration of operational excellence and sustainability, with cost secondary to quality and environmental performance.

Table 9. Main criteria weights

Main Criteria	Weight
Quality	0.30
Cost	0.08
Delivery	0.10
Problem Solving	0.17
Environment	0.20
Technical Requirements	0.14

Note: Weights are rounded to two decimals for presentation; the unrounded weights (0.296, 0.080, 0.103, 0.174, 0.203 and 0.144) sum to 1.000, as reflected in the global weights reported for the sub-criteria.

Local and global weights for all sub-criteria were calculated using the same methodology, as presented in Table 11.

Table 10. Sub-criteria weights

Main Criteria	Local Weight	Sub-Criteria	Local Weight	Global Weight
Quality	0.30	Number of NCR	0.73	0.218
		Response time to NCR	0.15	0.046
		Quality certification	0.11	0.033
Cost	0.08	Price	0.87	0.070
		Payment terms	0.13	0.010
Delivery	0.10	On-time delivery	0.52	0.053
		Accuracy	0.36	0.037
		Lead time	0.12	0.013
Problem Solving	0.17	Response time to problem	0.40	0.070
		Problem resolution time	0.33	0.056
		Technical support	0.27	0.047
Environment	0.20	Environmental certification	0.17	0.034
		Hazardous material control	0.70	0.142
		Environmental product declaration	0.13	0.027
Technical Requirements	0.14	Chemical composition	0.83	0.119
		Packaging conditions	0.17	0.025

Analysis of global weights reveals that "Number of NCR" (21.8%) emerged as the single most critical evaluation factor, followed by "Hazardous Material Control" (14.2%) and "Chemical Composition" (11.9%). This ranking underscores three insights: quality consistency through non-conformance control is the paramount procurement concern; environmental safety protocols are equally critical to operational success; and technical specification compliance remains essential for

specialized materials requiring precise chemical compositions.

(6) Supplier Evaluation

The four wire material suppliers, namely Supplier A (Switzerland), Supplier B (India), Supplier C (South Korea), and Supplier D (Austria), were systematically evaluated against the established criteria framework. Following the identical Fuzzy AHP process used for criteria weighing, experts performed pairwise comparisons of suppliers against each sub-criterion, with results processed through consistency testing, fuzzy transformation, and Chang's extent analysis to derive performance scores. These scores were multiplied by their global weights (Table 11) to produce the weighted performance results presented in Table 12.

The performance evaluation reveals significant variation in supplier capabilities across criteria dimensions. Supplier A shows exceptional strength in quality criteria, excelling in "Number of NCR" and "Chemical Composition" (the two most heavily weighted criteria); Supplier D performs strongly in "Hazardous Material Control," reflecting robust environmental safety protocols; and Supplier C shows advantages in delivery-related metrics.

Aggregated weighted scores across sub-criteria determined total performance and final rankings, as shown in Table 13 and visualized in Figure 5.

Table 11. Supplier performance evaluation

Sub-Criteria	Supplier A	Supplier B	Supplier C	Supplier D
Number of NCR	0.106	0.050	0.042	0.019
Response Time to NCR	0.013	0.025	0.006	0.003
Quality Certification	0.015	0.013	0.003	0.001
Price	0.027	0.019	0.017	0.007
Payment Terms	0.003	0.001	0.006	0.001
On-Time Delivery	0.012	0.012	0.026	0.004
Accuracy	0.003	0.014	0.013	0.007
Lead Time	0.002	0.002	0.008	0.001
Response Time to Problem	0.039	0.012	0.013	0.005
Problem Resolution Time	0.027	0.019	0.008	0.004
Technical Support	0.024	0.015	0.005	0.002
Environmental Certification	0.019	0.009	0.002	0.004
Hazardous Material Control	0.039	0.018	0.008	0.078
Environmental Product Declaration	0.005	0.017	0.003	0.002
Chemical Composition	0.079	0.022	0.010	0.007
Packaging Conditions	0.014	0.006	0.002	0.002

