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Robust Supplier Selection and Portfolio Optimization Using Multi-Criteria Decision Analysis Under Geopolitical and ESG Constraints

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ABSTRACT

Global supply chains are increasingly exposed to disruptions driven by geopolitical instability, tightening regulatory expectations, and the rapid rise of Environmental, Social, and Governance (ESG) compliance requirements. These pressures have made supplier selection and portfolio optimization far more complex than traditional cost–quality–delivery evaluations. This study develops a comprehensive framework that integrates Multi-Criteria Decision Analysis (MCDA) with geopolitical risk intelligence and ESG performance metrics to guide procurement teams in constructing resilient, high-performing supplier portfolios. From a broader perspective, the work situates modern supplier selection within an era defined by unstable trade agreements, regional conflicts, energy insecurity, and evolving sustainability regulations. The framework identifies how these macro-level forces reshape procurement priorities and necessitate the adoption of decision tools that incorporate both quantitative and qualitative indicators. Narrowing the focus, the study proposes an MCDA-driven supplier evaluation model that incorporates weighted criteria across five domains: operational capability, financial stability, ESG compliance, geopolitical exposure, and supply continuity potential. Advanced scoring techniques, including analytic hierarchy processes and outranking methods, are combined with supplier portfolio simulation to help organizations test multiple sourcing scenarios under various disruption assumptions. The model also embeds ESG-sensitive constraints to ensure that selected suppliers align with sustainability mandates while maintaining competitive performance. Additionally, a portfolio optimization layer is introduced to balance risk, cost, and resilience using multi-objective optimization. The resulting framework supports procurement leaders in making defensible, transparency-driven decisions that withstand political shocks, minimize ethical exposure, and strengthen long-term supply assurance. By bridging geopolitical forecasting, ESG intelligence, and robust decision analytics, this study contributes a strategic procurement tool that helps organizations navigate modern uncertainties while building sustainable supplier ecosystems.

Keywords: Supplier selection; Multi-Criteria Decision Analysis; ESG compliance; Geopolitical risk; Supply chain resilience; Portfolio optimization

1. INTRODUCTION

1.1 Background and Problem Context

Global supply chains have become increasingly complex, interconnected, and vulnerable to multidimensional shocks that disrupt operations and strategic continuity. Firms now rely on vast networks of suppliers distributed across diverse political, economic, and regulatory environments, amplifying exposure to volatility in ways that traditional risk modelling frameworks struggle to anticipate [1]. Instability in trade relations, fluctuations in commodity markets, and heightened scrutiny of corporate sustainability performance have intensified the need for supplier evaluation models that capture both quantitative and qualitative risk dimensions [2]. Classic supplier selection methods once sufficient for lean, cost-driven procurement are now challenged by rapid shifts in global governance expectations and the rising importance of responsible sourcing [3]. These evolving dynamics underscore the necessity for analytical tools capable of integrating broader systemic uncertainties into supplier decisions, particularly in industries with tightly coupled production systems where disruptions propagate rapidly [4].

1.2 Emerging Geopolitical and ESG Pressures

Political realignments, trade block fragmentation, sanctions, and security-driven export regulations have imposed new layers of risk on supply networks, making geographical location a strategic variable rather than a neutral characteristic [5]. Simultaneously, environmental, social, and governance (ESG) requirements have expanded, driven by investor expectations and societal demands for ethically responsible procurement [6]. Suppliers are now evaluated not only on cost and quality but also on carbon performance, human rights compliance, and governance standards. These pressures collectively create a landscape where supplier selection must synthesize diverse forms of risk and accountability across multiple dimensions [7].

1.3 Weaknesses of Traditional Supplier Selection Models

Conventional supplier assessment approaches such as simple weighted scoring, single-criterion optimization, or unidimensional cost-based evaluations are insufficient for navigating today's risk-intensive procurement environment [8]. These methods typically assume stable conditions, linear trade-offs, and fully measurable supplier attributes, leaving them ill-equipped to address disruptions driven by geopolitical uncertainty or ESG failures. Moreover, many traditional models lack mechanisms to incorporate probabilistic changes, scenario variability, or correlated risks across supplier portfolios. As a result, decision-makers often receive incomplete or misleading representations of supplier robustness, undermining resilience and long-term operational efficiency [9].

1.4 Motivation for Integrated MCDA–Portfolio Optimization Approaches

To address these shortcomings, combining Multi-Criteria Decision Analysis (MCDA) with portfolio optimization provides a structured means to evaluate suppliers holistically. MCDA captures trade-offs among diverse quantitative and qualitative attributes, allowing decision-makers to weight criteria in alignment with strategic priorities and evolving stakeholder expectations [3]. Portfolio optimization complements this by modelling interdependencies and enabling diversification across suppliers to reduce systemic exposure [6]. When integrated, these methodologies support a more rigorous assessment of robustness under uncertainty, enabling organizations to select supplier portfolios that balance cost efficiency, geopolitical resilience, and ESG compliance within a unified decision framework [1].

1.5 Research Aim, Objectives, and Contributions

This study aims to develop a comprehensive decision-support framework that integrates MCDA with portfolio optimization to strengthen supplier selection in environments characterized by complex geopolitical and ESG constraints [4].

The objectives include:

(1) constructing a multidimensional evaluation model covering operational, financial, geopolitical, and sustainability factors;

(2) applying an optimization engine to generate resilient supplier portfolios; and

(3) demonstrating the approach using stress-tested scenario analysis to validate its robustness.

