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An Integrated Three-Phase Green Quality Function Deployment Framework for Evaluating Lean–Green Criteria Under Uncertainty

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ABSTRACT

Manufacturers need decision models that translate environmental and customer requirements into operational priorities while integrating lean and green practices within a unified programme. This study develops and applies an integrated decision framework to identify, structure and prioritise lean–green manufacturing criteria and to examine how their relative importance changes as strategic requirements are translated into technical, environmental and operational priorities. An initial literature-derived set of 15 criteria and 55 subcriteria was refined through expert screening to eight criteria and 42 subcriteria. Fuzzy analytic network process (FANP) was first used to capture interdependencies among the retained criteria and derive their network-based priorities. These priorities were subsequently carried through three linked green quality function deployment (GQFD) matrices, sequentially relating lean–green criteria to gearbox technical characteristics, environmental requirements and lean enablers. The resulting lean-enabler weights were then incorporated into interval VIKOR to obtain the final compromise priorities under uncertainty. FANP ranked workforce, environmental performance and process highest, whereas the final analysis placed supply chain, performance outcomes and environmental performance in the leading positions. This cross-stage reordering shows that structural importance within an interdependent decision network does not necessarily translate directly into implementation priority and demonstrates the value of tracing how lean–green priorities are reconfigured across successive deployment stages.

1 | Introduction

Lean manufacturing constitutes a sociotechnical management system centred on customer value creation, waste elimination, process stability and continuous improvement. Green manufacturing complements these operational priorities through the systematic reduction of material and energy intensity, emissions, hazardous substances and other life-cycle environmental burdens. Lean–green manufacturing represents the strategic integration of these two domains within a unified production system that jointly governs operational efficiency, customer value, resource productivity and environmental performance (Dües et al. 2013; Gholami et al. 2021; Villegas et al. 2026).

The strategic significance of lean–green integration arises from the requirement to align productivity, quality, responsiveness,

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resource efficiency, emissions reduction and stakeholder expectations within a coherent implementation system. Lean practices can generate environmental benefits through lower defect rates, reduced material losses, improved process control and shorter throughput times. Their environmental consequences, however, remain sensitive to process configuration, transport intensity, energy consumption, technology choices and supply-chain design. Effective implementation therefore requires an explicit decision architecture capable of coordinating customer requirements, technical characteristics, organisational capabilities, supply-chain relationships and environmental priorities (Johansson and Sundin 2014; Farrukh et al. 2022; Villegas et al. 2026).

These conditions create a multicriteria strategic decision environment in which manufacturers must determine the relative importance of competing capabilities and outcomes; incorporate interdependencies among workforce, processes, suppliers, supply chains and environmental performance; and preserve the uncertainty embedded in expert judgement. Quality function deployment (QFD) offers a structured mechanism for translating stakeholder requirements into technical and operational responses. Fuzzy multicriteria decision-making methods complement this deployment logic by representing linguistic assessments and producing analytically consistent priority structures under uncertainty (Chan and Wu 2002; Masui et al. 2003; Hsu et al. 2022).

Contemporary research has advanced lean–green implementation through maturity assessment, barrier analysis, critical success factor prioritisation, structural modelling and hybrid decision-support methods (Gholami et al. 2021; Oliveira et al. 2022; Garza-Reyes et al. 2026; Hou et al. 2026). Despite these advances, the literature remains analytically fragmented across factor identification, structural weighting, requirement deployment and final prioritisation. Three interrelated gaps are particularly significant. First, extant studies offer insufficient traceability between customer and environmental requirements, product characteristics and implementable lean enablers. Second, the interdependencies among organisational, technical, environmental, supplier and supply-chain dimensions are frequently analysed separately from the subsequent requirement-deployment process. Third, existing research has not clearly differentiated the structural influence of a criterion within an interdependent decision network from its deployment salience following the incorporation of technical and environmental relationships. These gaps establish the need for an integrated multistage decision architecture that connects criteria development, interdependent weighting, requirement deployment and compromise prioritisation. These gaps motivate the following research questions (RQs):

RQ1. Which criteria and subcriteria constitute a context-relevant lean–green implementation architecture for gearbox manufacturing?

RQ2. How do the relative priorities of lean–green criteria evolve across interdependent weighting, requirement deployment and compromise prioritisation under uncertainty?

To address these research questions, the study develops and applies an integrated sequential decision-support framework within NMI, an Iranian gearbox manufacturer. A synthesis of prior studies, followed by expert assessment, establishes a context-relevant lean–green criteria architecture. FANP subsequently incorporates criterion interdependencies and derives network-based priorities. Three linked green quality function deployment (GQFD) matrices propagate customer and environmental requirements across product characteristics, environmental requirements and lean enablers. Interval extended VIKOR then generates the final compromise prioritisation. The resulting framework preserves analytical traceability across all stages and establishes a coherent pathway from strategic requirements to operational implementation priorities.

The study pursues two research objectives:

RO1. To identify, refine and establish a content-validated architecture of lean–green manufacturing criteria and subcriteria for gearbox production.

RO2. To develop and apply an integrated FANP–three-phase GQFD–interval VIKOR framework that combines interdependent weighting, requirement deployment and compromise prioritisation under uncertainty.

The study advances lean–green integration research through three interrelated contributions. First, it conceptualises lean–green implementation as a traceable requirement-deployment architecture linking stakeholder and environmental requirements with product characteristics, lean enablers and strategic implementation priorities. Second, it articulates and operationalises the distinction between network-based importance and deployment salience. FANP determines the structural influence of criteria within the interdependent decision network, while the linked GQFD and interval VIKOR stages identify the priorities that acquire strategic significance across the complete deployment pathway. Third, the framework integrates organisational, technical, environmental, supplier and supply-chain dimensions within a unified decision structure, thereby connecting environmental strategy with operational and cross-boundary implementation priorities. Collectively, these contributions provide a coherent analytical account of how lean–green priorities are generated, propagated and reconfigured across successive decision stages.

The remainder of the paper is organised as follows. Section 2 develops the conceptual foundations and positions the research gap. Section 3 presents the research design and analytical framework. Section 4 reports the empirical application and analytical results. Section 5 interprets the findings and develops their theoretical, managerial and policy implications. Section 6 concludes the study and defines the agenda for future research.

2 | Literature Review

This section develops the conceptual and analytical foundations of the study across four interrelated domains. Section 2.1 positions lean–green manufacturing as an integrated strategic system; Section 2.2 examines QFD and GQFD as requirement-deployment architectures; Section 2.3 evaluates decision-analytic approaches to interdependent weighting and

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compromise prioritisation; and Section 2.4 synthesises the research gap and establishes the analytical positioning of the proposed framework.

2.1 | Lean–Green Manufacturing

Lean–green manufacturing integrates operational excellence and environmental management within a coordinated strategic system. Lean capabilities strengthen process flow, quality, responsiveness, cost efficiency and continuous improvement through the systematic elimination of operational waste. Green capabilities advance pollution prevention, resource productivity, emissions reduction, life-cycle stewardship and regulatory responsiveness. Their integration establishes complementary mechanisms through which process discipline can enhance environmental performance and environmental priorities can direct operational improvement towards lower impact production and supply-chain configurations (Dües et al. 2013; Saetta and Caldarelli 2020; Gholami et al. 2021).

The strategic performance of this integration depends on a portfolio of interdependent organisational and interorganisational capabilities. Top-management commitment establishes strategic direction, governance and resource allocation; workforce competence and participation embed lean–green principles within operational routines; performance measurement aligns continuous improvement with environmental objectives; and collaboration with customers and suppliers extends implementation across organisational boundaries (Kitsis and Chen 2021; Farrukh et al. 2022, 2023; Hebaz et al. 2022). Process innovation and sustainability-oriented innovation further strengthen the conversion of these capabilities into operational, environmental and supply-chain outcomes (Cherrafi et al. 2018; Jum'a et al. 2022).

Recent research has expanded lean–green scholarship towards strategic implementation, barrier prioritisation, digitally enabled product development and circular operations. Garza-Reyes et al. (2026) structure and prioritise the organisational, institutional, behavioural, knowledge and technological barriers governing green–lean implementation. Hou et al. (2026) establish the hierarchical relationships among critical success factors for lean–green product development within an Industry 4.0 environment. Villegas et al. (2026) further integrate lean, green and circular practices within sustainable operations and supply-chain transformation. Collectively, these developments position lean–green implementation as a multidimensional transformation shaped by leadership, workforce capability, process design, technological infrastructure, environmental governance and cross-boundary coordination.