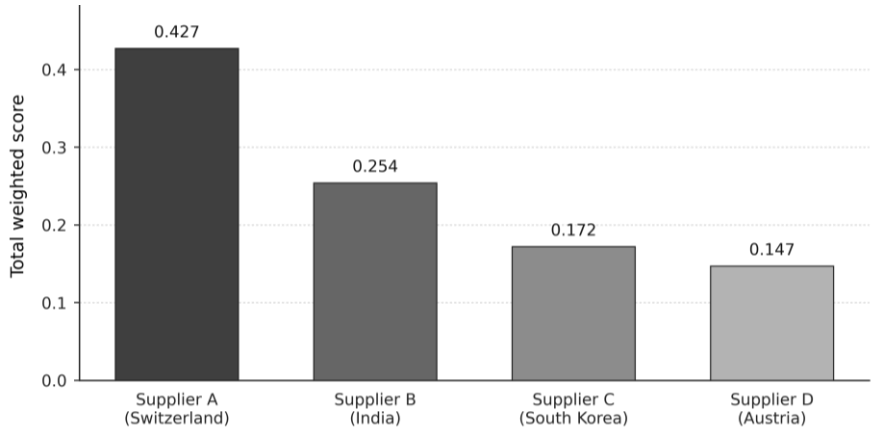


Figure 5. Comparison of total weighted performance scores of the four suppliers

Table 12. Final supplier ranking

Alternative	Total Score	Rank
Supplier A	0.427	1
Supplier B	0.254	2
Supplier C	0.172	3
Supplier D	0.147	4

The final rankings place Supplier A (Switzerland) highest (0.427), driven by strong performance in quality control ("Number of NCR" at 0.106), problem-solving, and technical requirements ("Chemical Composition" at 0.079).

Supplier B (India) ranked second (0.254) with balanced performance, and Supplier C (South Korea) third (0.172) on delivery strengths such as "On-Time Delivery" (0.026). Supplier D (Austria) ranked fourth (0.147); despite the strongest "Hazardous Material Control" score (0.078), its overall ranking was pulled down by weaker quality and technical performance.

Supplier A is therefore recommended as the primary supplier for ERNiCrMo-3 wire, offering the balance of quality, environmental performance, and technical capability that best aligns with Company CBM's green supply chain objectives and long-term sustainability goals.

4.4 Sensitivity analysis

To validate the robustness of the green supplier selection framework, sensitivity analysis was conducted by varying the Environment criterion weight from 10% to 50%. While prior research conducted sensitivity analysis by varying the most dominant criterion to test model stability [35], this study

introduces an alternative scenario exploring how environmental prioritization influences green supplier selection outcomes, directly addressing the thematic focus of this research.

The analysis examines five scenarios with Environment criterion weights of 10%, 20% (original), 30%, 40%, and 50%. In each case, the remaining criteria, namely Quality, Problem Solving, Technical Requirements, Delivery, and Cost, were proportionally adjusted to maintain a total of 100%. In each scenario, when the Environment weight was assigned a new value, the weight of every remaining criterion was reallocated proportionally to its original share according to Eq. (4). This proportional reallocation preserves the relative importance structure among the non-environmental criteria established by the experts, guarantees that all weights sum to unity, and thereby ensures consistency across scenarios and fair comparison of supplier rankings. Adjusted weight distributions for each scenario are shown in Table 14.

$$w_j' = w_j \times (1 - w_E') / (1 - w_E) \quad (4)$$

where, w_j and w_j' denote the original and adjusted weights of criterion j, respectively, $w_E = 0.203$ is the original Environment weight, and w_E' is the Environment weight assigned in the scenario.

Using these adjusted weights, new global weights were calculated for all 16 sub-criteria by multiplying the adjusted main criteria weights with their respective local sub-criteria weights. Subsequently, supplier performance scores were recalculated and rankings determined for each scenario. Table 15 presents the supplier ranking results under sensitivity analysis, and Figure 6 visualizes the corresponding score trajectories.

Table 14. Main criteria weight variations for sensitivity analysis

Environment	Quality	Problem Solving	Technical Requirements	Delivery	Cost	Total
0.10	0.33	0.20	0.16	0.12	0.09	1.00
0.20 (Original)	0.30	0.17	0.14	0.10	0.08	1.00
0.30	0.26	0.15	0.13	0.09	0.07	1.00
0.40	0.22	0.13	0.11	0.08	0.06	1.00
0.50	0.19	0.11	0.09	0.06	0.05	1.00

Note: Weights are rounded to two decimals for presentation; each scenario sums to 1.000 before rounding, and the Total column reports the unrounded sum.