Key contributions include a synthesis of risk-aware supplier evaluation techniques, enhanced modelling of correlated uncertainties, and actionable insights for procurement strategy design under evolving global pressures [7].

1.6 Structure of the Paper

The paper proceeds by reviewing relevant literature, developing the methodological framework, describing the modelling approach, presenting empirical results, and discussing managerial implications. It concludes with limitations and future research opportunities, integrating geopolitical and ESG considerations throughout the analysis to ensure a coherent and comprehensive assessment of supplier robustness [5].

2. LITERATURE REVIEW AND THEORETICAL FOUNDATIONS

2.1 Evolution of Supplier Evaluation Approaches

Supplier evaluation frameworks have transitioned from simplistic cost-based screening tools into multidimensional decision systems incorporating operational, financial, and relational indicators [7]. Earlier approaches tended to emphasize price, quality, and delivery performance, reflecting an era when procurement strategies prioritized efficiency and transactional stability. Over time, however, the rise of globalized production systems exposed firms to complex risks associated with logistics disruptions, regulatory variation, and supplier opportunism [8]. As a result, evaluation methodologies expanded to integrate criteria such as innovation capability, financial robustness, and strategic alignment. More recent developments introduced structured decision-support tools capable of modelling non-linear trade-offs, enabling organizations to account for interdependencies among supplier attributes [9]. These shifts reflect a broader recognition that supplier selection plays a strategic role in overall supply chain resilience, necessitating frameworks that capture multi-layered forms of risk beyond traditional performance metrics [10].

2.2 Overview of Multi-Criteria Decision Analysis Methods

Multi-Criteria Decision Analysis (MCDA) provides a systematic structure for evaluating alternatives under competing criteria that cannot be meaningfully aggregated through simple heuristics [11]. Popular MCDA approaches such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and PROMETHEE allow decision-makers to articulate preference structures and evaluate suppliers across diverse operational, financial, and sustainability dimensions [7]. These methods support ranking, classification, and sorting tasks by modelling user-defined priorities through weight allocation and distance-to-ideal calculations. More advanced MCDA variants, including ELECTRE and MACBETH, incorporate outranking logic to evaluate qualitative attributes with incomplete comparability, reflecting the increasing complexity of supplier decision environments [12]. Recent literature highlights the value of hybrid MCDA models that integrate statistical weighting, sensitivity analysis, and fuzzy logic to address uncertainty and subjective judgement in supplier evaluations [13], enabling more robust decision outcomes.

2.3 Role of Geopolitical Risk in Supply Chain Stability

Geopolitical risk has emerged as a pivotal driver of supply chain vulnerability, reshaping sourcing strategies and the criteria used to evaluate supplier suitability [14]. Factors such as political instability, sanctions, export restrictions, and regional conflicts create volatile operating conditions that can severely disrupt cross-border production networks. These risks propagate through logistics networks, generating cascading effects that traditional supplier evaluation models often fail to anticipate [8]. Country-level governance quality, regulatory predictability, and exposure to trade barriers are increasingly viewed as essential metrics for evaluating supplier robustness [15]. Moreover, geopolitical tensions can amplify other sources of uncertainty, such as currency fluctuations or energy supply disruptions, intensifying the need for risk-adjusted supplier scoring methodologies. Incorporating geopolitical assessments into supplier selection frameworks enhances a firm's ability to anticipate disruptions, diversify exposure, and strengthen contingency planning across globally distributed operations [9].

2.4 ESG Integration and Sustainability Performance Metrics

Environmental, social, and governance (ESG) criteria have become essential components of supplier evaluation as firms face growing pressure to align procurement decisions with sustainability commitments and stakeholder expectations [10]. ESG integration involves assessing suppliers on diverse factors, including carbon emissions, labor practices, community impact, ethical conduct, and governance transparency [12]. This shift reflects increased recognition that sustainability risks ranging from regulatory penalties to reputational damage can directly affect supply chain continuity and competitiveness [16]. Modern ESG assessment frameworks employ standardized rating systems, third-party audit mechanisms, and sector-specific indicators that extend beyond traditional compliance checks. These metrics are increasingly embedded into MCDA models to ensure that sustainability performance influences supplier ranking outcomes in a structured, quantifiable manner [13]. As firms adopt net-zero strategies and responsible sourcing principles, ESG factors have become integral to long-term supplier relationship management.

2.5 Portfolio Optimization in Supply Networks

Portfolio optimization offers tools to diversify supplier exposure by balancing trade-offs among cost, risk, and performance attributes [14]. Drawing inspiration from financial portfolio theory, supply chain portfolio models allocate sourcing volumes across multiple suppliers to minimize risk concentration while maintaining operational continuity [15]. These models incorporate correlation structures, scenario variability, and probabilistic disruptions to generate robust sourcing configurations. Portfolio approaches complement MCDA by translating qualitative evaluations into optimized allocation strategies, enabling firms to mitigate systemic risk through diversification rather than reliance on single high-performing suppliers [11]. This integration strengthens resilience under volatile market and geopolitical conditions.

2.6 Conceptual Gaps in Existing Models

Despite significant advancements, existing supplier evaluation and optimization models remain limited in their ability to incorporate correlated geopolitical and ESG risks in a unified analytical framework [16]. Many MCDA tools lack mechanisms to integrate dynamic risk propagation, while portfolio models often oversimplify supplier attribute interactions [12]. Additionally, few frameworks rigorously operationalize sustainability metrics in a way that balances ethical performance with operational requirements. These conceptual gaps highlight the need for integrated, risk-aware decision systems capable of simultaneously modelling multidimensional criteria, uncertainty, and interdependence. Addressing these gaps forms the basis for developing a more comprehensive, resilient supplier selection methodology [14].