2.2 | QFD and GQFD

QFD constitutes a cross-functional planning architecture for translating stakeholder requirements into measurable technical characteristics and operational responses. Through the house of quality (HOQ) and its associated relationship matrices, QFD integrates requirement importance, relationship intensity and functional knowledge within a transparent deployment process. Its principal analytical strength lies in preserving traceability between strategic requirements and the design or operational decisions through which those requirements are realised (Chan and Wu 2002).

GQFD extends this architecture by incorporating environmental requirements and life-cycle considerations into product and process development. Environmental attributes—including material and energy efficiency, emissions, toxicity, recyclability, maintainability and end-of-life performance—are integrated with customer value and technical feasibility within the deployment structure (Masui et al. 2003; Wu and Ho 2015). GQFD consequently provides an analytical bridge between environmental strategy and the product, process and operational decisions required for its implementation.

The literature has progressively combined QFD with fuzzy representations, optimisation and MCDM methods to strengthen sustainable design and implementation decisions. Rough-set QFD has been applied to environmental performance evaluation; multiphase fuzzy QFD has supported sustainable service design; and integrated QFD–MCDM frameworks have addressed supply-chain agility and sustainability risk (Yang et al. 2011; Chowdhury and Quaddus 2016; Hsu et al. 2022). These studies demonstrate the capacity of hybrid QFD architectures to accommodate multiple stakeholder requirements, conflicting objectives and uncertain assessments.

A particularly relevant antecedent is the fuzzy decision-support system developed by Aghaei and Avakh Darestani (2024) for evaluating lean–green and company-specific production systems. That study confirms the value of combining contextualised lean–green criteria, QFD and fuzzy decision analysis within an industrial decision environment. The present framework advances this methodological trajectory through three consecutively linked GQFD matrices. Phase I deploys lean–green criteria into gearbox technical characteristics, Phase II propagates the resulting priorities into environmental requirements and Phase III translates environmental requirements into lean enablers. This sequential architecture establishes continuous analytical traceability from strategic and stakeholder requirements to operational implementation priorities.

2.3 | Decision-Making Approaches in Lean–Green Implementation

Lean–green decision models perform three principal analytical functions: estimating criterion importance, structuring relationships among decision factors and establishing implementation priorities. Hierarchical weighting methods such as AHP and the best–worst method derive relative importance within predefined decision structures. Relational methods such as DEMATEL, ISM and MICMAC identify influence patterns, causal prominence, hierarchical levels and driving–dependence structures. Ranking methods such as TOPSIS, PROMETHEE and VIKOR evaluate alternatives or implementation priorities against multiple and potentially conflicting criteria. The suitability of each approach is therefore determined by the analytical function assigned to it within the overall decision architecture.

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ANP extends hierarchical weighting through a network representation that accommodates dependence and feedback among decision elements (Saaty 1996). This capability is particularly relevant to lean–green implementation because leadership strategy, workforce capability, process improvement, environmental performance, supplier relationships and supply-chain coordination interact across functional and organisational boundaries. Fuzzy ANP further represents pairwise assessments expressed through linguistic judgements, allowing expert knowledge and assessment uncertainty to be incorporated into network-based priority estimation.

VIKOR performs a complementary analytical function by constructing a compromise prioritisation under conflicting criteria. The method integrates overall group utility, represented by S, with the maximum individual regret, represented by R, and produces a compromise index Q. Its interval extension retains lower and upper assessments throughout the ranking procedure, thereby preserving the uncertainty represented in the expert decision matrix (Sayadi et al. 2009). This compromise logic is appropriate when implementation priorities must exhibit strong aggregate performance while controlling their most consequential criterion-level shortfall.

Existing hybrid models demonstrate substantial progress in lean–green decision support. Oliveira et al. (2022) combine AHP and TOPSIS 2-tuple methods to assess lean–green product-development maturity; Soltani et al. (2023) integrate Pythagorean-fuzzy DEMATEL and TOPSIS to identify and prioritise lean improvement actions; Aghaei and Avakh Darestani (2024) combine fuzzy decision analysis and QFD for company-specific lean–green evaluation; Garza-Reyes et al. (2026) integrate structured review, empirical validation and AHP-based barrier prioritisation; and Hou et al. (2026) employ ISM and MICMAC to establish the hierarchy and interrelationships among green–lean product-development success factors.

The analytical configuration developed in this study assigns a distinct and complementary function to each method. FANP derives network-sensitive criterion weights; three-phase GQFD propagates requirements through technical, environmental and implementation layers; and interval VIKOR establishes the final compromise prioritisation. This configuration integrates structural weighting, requirement deployment and compromise analysis within a continuous decision pathway and enables the transformation of priorities across successive analytical stages to be explicitly examined.

Table 1 synthesises representative lean–green and adjacent sustainable-manufacturing studies by criterion-domain coverage and analytical design. The comparison clarifies the analytical positioning of the proposed framework relative to prior practice, structural-analysis, weighting and prioritisation studies.

2.4 | Research Gap

As shown in Table 1 above, the literature establishes a substantial foundation concerning lean–green practices, implementation capabilities, organisational drivers, barriers, critical success factors and performance outcomes. It also demonstrates the value of QFD, structural modelling and hybrid MCDM for supporting sustainable-manufacturing decisions. The comparative synthesis in Table 1 nevertheless identifies three interconnected analytical gaps.

First, requirement-to-action traceability remains incomplete. Existing studies identify influential practices, enablers, barriers and performance dimensions, while the analytical pathway connecting stakeholder and environmental requirements with technical characteristics, environmental priorities, lean enablers and final implementation decisions remains underdeveloped. This discontinuity constrains the conversion of strategic environmental objectives into coordinated operational actions.

Second, interdependent criterion weighting and requirement deployment have generally evolved as separate analytical streams. Structural and network methods capture relationships among organisational and operational factors, while QFD-based models translate requirements across technical domains. Their integration within a continuous deployment architecture is essential for preserving the influence of interdependencies as priorities move across successive decision layers.

Third, the literature predominantly reports a final set of weights, causal relationships or rankings. The distinction between the structural influence of a criterion within an interdependent network and its deployment salience after customer, technical, environmental and operational relationships have been incorporated remains conceptually and analytically insufficiently developed. Establishing this distinction provides an explanation of how and why implementation priorities are reconfigured across decision stages.

The proposed framework addresses these gaps through an expert-refined lean–green criteria architecture integrated with FANP, three consecutively linked GQFD matrices and interval extended VIKOR. FANP establishes network-based importance; GQFD propagates priorities through technical, environmental and lean-enabler layers; and interval VIKOR determines the compromise prioritisation emerging from the complete deployment pathway. The framework consequently contributes a unified analytical architecture that connects criteria development, interdependent weighting, requirement deployment, uncertainty representation and final implementation prioritisation. Its explanatory contribution lies in establishing how lean–green priorities are generated, propagated and reconfigured across successive stages of strategic and operational decision-making.

3 | Research Methodology

The study adopts a case-study design in the gearbox-manufacturing context of NMI. Candidate lean–green criteria and subcriteria were identified from prior lean, green and lean–green studies and organised into an initial literature-derived pool. Expert evaluation then refined this pool before the retained criteria entered the FANP, GQFD and interval VIKOR analyses.

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TABLE 1 | Comparative synthesis of representative lean–green studies: domain coverage and analytical design.