Table 13. Supplier ranking results under sensitivity analysis

Environmental Weight	Supplier A	Supplier B	Supplier C	Supplier D	Ranking
0.10	0.443	0.259	0.186	0.112	A-B-C-D
0.20 (Original)	0.427	0.254	0.172	0.147	A-B-C-D
0.30	0.413	0.250	0.158	0.179	A-B-D-C
0.40	0.398	0.245	0.145	0.212	A-B-D-C
0.50	0.383	0.240	0.131	0.246	A-D-B-C

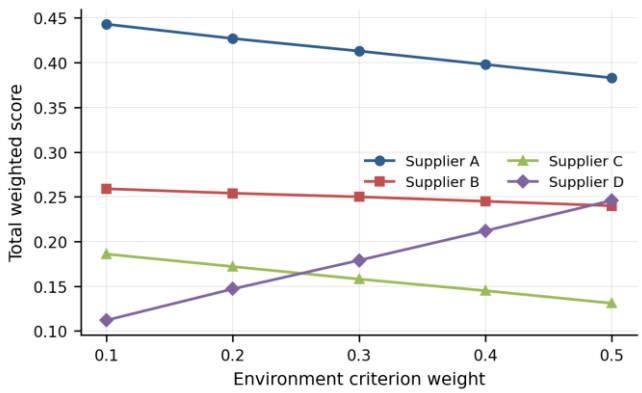


Figure 2. Supplier score trajectories under Environment weight variation

The results show that Supplier A maintains the top ranking across all scenarios, indicating the stability of the green supplier selection framework. This consistency occurs not because Supplier A excels primarily in environmental criteria, but because it demonstrates balanced performance across quality, technical, and environmental dimensions. Supplier A's performance includes strong quality control (Number of NCR: 0.106) and technical precision (Chemical Composition: 0.079) while maintaining solid environmental performance across all green criteria. This balanced profile represents the characteristics of an effective green supplier who can deliver operational reliability alongside environmental considerations.

The analysis reveals an important insight into green supplier selection: while Supplier D achieves the highest individual environmental performance (Hazardous Material Control: 0.078) and rises to second position when Environment weight reaches 50%, it does not surpass Supplier A's overall green supplier profile. This outcome illustrates that effective green supplier selection requires identifying suppliers who can deliver both operational excellence and environmental stewardship, rather than focusing solely on environmental performance. The ranking changes become apparent starting at the 30% Environment weight threshold, suggesting this as a point where environmental considerations begin to substantially influence supplier selection outcomes while still maintaining the overall ranking hierarchy.

The mechanisms behind these ranking shifts can be explained by the structure of each supplier's performance profile. Supplier D's total score rises steeply (from 0.112 to 0.246) because its performance is concentrated in Hazardous Material Control (0.078), the most heavily weighted environmental sub-criterion, so every increase in the Environment weight amplifies its strongest dimension. Conversely, Supplier C declines (from 0.186 to 0.131) because its comparative advantage lies in Delivery-related sub-criteria, whose weights shrink as the Environment weight expands, while Supplier B remains nearly constant owing to its evenly distributed performance. From a decision-making perspective, the crossover between Suppliers C and D at the 30% threshold, and between Suppliers B and D at the 50% threshold, indicates that organizations with strong environmental mandates, for

example those facing strict emission-reduction targets, may reach different sourcing decisions for lower-ranked suppliers even though the identity of the best supplier remains robust. Decision-makers can therefore treat the 30% Environment weight as a practical tipping point when calibrating procurement policies to corporate sustainability ambitions.

These findings support the green supplier selection framework's approach, where optimal results emerge from comprehensive green supplier capabilities rather than narrow environmental focus alone. The framework's ability to maintain ranking stability while accommodating varying environmental priorities provides practical guidance for organizations implementing green supplier selection strategies in oil and gas manufacturing contexts. The stability of Supplier A's position across different weighting scenarios demonstrates that the framework successfully identifies suppliers with the multidimensional excellence required for sustainable procurement in oil and gas manufacturing.

4.5 Discussion

The findings demonstrate that environmental considerations can be systematically integrated into supplier selection for specialized materials in oil and gas manufacturing through structured multi-criteria frameworks. The Delphi process successfully validated 16 sub-criteria across six main categories, with Quality (30%) and Environment (20%) emerging as the most critical dimensions. The achievement of perfect expert consensus (CV = 0.00%, IQR = 0.00) for both Number of NCR (21.8%) and Hazardous Material Control (14.2%) substantiates the equal importance experts attribute to quality control and environmental safety in specialized wire material procurement, reflecting the fundamental principles of GSCM that emphasize embedding environmental considerations throughout procurement processes [16].