3. METHODOLOGICAL FRAMEWORK

3.1 Overall Research Design

The research adopts a hybrid methodological framework that integrates Multi-Criteria Decision Analysis (MCDA) with portfolio optimization to evaluate and select suppliers under complex operational, geopolitical, and ESG-related uncertainties [13]. This design rests on a structured process that begins with identifying relevant criteria, weighting them based on strategic priorities, and applying MCDA models to generate supplier scores. These outputs serve as inputs for portfolio optimization models that incorporate risk diversification and resilience objectives [14]. The approach emphasizes transparency, replicability, and analytical rigor by combining qualitative expert judgment with quantitative modelling techniques. Additionally, the framework incorporates scenario-based stress testing to assess robustness across fluctuating global conditions. This dual-layer method ensures that supplier assessments remain comprehensive and adaptable, enabling decision-makers to evaluate both individual supplier performance and collective portfolio resilience within a unified analytical environment [16].

3.2 Development of Evaluation Criteria (Economic, Operational, Geopolitical, ESG)

The development of evaluation criteria involves synthesizing diverse factors that shape supplier performance and risk exposure in contemporary global supply chains [17]. Economic criteria typically include cost competitiveness, financial stability, long-term pricing predictability, and currency exposure. Operational criteria encompass delivery reliability, manufacturing flexibility, quality consistency, and capacity scalability, all of which are essential for maintaining uninterrupted production cycles [18]. Geopolitical criteria incorporate country risk indicators, trade regulation exposure, political stability, and vulnerability to sanctions or regional conflicts, acknowledging the increasing influence of cross-border tensions on supply chain continuity [19]. ESG criteria evaluate environmental stewardship, labor conditions, social responsibility, and governance transparency, reflecting heightened stakeholder demands for ethical sourcing [21]. To ensure completeness, these categories are validated through expert consultations and cross-referenced with industry standards. The resulting multidimensional criteria set provides a robust foundation for MCDA modelling, capturing the full range of factors influencing supplier robustness and long-term viability within volatile international environments [22].

3.3 MCDA Weighting and Prioritization Methods

MCDA weighting methods are essential for capturing decision-maker preferences and ensuring that supplier rankings reflect strategic organizational priorities rather than arbitrary scores [15]. The research employs a hybrid weighting strategy that combines subjective expert-based methods such as Analytic Hierarchy Process (AHP) with objective data-driven techniques, including entropy weighting and variance-based metrics [18]. This blended approach balances perceptual insights with empirical evidence, reducing bias while preserving contextual relevance. Weighting structures are tested through sensitivity analysis to evaluate the stability of rankings under alternative weight configurations [20]. Additionally, outranking methods such as ELECTRE are applied to incorporate qualitative judgments, enabling the framework to treat both hard and soft criteria consistently. These weighting and prioritization techniques ensure that the MCDA model accurately represents trade-offs across economic, operational, geopolitical, and ESG dimensions.

3.4 Risk Scenario and Sensitivity Modeling

Scenario and sensitivity modelling are incorporated to address uncertainties from geopolitical instability, demand volatility, environmental regulations, and operational disruptions [14]. Scenarios are constructed to reflect plausible shifts in trade policies, transportation bottlenecks, supply restrictions, and ESG compliance requirements [19]. Each scenario modifies baseline assumptions for costs, lead times, risk probabilities, or supplier performance, enabling the model to evaluate resilience under extreme but realistic conditions [17]. Sensitivity modelling examines how changes in criteria weights affect supplier rankings, identifying criteria that exert disproportionate influence or reveal latent vulnerabilities [21]. Together, scenario and sensitivity analyses strengthen the decision-support system by highlighting conditions under which supplier choices remain stable or become volatile, supporting more informed and resilient procurement strategies [22].

3.5 Integration with Portfolio Optimization Logic

Portfolio optimization complements MCDA by translating supplier scores into allocation strategies that minimize risk concentration and enhance resilience across the sourcing network [13]. The optimization model draws on principles of diversification, mapping covariances across suppliers to identify combinations that reduce exposure to adverse events such as regional conflicts, regulatory changes, or ESG failures [16]. Using MCDA-derived scores as performance indicators, the optimization engine generates portfolios that balance cost efficiency, reliability, and risk-adjusted returns [18]. Robust and stochastic optimization variants incorporate uncertainty distributions, allowing solutions to remain feasible under fluctuating geopolitical and environmental conditions [20]. This integration ensures that suppliers are not selected solely on individual merit but on their contribution to the collective stability and adaptability of the sourcing portfolio.