			Lean–green domain								Methodological features					
Study	**Context**	**Sector**	**LS**	**WF**	**EP**	**PR**	**TT**	**PO**	**SR**	**SC**	**STR**	**PWR**	**QFD**	**MPD**	**UNC**	**Principal contribution**
Dües et al. (2013)	Literature-based study; not empirically applied	Manufacturing supply chains		✓	✓	✓	✓	✓	✓	✓						Identifies lean–green synergies and positions lean practices as a catalyst for greening supply chains
Cherrafi et al. (2018)	Cross-sectional multicountry survey; multiple countries	Manufacturing			✓	✓	✓	✓		✓	✓					Models the relationships among lean practices, green practices, process innovation and green supply-chain performance
Saetta and Caldarelli (2020)	Industrial case study; Italy	Foundry manufacturing			✓	✓	✓	✓								Demonstrates the operational complementarity of lean and green production in an industrial foundry
Agarwal et al. (2021)	Industry case study; India	Rubber industry	✓	✓	✓	✓				✓	✓					Identifies and structures context-specific green supply-chain implementation barriers using ISM/MICMAC
Gholami et al. (2021)	Action-research industrial case study; country not reported	Substrate manufacturing			✓	✓	✓	✓								Demonstrates the industrial application of Green Lean Six Sigma for operational and environmental improvement
Kitsis and Chen (2021)	Cross-sectional empirical survey; the United States	Manufacturing and supply chains	✓		✓			✓		✓	✓					Models how stakeholder pressures and top-management commitment shape green supply-chain practices and associated outcomes
Wang et al. (2022)	Regional green manufacturing evaluation; China	Provincial manufacturing systems			✓	✓	✓	✓				✓				Evaluates regional green manufacturing performance using combination weighting and TOPSIS
Oliveira et al. (2022)	Comparative multicase study; Brazil and Japan	Metalworking SMEs/product development	✓	✓	✓	✓	✓		✓			✓			✓	Evaluates lean–green product-development maturity using AHP and TOPSIS 2-tuple across Brazilian and Japanese SMEs

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TABLE 1 | (Continued)

Study	Context	Sector	Lean–green domain								Methodological features					Principal contribution
			LS	WF	EP	PR	TT	PO	SR	SC	STR	PWR	QFD	MPD	UNC	
Farrukh et al. (2022)	Cross-country qualitative expert-interview study; New Zealand and Pakistan	Manufacturing			✓	✓		✓								Identifies and compares Green Lean Six Sigma drivers across developed- and developing-economy contexts
Farrukh et al. (2023)	Comparative multiple-case study; New Zealand and Pakistan	Flexible-packaging manufacturing	✓	✓	✓	✓		✓								Explores and compares internal and external Green Lean Six Sigma motivators across developed- and developing-economy manufacturing contexts
Hebaz et al. (2022)	Academia–industry expert assessment; Morocco, the United States, New Zealand and France	Manufacturing supply chains	✓		✓	✓	✓	✓	✓	✓		✓				Evaluates and prioritises lean, green and supply-chain practices for sustainable performance using the best–worst method
Shin and Cho (2022)	SME empirical study; South Korea	Restaurant/ service operations			✓				✓	✓	✓					Examines supplier-implemented green supply-chain practices and their relationship with SME environmental performance
Li et al. (2023)	Optimisation-focused manufacturing study; China	Manufacturing			✓	✓	✓	✓				✓				Optimises green flexible job-shop scheduling by jointly considering production efficiency and energy-related objectives
Soltani et al. (2023)	Industrial case study; country not reported	Manufacturing			✓	✓	✓	✓			✓	✓			✓	Integrates VSM, Pythagorean-fuzzy DEMATEL and PF-TOPSIS to analyse and prioritise sustainable lean improvement solutions
Debnath et al. (2023)	Industry-based empirical study; Bangladesh	Apparel manufacturing	✓	✓	✓		✓	✓	✓	✓	✓				✓	Identifies and structures critical success factors for green supply-chain implementation using Grey-DEMATEL

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TABLE 1 | (Continued)

Study	Context	Sector	Lean–green domain								Methodological features					Principal contribution
			LS	WF	EP	PR	TT	PO	SR	SC	STR	PWR	QFD	MPD	UNC	
Aghaei and Avakh Darestani (2024)	Single-OEM industrial case study; country not reported	Tractor-manufacturing supply chain			✓	✓	✓	✓		✓		✓	✓		✓	Develops a fuzzy QFD-based decision-support model for lean–green and company-specific production-system evaluation
Garza-Reyes et al. (2026)	Mixed-methods empirical study; Indonesia	Manufacturing	✓	✓			✓				✓	✓				Validates, structures and prioritises green–lean implementation barriers through SLR, EFA and AHP and develops sequenced implementation guidance
Hou et al. (2026)	Expert-panel structural study; predominantly Chinese panel	Manufacturing product development	✓	✓	✓	✓	✓			✓	✓					Identifies 19 critical success factors and establishes their hierarchical and interdependent structure for green–lean product development in the Industry 4.0 era
Villegas et al. (2026)	Industrial case study; Peru	Textile manufacturing and supply chain			✓	✓	✓	✓		✓						Demonstrates the integration of lean, green and circular practices for sustainable operations and supply-chain transformation
Current study	Single-company, expert-informed industrial case study; Iran	Automotive gearbox manufacturing	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Integrates FANP, three-phase GQFD and interval VIKOR to connect network-based importance, requirement deployment and compromise prioritisation under uncertainty

Abbreviations: EP = environmental performance; LS = leadership strategy; MPD = multiphase deployment; PO = performance outcomes; PR = process; PWR = preference-based weighting/ranking; QFD = quality function deployment; SC = supply chain; SR = supplier relationships; STR = structural/factor/relational analysis; TT = techniques and tools; UNC = uncertainty modelling; WF = workforce.

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The methodological architecture integrates the fuzzy analytic network process (FANP), three-phase GQFD and interval extended VIKOR in a sequential framework. These methods perform complementary analytical functions: FANP determines the relative importance of interdependent lean–green criteria and subcriteria under judgemental uncertainty; three-phase GQFD systematically propagates these priorities through technical characteristics and environmental requirements to lean enablers; and interval extended VIKOR provides the final compromise-based prioritisation of the lean–green criteria under interval-valued expert assessments. The research process and general framework are presented in Figure 1.

Data collection combined literature sources, company information, expert questionnaires, interviews and operational observations. Literature sources supported candidate-item identification; NMI information supplied the case-specific technical inputs; and expert input supported criteria screening, pairwise comparisons, GQFD relationship assessments and interval VIKOR evaluations.

The initial candidate structure comprised 15 criteria and 55 subcriteria. The panel comprised 15 experts who met three competence criteria: an organisational position at specialist level or above, a master's degree or higher and at least 10 years of professional experience. The same panel participated in the questionnaire-based analytical stages.

The candidate criteria and subcriteria were screened for importance, contextual relevance and conceptual overlap. Subcriteria with expert-rated importance below 50% were excluded. The panel also consolidated overlapping constructs and removed items subsumed by broader retained constructs, including some items that exceeded the numerical threshold. This refinement yielded eight criteria and 42 subcriteria for the FANP analysis.