Analysis reveals a discrepancy: experts prioritized environmental performance, yet Company CBM's current procurement framework excludes environmental metrics entirely, a gap consistent with GSCM literature on the difficulty of translating strategic sustainability awareness into procurement practice [2]. The developed Delphi–Fuzzy AHP framework addresses this critical gap by systematically transforming qualitative expert insights including Hazardous Material Control, Environmental Certification, and Environmental Product Declarations into quantified evaluation weights that can be directly implemented in supplier selection processes.

The Fuzzy AHP results further substantiate the multidimensional nature of green supplier performance. Supplier D achieved the highest individual score for Hazardous Material Control (0.078) yet ranked lowest overall (0.147) due to comparatively weaker performance in quality and technical criteria. Conversely, Supplier A demonstrated a well-balanced profile, achieving a cumulative score of 0.063 across all environmental sub-criteria while excelling in Number of NCR (0.106) and Chemical Composition (0.079). This outcome aligns with prior findings [11], which emphasize that effective green suppliers must integrate environmental stewardship with robust quality and technical performance rather than relying on single-dimension excellence.

Sensitivity analysis further validates these findings through systematic variation of Environment criterion weight from 10% to 50%. The consistent maintenance of Supplier A's top ranking, even when Environment weight reached 50%, demonstrates that optimal green supplier selection emerges from comprehensive multidimensional capabilities rather than narrow environmental focus. This stability corresponds with prior research [12], which reported that environmental and safety criteria collectively dominate supplier evaluation in oil and gas industries due to stringent regulatory requirements, elevated operational risks, and the imperative to minimize environmental hazards.

These findings underscore the critical need for Company CBM to integrate environmental metrics into its supplier evaluation processes, particularly given that 82.5% of the company's emissions originate from supply chain activities.

The integrated results confirm that effective green supplier selection requires balanced excellence across operational and environmental dimensions rather than isolated environmental optimization, positioning Company CBM to develop a transparent, data-driven, sustainability-oriented supplier evaluation system.

5. CONCLUSION

This research successfully develops and validates a novel Delphi–Fuzzy AHP framework that addresses a critical implementation gap in green supplier selection for oil and gas manufacturing. The integrated methodology systematically validates 16 sub-criteria across six main categories—Quality, Environment, Problem Solving, Technical Requirements, Delivery, and Cost—with Quality (30%) and Environment (20%) identified as the most influential dimensions. The achievement of perfect expert consensus for Number of NCR (21.8%) and Hazardous Material Control (14.2%) establishes these as paramount evaluation factors, demonstrating the successful integration of operational excellence and environmental stewardship in specialized material procurement.

The comprehensive supplier evaluation reveals that Supplier A achieved optimal performance through balanced excellence across all criteria categories, while Supplier D's ranking demonstrates that environmental performance alone is insufficient for effective green supplier selection—establishing that optimal selection necessitates multidimensional excellence rather than narrow environmental focus. Sensitivity analysis substantiates this robustness, with Supplier A maintaining its ranking across varied environmental priority scenarios. From a practical standpoint, these findings necessitate immediate integration of environmental metrics into Company CBM's supplier evaluation processes through formalized Standard Operating Procedures, structured supplier monitoring with environmental Key Performance Indicators, and change management initiatives aligning procurement with sustainability objectives.

The study acknowledges limitations: the expert panel comprised exclusively Company CBM personnel, potentially introducing organizational bias, and the single-company, single-material context may limit generalizability, so the framework should be re-calibrated with local expert panels before transfer to other settings. Future research should incorporate external expert perspectives, validate the framework across multiple organizations and material categories, and integrate tools such as life cycle assessment and AI-driven supplier performance prediction.

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NOMENCLATURE

AHP	Analytical Hierarchy Process
CI	Consistency Index
CR	Consistency Ratio
CV	Coefficient of Variation (%)
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
Fuzzy AHP	Fuzzy Analytical Hierarchy Process
GSCM	Green Supply Chain Management
IQR	Interquartile Range
MCDM	Multi-Criteria Decision Making
NCR	Non-Conformance Report
RI	Random Consistency Index
TFN	Triangular Fuzzy Number
l, m, u	lower, modal, and upper values of a TFN
n	number of criteria or experts
w_j	weight of criterion j
w_E	original weight of the Environment criterion
w_E'	adjusted weight of the Environment criterion in a sensitivity scenario
w_j'	adjusted weight of criterion j

Greek symbols

λ_{max}	maximum eigenvalue of a pairwise comparison matrix