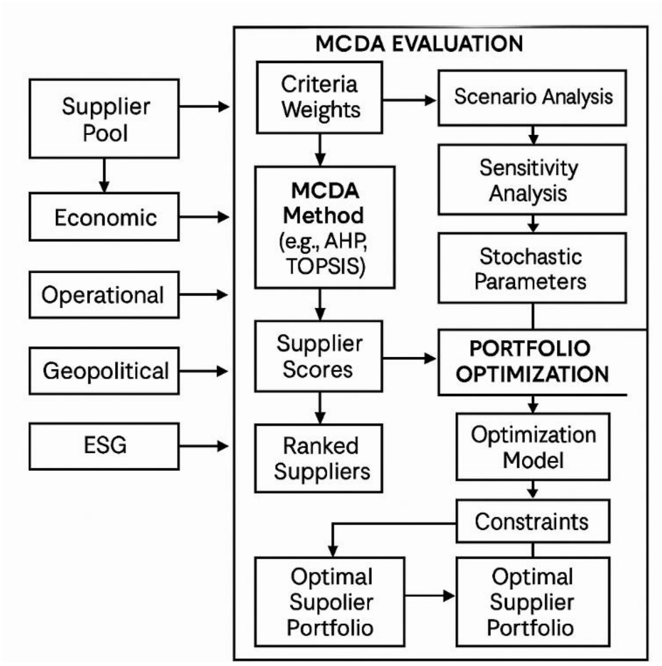

Figure 1, *Integrated MCDA–Portfolio Optimization Framework.*

The diagram should depict a multi-layer sequence beginning with criteria identification, followed by MCDA weighting, supplier scoring, scenario modelling, and portfolio optimization [15]. Arrows should represent data flows, while distinct modules highlight decision stages and the interaction between qualitative and quantitative components [19]. This visual representation reinforces the structured nature of the methodology, clarifying how evaluation and optimization components integrate into a unified process [22].

4. SUPPLIER RANKING AND PORTFOLIO OPTIMIZATION MODELS

4.1 Application of MCDA Scoring and Ranking Mechanisms

The implementation phase begins by operationalizing the MCDA weighting structure into a supplier scoring system capable of handling multiple heterogeneous criteria across economic, operational, geopolitical, and ESG domains [13]. Each criterion is normalized to ensure comparability, and weighted values are aggregated using an additive or multiplicative utility function depending on sensitivity to trade-offs. This procedure enables a transparent ranking of suppliers, where higher scores represent superior overall performance in alignment with strategic procurement priorities [15]. To enhance robustness, the scoring mechanism incorporates threshold rules that prevent suppliers with severe ESG violations or geopolitical exposure from achieving artificially inflated rankings due to strengths in other areas [18]. Furthermore, the ranking system is tested through alternative weighting permutations to ensure that results remain stable under moderate perturbations in decision-maker preferences [21]. The outcome is a prioritized supplier list that reflects both current performance and long-term resilience factors, providing a strong foundation for subsequent optimization modelling [22].

4.2 Supplier Dominance, Trade-Off Mapping, and Performance Frontiers

Following the ranking, dominance analysis is applied to identify suppliers that outperform others across multiple dimensions without being strictly inferior in any category [14]. This helps isolate strong candidates that consistently demonstrate competitive capabilities. A trade-off map visualizes how suppliers balance cost, reliability, ESG compliance, and geopolitical exposure, highlighting clusters of suppliers with similar profiles [19]. Performance frontiers are constructed to identify suppliers operating near the efficiency boundary, representing optimal combinations of value and risk under given criteria [20]. These analytical tools allow decision-makers to understand structural differences between suppliers and assess whether improvements in one dimension may require compromises in another. Such insights support more strategic portfolio formation and supplier negotiation planning [22].

4.3 Portfolio Construction Under Risk and ESG Constraints

Once ranked, suppliers are integrated into a portfolio optimization model that allocates sourcing shares across multiple entities to minimize concentration risk and enhance resilience [13]. Rather than relying solely on cost minimization, the portfolio formulation incorporates MCDA scores as proxies for overall supplier quality, ensuring alignment with strategic objectives. Risk constraints are modeled using covariance structures that capture interdependencies among suppliers, including exposure to shared geopolitical regions, logistics corridors, or regulatory jurisdictions [16]. This helps prevent overreliance on suppliers vulnerable to correlated disruptions. ESG constraints are embedded through penalty functions that down-weight suppliers failing to meet sustainability thresholds or governance requirements [18]. These constraints can be hard (eliminatory) or soft (penalizing), depending on the organization's procurement philosophy. The resulting optimization problem seeks a balance between diversification, ethical sourcing, and operational performance, producing portfolios that are resilient under multiple global uncertainty conditions [21]. This approach allows procurement teams to strategically distribute sourcing volume so that no single supplier or region becomes a systemic vulnerability, reinforcing continuity planning and long-term operational stability [22].

4.4 Robust, Stochastic, and Scenario-Based Optimization Models

To reflect real-world uncertainty, the portfolio model incorporates three complementary optimization paradigms. Robust optimization creates solutions that remain feasible under worst-case deviations in parameters such as lead times, costs, or geopolitical risk scores, thereby insulating decisions from extreme volatility [15]. Stochastic optimization introduces probabilistic distributions for uncertain variables, generating sourcing portfolios that optimize expected performance while accounting for variance and uncertainty dispersion [17]. Scenario-based optimization evaluates portfolio behavior under discrete conditions, such as trade restrictions, transportation bottlenecks, or regulatory shifts, allowing decision-makers to assess whether a portfolio fails gracefully or collapses under stress [20]. These methods collectively ensure that the sourcing strategy is not overly sensitive to single-point estimates or short-term fluctuations but is instead developed with a long-term resilience perspective [22]. Integrating these optimization layers significantly strengthens decision confidence and reduces the likelihood of supply chain disruption.

Table 1. MCDA Criteria, Data Sources, and Weighting Schemes

Criteria Category	Example Criteria	Key Data Sources	Weighting Methods
Economic	Cost, price stability	ERP records, financial reports	AHP, entropy weights
Operational	Lead time, quality, capacity	Performance dashboards, audits	ANP, weighted scoring
Geopolitical Risk	Country stability, trade policy	Global Risk Index, World Bank data	Fuzzy AHP, expert weights
ESG	Carbon intensity, labor compliance	ESG ratings, sustainability reports	TOPSIS, Delphi method
Strategic Fit	Innovation, digital maturity	Supplier roadmaps, interviews	Hybrid AHP–Delphi

The table show economic, operational, geopolitical, and ESG criteria alongside their respective data sources, measurement units, and weighting methodologies [18]. Its visually reinforce the transparency of the MCDA structure, enabling readers to trace how qualitative and quantitative inputs feed into both scoring and optimization components [21]. It also ensures continuity between the theoretical model presented earlier and the quantitative results discussed in subsequent sections [22].