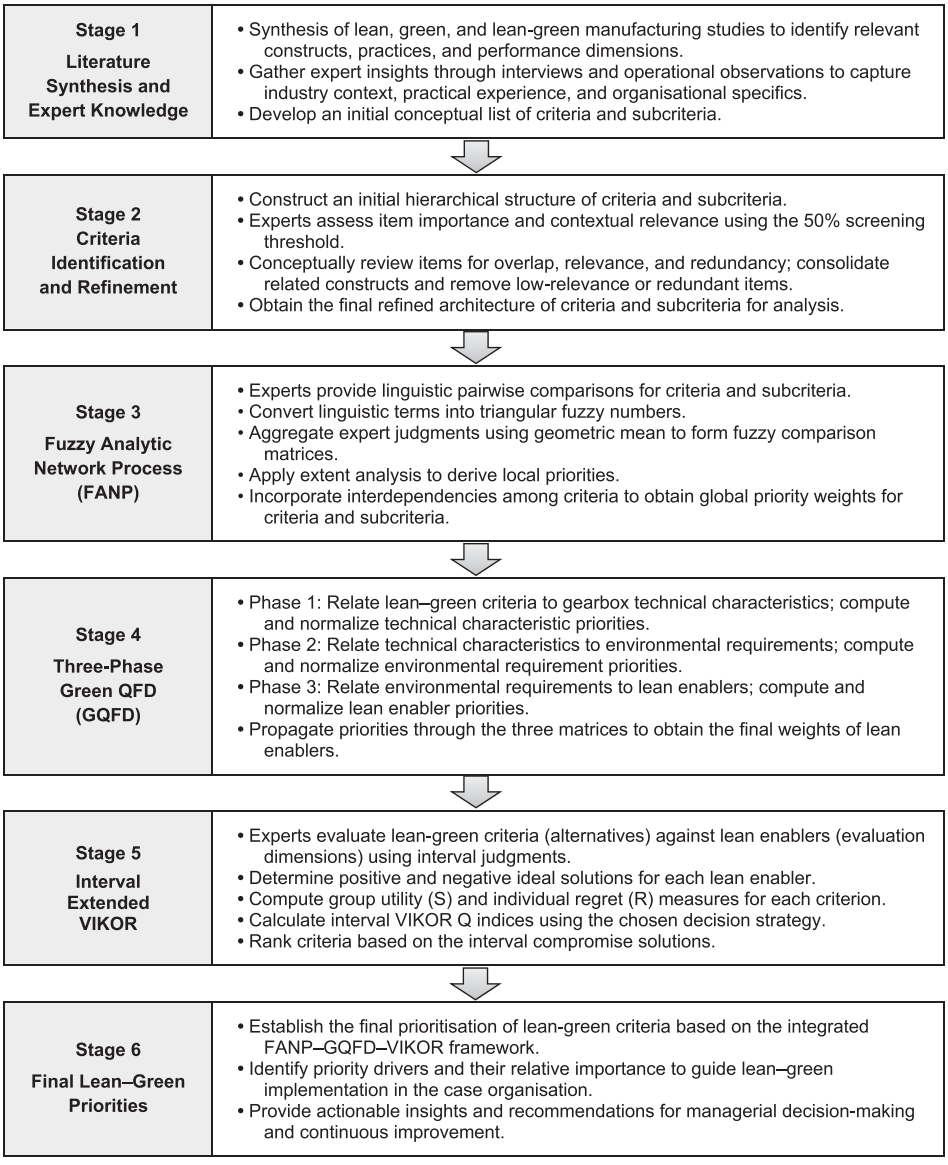


FIGURE 1 | Integrated research methodology.

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TABLE 2 | Random index (RI) values.

n	1	2	3	4	5	6	7	8	9	10	11	12	13
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.42	1.45	1.49	1.51	1.56	1.57

Content validity was assessed through expert review of the candidate constructs and questionnaire content prior to the analytical stages. Internal consistency of the questionnaire used for criteria screening was assessed using Cronbach's alpha in SPSS ($\alpha = 0.796$). Consistency of the FANP pairwise judgements was evaluated separately using the CI and CR procedure described in Section 3.1. Microsoft Excel was used for the FANP, GQFD and interval VIKOR calculations.

3.1 | Calculation of Consistency Ratio (CR)

Because FANP relies on pairwise judgements, the logical consistency of the comparison matrices was assessed before their priorities were used in subsequent calculations. Consistency assessment follows the eigenvalue-based pairwise-comparison logic established in the AHP/ANP tradition, while explicit reporting of judgement consistency is important for transparent and reproducible ANP applications (Saaty 1980; Mu et al. 2020).

The consistency index (CI) is calculated as

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1} \tag{1}$$

where $\lambda_{\max}$ denotes the maximum eigenvalue of the pairwise-comparison matrix and n denotes the order of the matrix.

The CR is subsequently calculated as

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

where RI represents the random index corresponding to matrix order n. The standard terms CI, RI and CR are used throughout the analysis to maintain consistency with established pairwise-comparison terminology. A comparison matrix is regarded as acceptably consistent when $\mathrm{CR} \leq 0.10$; matrices exceeding this threshold require reconsideration of the underlying pairwise judgements. Table 2 presents the RI values used in the consistency assessment.

If the resulting CR is less than or equal to 0.10, the pairwise comparisons are sufficiently consistent and the analysis can proceed. Otherwise, the decision makers are required to revise the relevant comparisons.

3.2 | FANP

FANP extends conventional ANP by incorporating fuzzy linguistic judgements into pairwise comparisons. Triangular fuzzy numbers were adopted because their lower–modal–upper representation captures the imprecision of linguistic assessments while remaining transparent and computationally compatible with geometric aggregation and Chang's extent-analysis procedure.

ANP is particularly appropriate to the present decision problem because lean–green criteria cannot be adequately represented through a strictly hierarchical structure: leadership strategy, workforce, environmental performance, process, techniques and tools, performance outcomes, supplier relationships and supply-chain dimensions may exhibit interdependence and feedback. The capacity of ANP to represent such dependencies is central to its use in complex multicriteria decision systems, and careful specification of the network and supermatrix is essential for methodological transparency (Mu et al. 2020).

A triangular fuzzy judgement is denoted by $\tilde{a} = (l, m, u)$, where l, m and u represent the lower, modal and upper values, respectively; its reciprocal is $\tilde{a}^{-1} = (1/u, 1/m, 1/l)$. The nine-point comparison scale adopted in the study was used to translate linguistic assessments into fuzzy pairwise-comparison values.

Based on the final criteria and subcriteria and expert judgement concerning their relationships, the FANP decision network was constructed as presented in Figure 2.

The FANP procedure was implemented in six linked analytical steps. First, the decision network was constructed using the final eight lean–green criteria and their 42 subcriteria, and the interdependencies among the main criteria were incorporated according to expert judgement.

Second, fuzzy pairwise-comparison matrices were developed for the relevant criteria and subcriteria. The individual assessments of the 15 experts were aggregated using the geometric mean. Accordingly, the aggregated fuzzy judgement for elements i and j can be represented within the text as $\tilde{a}_{ij} = \left(\prod_{r=1}^{15} \tilde{a}_{ij}^{(r)} \right)^{1/15}$. The corresponding pairwise-comparison matrices were accepted only after satisfying the consistency requirement described by Equations (1) and (2).

For the extent-analysis calculations, let $\tilde{M} = \left[\tilde{M}_{ij} \right]$ denote the resulting aggregated fuzzy pairwise-comparison matrix.

Third, local fuzzy priorities were calculated using the extent-analysis procedure. For each element, the fuzzy synthetic extent was obtained from its row-wise fuzzy comparisons relative to the inverse of the total fuzzy comparison sum; compactly, $\tilde{S}_i = \left(\sum_j \tilde{M}_{ij} \right) \otimes \left[\sum_p \sum_q \tilde{M}_{pq} \right]^{-1}$. Degrees of possibility between the resulting fuzzy synthetic extents were then evaluated, and the minimum possibility values were normalised to derive the local priority vectors.

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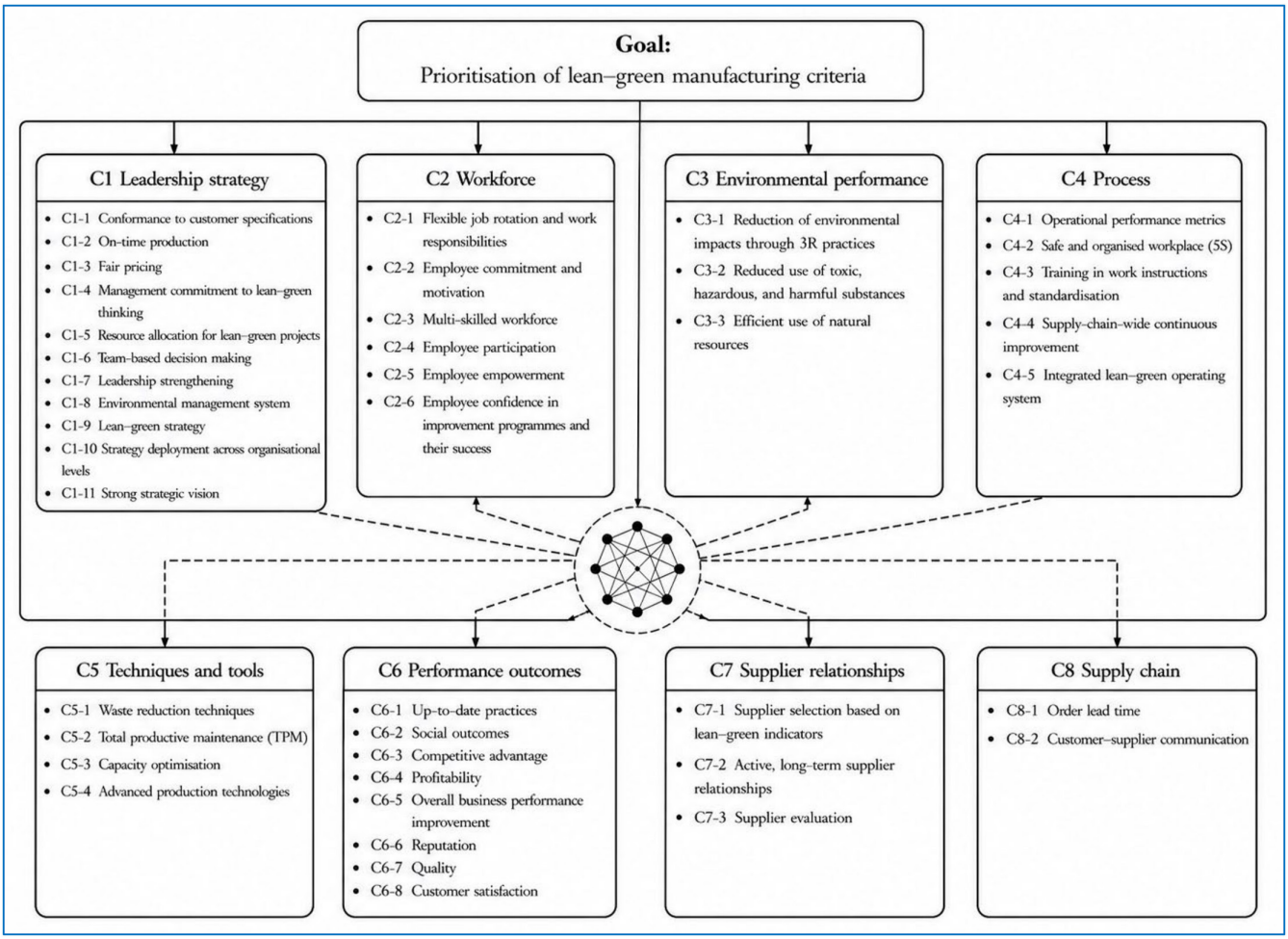


FIGURE 2 | FANP decision network for the lean–green criteria and subcriteria.

Fourth, these local priority vectors were assembled into the unweighted supermatrix W_u so that the dependence relationships among the network elements were explicitly represented. Fifth, the relevant cluster priorities were incorporated to obtain a weighted, column-stochastic supermatrix W_w. Sixth, the weighted supermatrix was successively raised to powers until its entries stabilised, producing the limit supermatrix W_∞ and the long-run priorities of the network elements. This convergence can be expressed compactly as $W_\infty = \lim_{k\to\infty}\left(W_w\right)^k$.

The resulting global priorities constitute the final FANP weights of the eight lean–green criteria. For consistency with the subsequent GQFD analysis, these weights are denoted by w_i^C, $i = 1, \ldots, 8$, and collected in the vector $\mathrm{w}^C = \left(w_1^C, \ldots, w_8^C\right)^T$. The FANP weights provide the quantitative input to the first phase of GQFD.

3.3 | QFD Model

QFD is a structured approach for translating requirements into technical or operational characteristics. Its principal matrix, the HOQ, begins by identifying the requirements to be satisfied—the 'Whats'—and their relative importance. The technical means through which these requirements can be addressed—the 'Hows'—are then identified, and a relationship matrix links the two sets of elements.

QFD has been extensively developed as a systematic mechanism for translating customer and stakeholder requirements into technical and design characteristics, with the HOQ providing the core structure for linking requirement importance to technical responses (Chan and Wu 2002). Within the proposed integrated framework, the same weighting logic provides the analytical mechanism through which priorities are propagated from one GQFD phase to the next.

For a generic HOQ containing n input requirements and m output characteristics, the absolute importance of output characteristic q is calculated as

$$AI_q = \sum_{p=1}^{n} w_p d_{pq} \tag{3}$$

where w_p denotes the importance weight of input requirement p, d_{pq} represents the relationship between input requirement p and output characteristic q and AI_q is the resulting absolute importance of output characteristic q.

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The corresponding relative weight is obtained through normalisation:

$$w_q = \frac{AI_q}{\sum_{s=1}^{m} AI_s} \tag{4}$$

where w_q denotes the normalised importance of output characteristic q. The symbols w_p and w_q in Equations (3) and (4) are used only as generic input- and output-weight notation for a generic HOQ; the phase-specific weights are denoted by w_i^C, w_j^T, w_k^R and w_l^A in Section 3.4.

Equations (3) and (4) are applied successively across the three GQFD phases so that the output weights generated in one phase constitute the input weights of the following phase.

3.4 | GQFD

GQFD extends the QFD approach by incorporating environmental considerations into the translation of requirements into technical and operational responses. In the present study, GQFD is used to identify and weight lean enablers, which subsequently constitute the evaluation dimensions of the interval extended VIKOR model.

This extension is consistent with the broader development of GQFD as a means of incorporating environmental considerations into product and process decision-making while retaining the requirement-to-technical-response logic of conventional QFD (Wu and Ho 2015).

The empirical contents of the three GQFD houses were established using both company-specific information and expert-informed inputs. The gearbox technical characteristics were derived from product and production information supplied by NMI, while the environmental requirements and lean enablers were identified and refined with reference to previous studies and the judgements of relevant industry experts. This combination operationalises the GQFD framework within the specific manufacturing context examined in the study. The three-phase GQFD architecture is presented in Figure 3.

To maintain consistent notation throughout the three houses, C_i, $i = 1, \ldots, 8$, denotes the lean–green criteria; T_j, $j = 1, \ldots, 11$, denotes the technical characteristics; R_k, $k = 1, \ldots, 22$, denotes the environmental requirements; and A_ℓ, $\ell = 1, \ldots, 10$, denotes the lean enablers. The corresponding relationship matrices can therefore be represented within the text as $D^{(1)} = \left[d_{ij}^{(1)}\right]_{8\times11}$, $D^{(2)} = \left[d_{jk}^{(2)}\right]_{11\times22}$ and $D^{(3)} = \left[d_{k\ell}^{(3)}\right]_{22\times10}$. The expert panel assessed the relationships within each GQFD house using the study's 1–3–9 scoring structure; blank cells indicate relationships for which no score was assigned.

In Phase I, the eight FANP-weighted lean–green criteria C_i constitute the rows of the first HOQ, while the 11 gearbox technical characteristics T_j constitute its columns. The FANP weights w_i^C are used as the row-importance values. Applying Equations (3) and (4) to the Phase I relationship matrix produces the relative technical-characteristic weights w_j^T.

In Phase II, the 11 technical characteristics T_j become the row requirements, weighted by the w_j^T values transferred from Phase

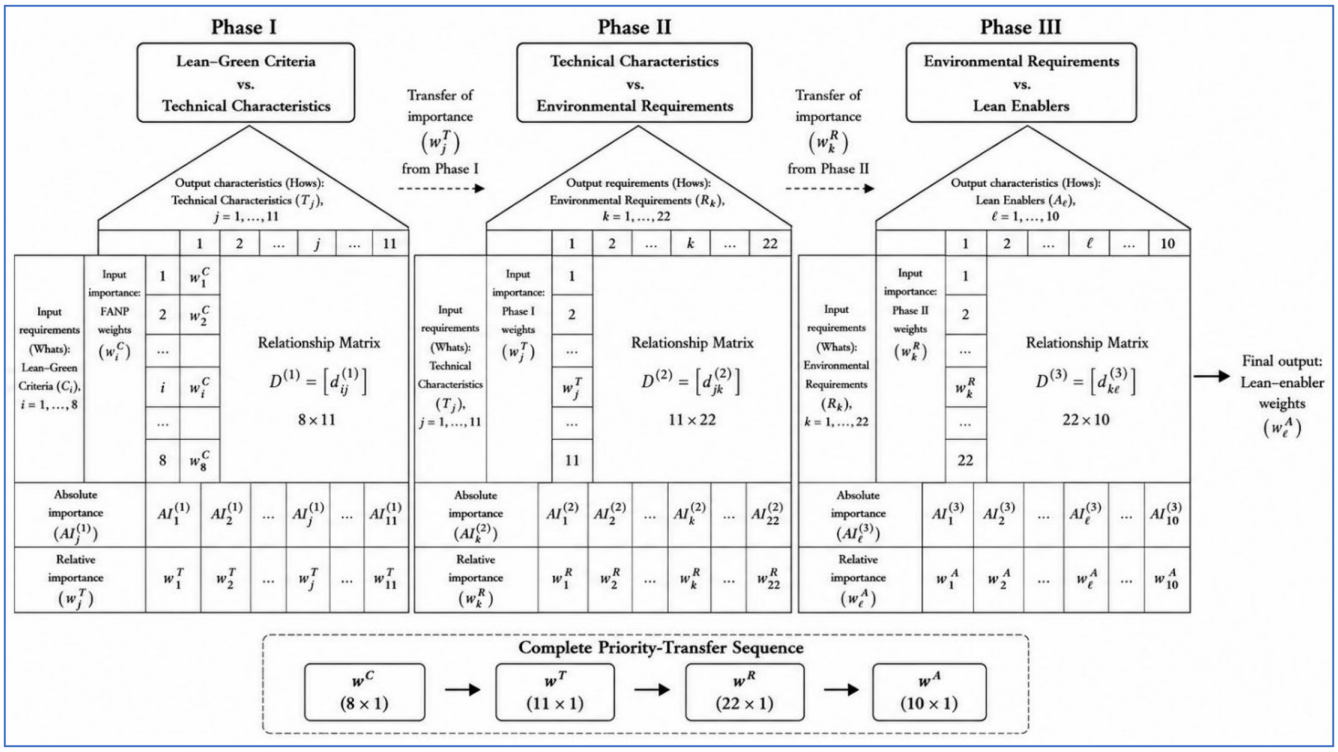


FIGURE 3 | Three-phase GQFD architecture.