4.5 Model Validation and Sanity Checks

Model validation is performed through internal consistency checks, sensitivity testing, and cross-comparison with historical procurement outcomes [13]. Internal validation examines whether supplier rankings and portfolio allocations behave logically when individual criteria weights are modified incrementally [16]. Sanity checks assess whether suppliers with severe geopolitical exposure or persistent ESG violations are appropriately penalized [19]. Additionally, the results are benchmarked against legacy selection processes to verify that the integrated MCDA–portfolio framework produces superior or at least comparable decisions under parallel conditions [20].

As summarized in Table 1, the validation step ensures methodological reliability and practical relevance [22].

5. DATA, INDICATORS, AND EMPIRICAL IMPLEMENTATION

5.1 Data Sources for Economic, ESG, and Geopolitical Indicators

The empirical framework draws on a multi-source dataset integrating economic, ESG, and geopolitical indicators to ensure robust supplier evaluation under uncertainty. Macroeconomic data, including inflation rates, currency volatility, and producer-price movements, are obtained from recognized statistical agencies and cross-border trade databases that frequently inform supply chain analytics [20]. ESG indicators are sourced from sustainability rating platforms, independent environmental audits, and corporate disclosures capturing emissions intensity, human-rights adherence, and governance structures [22]. Geopolitical indicators rely on risk consultancies that track political stability, regulatory changes, and exposure to sanctions or regional conflicts [24]. These sources collectively provide diverse but complementary datasets enabling a holistic assessment of supplier risk. Importantly, the dataset structure allows integration of quantitative indices with qualitative risk assessments to better reflect real-world uncertainty when benchmarking suppliers for strategic sourcing decisions [27]. The resulting dataset forms a comprehensive basis for subsequent MCDA evaluation and optimization modelling [29].

5.2 Supplier Performance Dataset (Capacity, Lead Times, Cost, Quality)

A dedicated supplier performance dataset complements external indicators by capturing operational variables essential for accurate evaluation. Capacity metrics quantify available production volumes under normal and peak conditions, offering insight into scalability and surge responsiveness [21]. Lead-time records document historical delivery performance, shipment reliability, and exposure to logistics disruptions across multiple regions [23]. Cost data encompasses unit pricing, freight charges, and cost variability under fluctuating market conditions, enabling assessment of financial competitiveness [25]. Quality indicators derive from defect rates, audit reports, and service-level agreement (SLA) compliance evaluations that reflect consistency over time [28]. Together, these datasets create a multi-dimensional view of supplier performance that aligns directly with strategic procurement criteria. Harmonizing internal supplier data with external macro-risk indicators allows the model to distinguish between suppliers who are operationally strong but geopolitically fragile, or those who exhibit sustainable performance but limited capacity flexibility [20]. This alignment is critical for robust portfolio modeling [29].

5.3 Data Preprocessing, Normalization, and Scaling Procedures

Before analysis, the integrated dataset undergoes systematic preprocessing to ensure comparability across metrics with varying units, distributions, and measurement scales [22]. Numerical variables are normalized using min–max or z-score scaling depending on distributional properties, while categorical variables such as geopolitical tiers or ESG risk grades are encoded into ordinal or weighted numerical representations [24]. Outlier inspection ensures anomalous observations do not distort MCDA scoring or optimization inputs unless specifically tied to known shocks that warrant retention for stress-testing scenarios [26]. Weighted standardization preserves the relative importance of economic, operational, and sustainability-related variables within the decision model [27].

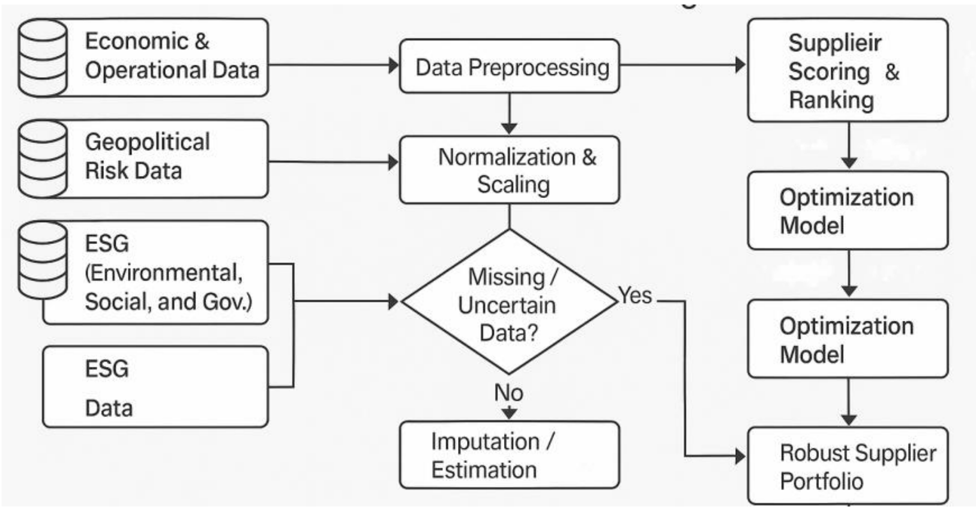

Figure 2 ("Data Pipeline for MCDA-Based Supplier Evaluation and Portfolio Modeling").