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I, while the 22 environmental requirements R_k form the columns. Application of the same QFD weighting and normalisation procedure produces the environmental-requirement weights w_k^R.

In Phase III, the 22 environmental requirements R_k, weighted by w_k^R, constitute the rows, while the 10 lean enablers A_ℓ constitute the columns. The resulting output is the final lean-enabler weight vector w_ℓ^A. Defining $\mathrm{w}^T = \left(w_1^T, \ldots, w_{11}^T\right)^T$, $\mathrm{w}^R = \left(w_1^R, \ldots, w_{22}^R\right)^T$ and $\mathrm{w}^A = \left(w_1^A, \ldots, w_{10}^A\right)^T$, the complete priority-transfer sequence can be represented compactly as $\mathrm{w}^C \to \mathrm{w}^T \to \mathrm{w}^R \to \mathrm{w}^A$.

The final w_ℓ^A values provide the evaluation weights for the subsequent interval extended VIKOR analysis. In that decision matrix, the eight lean–green criteria C_i constitute the alternatives to be prioritised, while the 10 lean enablers A_ℓ constitute the evaluation dimensions.

3.5 | Extended VIKOR

The VIKOR method addresses multicriteria problems in which alternatives must be ranked under conflicting evaluation dimensions and seeks a compromise solution that balances overall group utility against the maximum individual regret. This compromise-ranking logic distinguishes VIKOR from distance-based ranking procedures that rely only on proximity to ideal and anti-ideal reference points (Opricovic and Tzeng 2004). Sayadi et al. (2009) subsequently extended the VIKOR framework to decision problems involving interval numbers, enabling uncertainty in the evaluation matrix to be retained throughout the compromise-ranking procedure.

After the Phase III lean-enabler weights were obtained, the experts evaluated each lean–green criterion against the 10 lean enablers using interval judgements on a 1–9 scale elicited through questionnaires and interviews. The resulting VIKOR decision matrix contains eight alternatives C_i, corresponding to the eight lean–green criteria, and 10 evaluation dimensions, corresponding to the 10 lean enablers. An interval assessment is represented as $\widetilde{f}_{il} = \left[f_{il}^L, f_{il}^U\right]$, while w_l^A denotes the final weight of lean enabler A_l obtained from GQFD. In the VIKOR calculations, $i = 1, \ldots, 8$ indexes the alternatives C_i, whereas $l = 1, \ldots, 10$ indexes the lean-enabler evaluation dimensions. To avoid confusion between the environmental-requirement notation R_k used in GQFD and the VIKOR regret measure, the latter is denoted by R_i^V.

The interval extended VIKOR procedure involves four linked operations: determining the positive and negative ideal values, calculating interval group utility and maximum regret, calculating the interval compromise index Q_i and comparing the resulting interval Q values to establish the final ranking.

First, the positive ideal solution (PIS) and negative ideal solution (NIS) are determined. Let J_b denote the set of benefit-type evaluation dimensions and J_c the set of cost-type dimensions.

$$f_l^* = \begin{cases} \max\limits_i f_{il}^U, & l \in J_b, \\ \min\limits_i f_{il}^L, & l \in J_c \end{cases} \tag{5}$$

The corresponding negative ideal value is

$$f_l^- = \begin{cases} \min\limits_i f_{il}^L, & l \in J_b, \\ \max\limits_i f_{il}^U, & l \in J_c \end{cases} \tag{6}$$

Second, the interval group-utility measure $S_i = \left[S_i^L, S_i^U\right]$ and the interval individual-regret measure $R_i^V = \left[R_i^{V,L}, R_i^{V,U}\right]$ are calculated. The lower bound of the group-utility measure is

$$S_i^L = \sum\nolimits_{l \in J_b} w_l^A \frac{f_l^* - f_{il}^U}{f_l^* - f_l^-} + \sum\nolimits_{l \in J_c} w_l^A \frac{f_{il}^L - f_l^*}{f_l^- - f_l^*} \tag{7}$$

The corresponding upper bound is

$$S_i^U = \sum\nolimits_{l \in J_b} w_l^A \frac{f_l^* - f_{il}^L}{f_l^* - f_l^-} + \sum\nolimits_{l \in J_c} w_l^A \frac{f_{il}^U - f_l^*}{f_l^- - f_l^*} \tag{8}$$

The lower bound of the individual-regret measure is

$$R_i^{V,L} = \max\left\{ \max_{l \in J_b}\left[w_l^A \frac{f_l^* - f_{il}^U}{f_l^* - f_l^-} \right], \max_{l \in J_c}\left[w_l^A \frac{f_{il}^L - f_l^*}{f_l^- - f_l^*} \right] \right\} \tag{9}$$

The corresponding upper bound is

$$R_i^{V,U} = \max\left\{ \max_{l \in J_b}\left[w_l^A \frac{f_l^* - f_{il}^L}{f_l^* - f_l^-} \right], \max_{l \in J_c}\left[w_l^A \frac{f_{il}^U - f_l^*}{f_l^- - f_l^*} \right] \right\} \tag{10}$$

Third, the interval VIKOR compromise index $Q_i = \left[Q_i^L, Q_i^U\right]$ is calculated. Its lower bound is

$$Q_i^L = v \frac{S_i^L - S^*}{S^- - S^*} + (1 - v) \frac{R_i^{V,L} - R^*}{R^- - R^*} \tag{11}$$

and its upper bound is

$$Q_i^U = v \frac{S_i^U - S^*}{S^- - S^*} + (1 - v) \frac{R_i^{V,U} - R^*}{R^- - R^*} \tag{12}$$

The best and worst group-utility reference values are

$$S^* = \min_i S_i^L, \qquad S^- = \max_i S_i^U \tag{13}$$

The corresponding reference values for individual regret are

$$R^* = \min_i R_i^{V,L}, \qquad R^- = \max_i R_i^{V,U} \tag{14}$$

The parameter $v \in [0, 1]$ controls the balance between the strategy of maximum group utility and that of minimum individual regret. In this study, $v = 0.50$ was adopted, assigning equal importance to the two compromise perspectives.

Finally, the interval Q_i values were ranked using the interval-comparison rules of Sayadi et al. (2009). For two intervals $a = \left[a^L, a^U\right]$ and $b = \left[b^L, b^U\right]$, a precedes b when $a^U \le b^L$; identical intervals receive the same rank. For partial overlap, when $a^L < b^L < a^U < b^U$, a precedes b, with the reverse configuration

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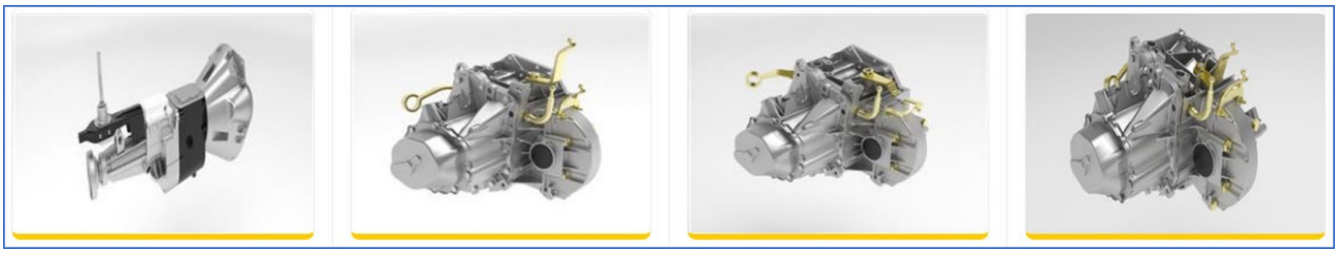


FIGURE 4 | Representative gearbox products manufactured by NMI Manufacturing Company (2023).

treated symmetrically. When one interval is nested within the other, for example, $a^L \le b^L \le b^U \le a^U$, their ordering is determined using the condition $\alpha\left(b^L - a^L\right) \ge (1-\alpha)\left(a^U - b^U\right)$. If the condition is satisfied, a precedes b; otherwise, b precedes a. The neutral decision setting $\alpha = 0.50$ was used in this study.

After applying these interval-comparison rules, the Q_i intervals are ordered from smallest to largest. A smaller Q_i interval indicates greater proximity to the compromise ideal and therefore a higher final priority. This final comparison stage preserves the uncertainty represented by the interval assessments instead of prematurely reducing each interval to a single crisp value.

4 | Analysis and Results

NMI Manufacturing Company operates in the automotive and motorcycle sectors and was established in 1986. The company is located in Alborz Industrial Town, Qazvin, and manufactures different types of automotive gearboxes. NMI has implemented ISO 9001, ISO/TS 16949 and ISO 14001 management standards and has pursued organisational excellence programmes since 2004 (NMI Manufacturing Company 2023). The present case application examines the lean–green production system within NMI's gearbox-manufacturing operations. Figure 4 presents representative gearbox products manufactured by NMI.

Following the screening procedure described in Section 3, the initial set of 15 criteria and 55 subcriteria was refined to eight criteria and 42 subcriteria. The screening instrument yielded Cronbach's $\alpha = 0.796$. The main criteria-comparison matrix yielded CR = 0.023, and all subcriterion matrices met the CR ≤ 0.10 acceptance criterion specified in Section 3. Accordingly, all pairwise-comparison matrices were retained for the FANP analysis, whose resulting priorities were subsequently propagated through the GQFD and interval extended VIKOR stages.

Results are reported in the same sequence as the analytical framework in Section 3. Section 4.1 presents the fuzzy pairwise comparisons, Section 4.2 derives the FANP priorities, Section 4.3 reports the three GQFD deployment phases and Section 4.4 presents the interval extended VIKOR analysis and final compromise ranking.

4.1 | Pairwise Comparisons

The experts' linguistic pairwise judgements for the retained criteria and subcriteria were converted into triangular fuzzy numbers and aggregated using the geometric mean, as specified in Section 3. Pairwise comparisons were conducted first for the eight main criteria and then within each subcriterion cluster. The main-criterion aggregates underpin the criterion-level calculations reported in Tables 3–7, while the subcriterion-level aggregates contribute to the local priority vectors incorporated into the FANP supermatrix and to the global subcriterion weights reported in Table 8.

TABLE 3 | First-stage quantities in Chang's extent analysis.

Main criterion C_k	Fuzzy row total for C_k $\sum_{j=1}^{8} \widetilde{M}_{kj}$
C1	(16.40, 32.01, 44.00)
C2	(4.50, 9.01, 19.06)
C3	(11.48, 21.13, 35.43)
C4	(3.63, 5.35, 13.03)
C5	(2.82, 3.93, 9.13)
C6	(17.11, 29.58, 43.33)
C7	(23.20, 37.65, 50.00)
C8	(2.07, 3.19, 5.83)
Grand fuzzy sum over the 8 × 8 criterion matrix $\sum_{i=1}^{8} \sum_{j=1}^{8} \widetilde{M}_{ij}$	(81.21, 141.85, 219.81)
Inverse grand fuzzy sum $\left(\sum_{i=1}^{8} \sum_{j=1}^{8} \widetilde{M}_{ij}\right)^{-1}$	(0.004549, 0.007050, 0.012314)

4.2 | Determining the Relative Weight of Elements

The extent-analysis procedure described in Section 3 transforms the aggregated fuzzy comparison matrix into local priority vectors. In the 8 × 8 main-criterion matrix, C_k denotes the focal row criterion and C_j the criterion against which it is compared, with $k, j \in \{1, \ldots, 8\}$. The triangular fuzzy entry in row k and column j is $\widetilde{M}_{kj}$. For a fixed criterion C_k, the fuzzy row total is $\sum_{j=1}^{8} \widetilde{M}_{kj}$. Using i as the dummy row index, the grand fuzzy sum over the complete main-criterion matrix is $\sum_{i=1}^{8} \sum_{j=1}^{8} \widetilde{M}_{ij}$. Its inverse enters the criterion-specific synthetic-extent calculation. Table 3 reports these quantities.

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TABLE 4 | Fuzzy synthetic extents for the main criteria.

Criterion/synthetic extent	Fuzzy row total for C_k $\sum_{j=1}^{8} \widetilde{M}_{kj}$	Inverse grand fuzzy sum $\left(\sum_{i=1}^{8} \sum_{j=1}^{8} \widetilde{M}_{ij}\right)^{-1}$	Synthetic extent $\widetilde{S}_k$
$C_1\left(\widetilde{S}_1\right)$	(16.40, 32.01, 44.00)	(0.004549, 0.007050, 0.012314)	(0.07461, 0.22566, 0.54181)
$C_2\left(\widetilde{S}_2\right)$	(4.50, 9.01, 19.06)	(0.004549, 0.007050, 0.012314)	(0.02047, 0.06352, 0.23470)
$C_3\left(\widetilde{S}_3\right)$	(11.48, 21.13, 35.43)	(0.004549, 0.007050, 0.012314)	(0.05223, 0.14896, 0.43628)
$C_4\left(\widetilde{S}_4\right)$	(3.63, 5.35, 13.03)	(0.004549, 0.007050, 0.012314)	(0.01651, 0.03772, 0.16045)
$C_5\left(\widetilde{S}_5\right)$	(2.82, 3.93, 9.13)	(0.004549, 0.007050, 0.012314)	(0.01283, 0.02771, 0.11242)
$C_6\left(\widetilde{S}_6\right)$	(17.11, 29.58, 43.33)	(0.004549, 0.007050, 0.012314)	(0.07784, 0.20853, 0.53355)
$C_7\left(\widetilde{S}_7\right)$	(23.20, 37.65, 50.00)	(0.004549, 0.007050, 0.012314)	(0.10555, 0.26542, 0.61569)
$C_8\left(\widetilde{S}_8\right)$	(2.07, 3.19, 5.83)	(0.004549, 0.007050, 0.012314)	(0.00942, 0.02249, 0.07179)

TABLE 5 | Degrees of possibility among the fuzzy synthetic extents.

$V\left(\widetilde{S}_i \geq \widetilde{S}_k\right)$	$\widetilde{S}_1$	$\widetilde{S}_2$	$\widetilde{S}_3$	$\widetilde{S}_4$	$\widetilde{S}_5$	$\widetilde{S}_6$	$\widetilde{S}_7$	$\widetilde{S}_8$
$\widetilde{S}_1$	—	1.0000	1.0000	1.0000	1.0000	1.0000	0.9165	1.0000
$\widetilde{S}_2$	0.4968	—	0.6811	1.0000	1.0000	0.5196	0.3901	1.0000
$\widetilde{S}_3$	0.8250	1.0000	—	1.0000	1.0000	0.8575	0.7396	1.0000
$\widetilde{S}_4$	0.3135	0.8444	0.4931	—	1.0000	0.3260	0.1943	1.0000
$\widetilde{S}_5$	0.1604	0.7197	0.3318	0.9055	—	0.1606	0.0281	1.0000
$\widetilde{S}_6$	0.9640	1.0000	1.0000	1.0000	1.0000	—	0.8827	1.0000
$\widetilde{S}_7$	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	—	1.0000
$\widetilde{S}_8$	0.0000	0.5557	0.1340	0.7840	0.9187	0.0000	0.0000	—

TABLE 6 | Minimum possibility values and normalised local FANP weights.