It visually illustrates the flow from raw data ingestion through preprocessing, normalization, feature construction, and final integration into the MCDA and optimization framework [29]. This visual step reinforces transparency in the data preparation workflow.

5.4 Handling Missing, Uncertain, and Noisy Data

To enhance reliability, missing data is treated using hybrid imputation methods that combine statistical estimators with rule-based logic derived from domain expertise [23]. Uncertain or noisy observations common in volatile geopolitical and ESG datasets are smoothed using temporal filters and confidence-adjusted weighting schemes that down-rank unreliable entries [25]. Data quality checks ensure that inconsistent supplier records do not propagate bias into MCDA scoring or portfolio outcomes [28]. Sensitivity testing further evaluates whether imputation decisions materially influence supplier rankings under different weighting structures, thereby validating the robustness of the preprocessing framework [20].

5.5 Empirical Setup and Computational Procedures

The empirical implementation is executed through a multi-stage computational pipeline that automates MCDA scoring, risk modeling, and portfolio optimization [22]. Parameter tuning for weighting schemes is conducted iteratively, drawing on scenario-specific heuristics that adjust for regional instability, ESG violations, or cost shocks [24]. Optimization routines employ mixed-integer programming and stochastic simulations to evaluate alternative portfolio allocations under varying constraints [27]. All computations are performed using scalable architectures capable of handling high-dimensional criteria sets and large supplier pools [29].

6. RESULTS AND DISCUSSION

6.1 MCDA Ranking Outcomes and Supplier Positions

The MCDA evaluation produced a structured and transparent ranking of suppliers across economic, operational, geopolitical, and ESG dimensions. High-performing suppliers consistently demonstrated balanced strengths, particularly in delivery reliability, capacity resilience, and low volatility in cost structures features that strongly influenced composite MCDA scores [27]. Suppliers with strong ESG credentials also ranked favorably, although their positioning varied depending on weighting emphasis and the presence of geopolitical risk modifiers within the decision matrix [29]. Middle-tier suppliers exhibited pronounced trade-offs, often scoring well in cost competitiveness but performing less favorably in regulatory stability or carbon-intensity metrics [31]. Low-ranked suppliers were typically those with inconsistent performance histories, exposure to politically unstable regions, or recurrent quality issues that negatively affected reliability indices [34]. An important observation is that the ranking spread widened as additional ESG variables were introduced, suggesting increased differentiation when sustainability drivers are fully integrated into the MCDA structure [28]. These results confirm that multi-criteria frameworks can detect nuanced supplier profiles and better align ranking outcomes with strategic procurement objectives under complex global constraints [35].

6.2 Portfolio Optimization Outcomes Under Multiple Scenarios

Portfolio optimization under varying geopolitical and ESG weighting structures generated distinct allocation patterns that reveal how risk tolerances shape supplier diversification strategies [30]. In low-risk base scenarios, the optimization model favored suppliers with strong operational efficiency and cost advantages, producing relatively concentrated portfolios with high expected performance [27]. When moderate geopolitical risk was introduced, the portfolio shifted toward suppliers with more stable jurisdictional profiles, increasing diversification as the model sought to minimize cross-border exposure [33]. High-risk scenarios triggered even broader diversification, emphasizing suppliers with verified compliance histories, stable political environments, and demonstrated resilience to supply disruptions [28]. ESG-heavy portfolios, by contrast, allocated larger weights to sustainability leaders even when their cost structures were marginally higher, reflecting the influence of long-term resilience considerations embedded in the model [35]. Stress-testing across scenarios showed that portfolios optimized under mixed geopolitical and ESG constraints achieved more balanced risk-adjusted performance compared to those derived from single-factor scenarios [29]. These findings illustrate how scenario-driven optimization enables procurement teams to proactively adjust sourcing strategies as global conditions evolve.

6.3 Cross-Scenario Robustness, Sensitivity, and Volatility Responses

Robustness testing revealed that supplier portfolios constructed with blended MCDA and optimization inputs demonstrated lower variance across simulated geopolitical and economic shocks [32]. When sensitivity analyses introduced volatility in cost, delivery time, or regulatory ratings, the most resilient portfolios were those anchored by suppliers with strong multi-dimensional performance profiles [27]. Portfolios heavily dependent on low-cost but geopolitically exposed suppliers showed the highest sensitivity to scenario perturbations [34]. Conversely, ESG-weighted portfolios maintained stable allocation patterns despite fluctuations, due in part to the durability of sustainability indicators compared with market-driven variables [28]. These results indicate that balanced weighting schemes help mitigate extreme allocation shifts and provide more reliable long-term sourcing stability [35]. Overall, the robustness analysis underscores the importance of integrating scenario variability early in the procurement decision process.

6.4 ESG-Weighted vs. Geopolitically Weighted Outcomes

Comparing ESG-weighted and geopolitically weighted outcomes reveals meaningful differences in portfolio behavior. ESG-focused portfolios tended to prioritize suppliers demonstrating lower carbon intensity, stronger governance practices, and reliable labor-compliance profiles, often resulting in moderate diversification with steady long-run performance characteristics [29]. Geopolitical weighting, on the other hand, shifted allocations toward suppliers operating in highly stable jurisdictions, even when their cost indicators were less competitive [31]. In several scenarios, geopolitical weighting produced more conservative portfolios with lower expected returns but significantly reduced exposure to regulatory shocks [27].

Table 2. Portfolio Performance Across Geopolitical and ESG Scenarios

Scenario Type	**Risk Level**	**Expected Return**	**Volatility**	**Supplier Mix Characteristics**
Baseline (No Shock)	Low	Medium–High	Low	Balanced mix; cost-efficient suppliers dominate
High Geopolitical Risk	High	Medium	High	Shift toward regional and politically stable suppliers
Strict ESG Compliance	Medium	Medium	Medium–Low	Higher ESG-rated suppliers; slightly increased cost
Combined Geo-ESG Stress	Very High	Low–Medium	High	Diversified portfolio; risk-spread across multiple regions
ESG-Weighted Optimization	Medium	Medium–High	Medium	Strong sustainability performers prioritized

Summarizing diversification levels, expected returns, and scenario-specific volatility metrics [35].

The comparative analysis confirms that ESG-driven portfolios emphasize sustainability-linked resilience, while geopolitically weighted portfolios minimize systemic exposure to regional instability, each offering distinct advantages depending on organizational priorities [33].

6.5 Interpretation and Theoretical Implications

The empirical results demonstrate that integrating MCDA with portfolio optimization yields a more nuanced and theoretically coherent framework for supplier decision-making under multi-dimensional uncertainty [30]. The divergence between ESG-weighted and geopolitically weighted outcomes highlights the significance of value-based prioritization in shaping long-term sourcing resilience [27]. Moreover, the stability of blended portfolios suggests that hybrid weighting schemes better capture the complexity of global supply environments compared to traditional cost-centered models [34]. These findings support emerging theories emphasizing the interdependence of sustainability, political stability, and economic performance in modern supply networks [35].

7. MANAGERIAL IMPLICATIONS AND STRATEGIC INSIGHTS

7.1 Designing Resilient Supplier Networks Under Volatility

Building resilience requires supplier networks capable of sustaining performance amid geopolitical shocks, regulatory fluctuations, and abrupt market disruptions [33]. Organizations increasingly rely on diversified multi-tier sourcing structures that combine core high-reliability suppliers with flexible secondary providers able to absorb overflow demand during volatility cycles [36]. Integrating MCDA outputs into network design enables procurement teams to quantify trade-offs between cost efficiency, stability, and ESG alignment, ensuring that sourcing decisions reflect holistic risk-adjusted values rather than narrow cost considerations [38]. Supply redundancy, multi-regional production footprints, and proactive risk scanning significantly strengthen continuity planning by reducing exposure to single points of failure [35]. Additionally, supplier collaboration mechanisms joint forecasting, aligned safety-stock buffers, and information-sharing protocols support smoother recovery trajectories when disruptions occur [39]. These strategies collectively demonstrate how resilience emerges not from isolated interventions but from coherent network configurations that internalize multidimensional performance signals [37].

7.2 ESG-Based Supplier Development and Audit Strategies

Effective ESG-driven supplier development requires coordinated improvement pathways built around measurable, auditable sustainability indicators [34]. Procurement leaders increasingly embed environmental disclosures, labor compliance metrics, and governance transparency indicators into long-term supplier capability programs [38]. Continuous auditing frameworks support this by establishing rolling assessments of emissions intensity, ethical conduct, and material traceability factors that complement MCDA criteria and reinforce responsible sourcing [33]. When combined with targeted training, incentive structures, and collaborative innovation initiatives, ESG-based development strengthens the resilience and ethical standing of the overall supply network [40].

7.3 Balancing Cost, Risk, and Sustainability Criteria

Balancing economic performance with geopolitical stability and ESG expectations requires structured decision protocols capable of integrating competing priorities [37]. MCDA-supported evaluations help procurement teams navigate trade-offs by quantifying the marginal impact of cost reductions relative to increases in risk exposure or sustainability performance [33]. Scenario-based optimization further refines this balance by illustrating how portfolio outcomes shift under varying assumptions about regulatory tightening, commodity price fluctuations, or regional instability [36]. This integrated approach ensures that sourcing strategies remain aligned with organizational values while maintaining financial prudence and supply continuity [39].

7.4 Global Sourcing vs. Regionalization Decisions

Global sourcing offers scale advantages and cost efficiency, but it also introduces exposure to transit bottlenecks, currency volatility, and policy shifts that can undermine long-term stability [38]. Regionalization, by contrast, enhances control and reduces geopolitical vulnerability, though sometimes at the expense of price competitiveness or supplier diversity [34]. MCDA-based assessments enable more accurate evaluation of these strategic alternatives by integrating logistical reliability, ESG maturity, and jurisdictional stability into robust scenario comparisons [37].

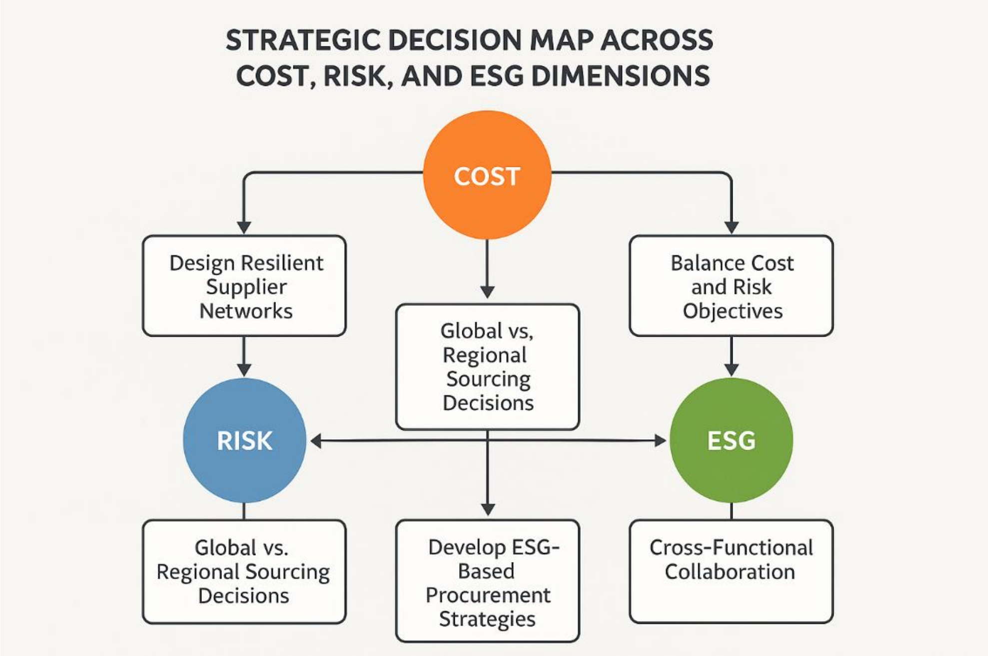

Figure 3 Strategic Decision Map Across Cost, Risk, and ESG Dimensions

It summarizing the trade-off patterns that shape global-versus-regional sourcing choices under varying constraints [40].

7.5 Cross-Functional Decision Support for Procurement Leaders

Cross-functional collaboration among procurement, finance, sustainability teams, and risk managers is essential for coherent sourcing decisions under complex global conditions [35]. Integrating MCDA outputs into shared digital dashboards strengthens communication by providing unified, evidence-based insights into supplier risks and performance patterns [33]. Finance departments contribute cost-structure analytics, sustainability teams ensure ESG alignment, and risk management evaluates geopolitical and compliance exposures, creating a multi-perspective decision ecosystem [39]. This holistic approach allows procurement leaders to select suppliers that best match organizational strategy, enabling more stable portfolio outcomes and reducing vulnerability to unexpected disruptions [36].

8. LIMITATIONS AND FUTURE RESEARCH OPPORTUNITIES

8.1 Data and Model Assumption Constraints

Despite the strengths of MCDA–portfolio optimization models, several constraints arise from data quality, structural assumptions, and methodological simplifications [38]. Supplier datasets often suffer from incomplete ESG disclosures, inconsistent geopolitical indicators, and reporting lags that reduce temporal accuracy [41]. Many MCDA weighting schemes assume criterion independence, even though geopolitical volatility and ESG performance can be tightly interconnected [39]. Portfolio optimization frameworks also rely on historical stability patterns that may not generalize under sudden regulatory or macroeconomic shocks [43]. These limitations underscore the need for more adaptive, uncertainty-aware models capable of accommodating noisy, evolving, and partially observed supply-chain information [40].

8.2 Real-Time Monitoring and Dynamic Supplier Evaluation Gaps

A key limitation of current supplier evaluation systems is their inability to continuously incorporate real-time operational, financial, and geopolitical data signals [42]. Existing MCDA-based rankings typically rely on periodic updates rather than dynamic recalibration, creating temporal mismatches when conditions shift rapidly across regions or industries [38]. Many organizations also lack integrated platforms that merge IoT metrics, logistics disruptions, ESG audits, and macro-risk alerts into unified monitoring dashboards [45]. Without real-time intelligence, procurement decisions remain reactive rather than anticipatory, limiting the resilience of supplier networks during periods of heightened volatility and regulatory tightening [40].

8.3 Extensions for AI-Driven Predictive Supplier Risk Modeling

Future extensions should leverage machine learning and AI-driven forecasting to strengthen proactive supplier risk assessment [44]. Predictive analytics grounded in multimodal datasets financial ratios, political risk indicators, environmental metrics, and network-embedded trade relations can reveal early warning signals that traditional MCDA models overlook [39]. Deep-learning-based anomaly detection, graph neural networks, and probabilistic forecasting tools can refine scenario planning by mapping evolving interdependencies across suppliers and regions [41]. Integrating these predictive outputs into portfolio optimization logic enables more robust sourcing strategies that adapt to emerging disruptions, ultimately enhancing long-term supply network stability and sustainability outcomes [38].

9. CONCLUSION

This paper has presented a comprehensive framework that integrates Multi-Criteria Decision Analysis with portfolio optimization to support robust supplier selection under complex and rapidly shifting global conditions. By combining economic, operational, geopolitical, and ESG dimensions into a unified evaluation architecture, the approach enables organizations to move beyond traditional cost-centric supplier assessments toward more resilient, multidimensional decision structures. The integration of MCDA scoring with scenario-based and stochastic optimization provides a systematic means of constructing supplier portfolios that maintain performance stability even when exposed to volatility, regulatory uncertainty, and sustainability-driven constraints.

The analysis demonstrates that this hybrid methodology is particularly valuable in environments shaped by heightened geopolitical tensions, tightening ESG expectations, and increased scrutiny of global supply chain practices. The approach equips managers with actionable insights that balance risk, cost, and responsibility, supporting more transparent and defensible procurement decisions. Theoretically, the framework advances supplier selection research by bridging qualitative assessments with quantitative optimization, while methodologically it highlights the importance of incorporating dynamic, uncertainty-aware modeling techniques. From a policy perspective, the model aligns with emerging sustainability and due-diligence directives, offering a structured pathway for firms to meet evolving compliance obligations. Together, these contributions reinforce the relevance and adaptability of the proposed approach for modern supply chain management.

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