Criterion code	Criterion	Minimum pairwise possibility $\min_{k=1,\ldots,8,\ k\neq i} V\left(\widetilde{S}_i \geq \widetilde{S}_k\right)$	Normalised local FANP weight w_i^{local}
C1	Leadership strategy	0.916473	0.220771
C2	Workforce	0.390127	0.093978
C3	Environmental performance	0.739572	0.178157
C4	Process	0.194271	0.046798
C5	Techniques and tools	0.028124	0.006775
C6	Performance outcomes	0.882675	0.212629
C7	Supplier relationships	1.000000	0.240892
C8	Supply chain	0.000000	0.000000

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TABLE 7 | Criterion-level FANP priorities and ranking.

Criterion	FANP weight w_i^C	Rank
Workforce	0.23	1
Environmental performance	0.18	2
Process	0.16	3
Supply chain	0.12	4
Leadership strategy	0.11	5
Performance outcomes	0.09	6
Supplier relationships	0.06	7
Techniques and tools	0.02	8

For a fixed main criterion C_k with $k = 1, \ldots, 8$, the fuzzy synthetic extent is $\widetilde{S}_k = \left(\sum_{j=1}^{8} \widetilde{M}_{kj}\right) \otimes \left(\sum_{i=1}^{8}\sum_{j=1}^{8} \widetilde{M}_{ij}\right)^{-1}$. Substitution of Table 3 values for C1 gives $\widetilde{S}_1 = (16.40, 32.01, 44.00) \otimes (0.004549, 0.007050, 0.012314) = (0.07461, 0.22566, 0.54181)$. Table 4 reports the resulting synthetic extent for each main criterion.

The fuzzy synthetic extents are then compared pairwise. For $i, k \in \{1, \ldots, 8\}, i \neq k$, $V\left(\widetilde{S}_i \geq \widetilde{S}_k\right)$ denotes the degree of possibility that the synthetic extent associated with criterion i is at least as large as that associated with criterion k. Table 5 reports the resulting pairwise possibility matrix.

For each criterion i, the retained minimum degree of possibility is $\min_{\substack{k=1,\ldots,8 \\ k \neq i}} V\left(\widetilde{S}_i \geq \widetilde{S}_k\right)$. Normalising these eight minima yields the local FANP priority vector reported in Table 6.

Normalisation yields $W^{local} = (0.22077, 0.09398, 0.17816, 0.04680, 0.00677, 0.21263, 0.24089, 0.00000)^T = \left(w_1^{local} \ldots w_8^{local}\right)^T$ for criteria C1–C8, respectively. To incorporate the dependence structure represented in Figure 2, the relevant local priority vectors populate the unweighted supermatrix W_u. Cluster weights transform W_u into the column-stochastic weighted supermatrix W_w, and successive powers of W_w yield the limit supermatrix W_∞ once the entries converge. Table 7 reports the criterion-level priorities, while Table 8 reports the corresponding criterion and global subcriterion weights used in the deployment analysis.

At criterion level, Workforce has the largest FANP weight (0.23), followed by Environmental performance (0.18) and Process (0.16). Supply chain (0.12) and Leadership strategy (0.11) follow, whereas Performance outcomes (0.09), Supplier relationships (0.06) and Techniques and tools (0.02) occupy the lower positions.

Table 8 reports the complete 42-subcriterion structure and the associated global weights. The criterion weights shown in Table 8 serve as the row-importance values in the first GQFD matrix.

4.3 | Three-Phase GQFD

The three-phase GQFD analysis propagates the FANP-derived priorities through linked technical, environmental and operational relationship matrices. As described in Section 3, the gearbox technical characteristics are case-specific inputs supplied by NMI, whereas the environmental requirements and lean enablers are literature-informed constructs refined through expert judgement. Relationship strength is coded on the study's 1–3–9 scale, and blank cells denote relationships for which no score was assigned. Equations (3) and (4) in Section 3 are applied in each phase, with the normalised output vector from one phase becoming the input-weight vector for the next.

4.3.1 | Phase I: Lean–Green Criteria and Gearbox Technical Characteristics

In Phase I, the eight FANP-weighted lean–green criteria form the weighted input set, and the 11 gearbox technical characteristics supplied by NMI form the output set. For each technical characteristic, the criterion contributions are aggregated across the eight lean–green criteria according to $AI_j^{(1)} = \sum_{i=1}^{8} w_i^C \, d_{ij}^{(1)}, j = 1, \ldots, 11$. Normalisation according to Equation (4) then gives the Phase I relative weight w_j^T. Table 9 reports the complete Phase I relationship matrix and the resulting technical-characteristic priorities.

Lubricant type (0.200) and Housing type (0.185) have the largest Phase I relative weights, followed by Visual condition (0.150), Auxiliary components (0.124) and Leak-test performance (0.103). The Phase I relative-weight vector is then used as the input-weight vector for Phase II.

4.3.2 | Phase II: Technical Characteristics and Environmental Requirements

Phase II treats the 11 technical characteristics as weighted inputs and the 22 environmental requirements as outputs. For each environmental requirement, the transferred Phase I weights are combined with the Phase II relationship scores according to $AI_k^{(2)} = \sum_{j=1}^{11} w_j^T \, d_{jk}^{(2)}, k = 1, \ldots, 22$. Normalisation then gives the Phase II environmental-requirement weight w_k^R. Collectively, the 22 requirements cover resource consumption, pollution prevention, end-of-life handling, safety, durability, recyclability and assembly. Table 10 reports the complete matrix and the resulting environmental priorities.

Reliability and durability receives the highest Phase II relative weight (0.121), followed by Waste reduction (0.096), Ease of reuse (0.085), Ease of joining (0.079), Ease of assembly (0.075) and Air pollution (0.072). The resulting environmental-weight vector becomes the input to Phase III.

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TABLE 8 | Final FANP weights of the lean–green criteria and subcriteria.

Criterion code	Criterion	Criterion weight	Subcriterion code	Subcriterion	Global subcriterion weight
C1	Leadership strategy	11%	C1-1	Conformance to customer specifications	1.25%
			C1-2	On-time production	1.13%
			C1-3	Fair pricing	1.13%
			C1-4	Management commitment to lean–green thinking	1.13%
			C1-5	Resource allocation for lean–green projects	1.06%
			C1-6	Team-based decision-making	1.01%
			C1-7	Leadership strengthening	0.94%
			C1-8	Environmental management system	0.95%
			C1-9	Lean–green strategy	0.88%
			C1-10	Strategy deployment across organisational levels	0.75%
			C1-11	Strong strategic vision	0.77%
C2	Workforce	23%	C2-1	Flexible job rotation and work responsibilities	2.30%
			C2-2	Employee commitment and motivation	5.52%
			C2-3	Multi-skilled workforce	1.61%
			C2-4	Employee participation	5.98%
			C2-5	Employee empowerment	4.83%
			C2-6	Employee confidence in improvement programmes and their success	2.76%
C3	Environmental performance	18%	C3-1	Reduction of environmental impacts through 3R practices	9.00%
			C3-2	Reduced use of toxic, hazardous and harmful substances	6.66%
			C3-3	Efficient use of natural resources	2.34%
C4	Process	16%	C4-1	Operational performance metrics	2.40%
			C4-2	Safe and organised workplace (5S)	4.16%
			C4-3	Training in work instructions and standardisation	2.40%
			C4-4	Supply-chain-wide continuous improvement	2.88%
			C4-5	Integrated lean–green operating system	4.16%

(Continues)

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TABLE 8 | (Continued)

Criterion code	Criterion	Criterion weight	Subcriterion code	Subcriterion	Global subcriterion weight
C5	Techniques and tools	2%	C5-1	Waste reduction techniques	0.64%
			C5-2	Total productive maintenance (TPM)	0.36%
			C5-3	Capacity optimisation	0.52%
			C5-4	Advanced production technologies	0.48%
C6	Performance outcomes	9%	C6-1	Up-to-date practices	1.44%
			C6-2	Social outcomes	1.35%
			C6-3	Competitive advantage	1.31%
			C6-4	Profitability	1.26%
			C6-5	Overall business performance improvement	1.24%
			C6-6	Reputation	1.11%
			C6-7	Quality	0.84%
			C6-8	Customer satisfaction	0.45%
C7	Supplier relationships	6%	C7-1	Supplier selection based on lean–green indicators	2.32%
			C7-2	Active, long-term supplier relationships	2.32%
			C7-3	Supplier evaluation	1.37%
C8	Supply chain	12%	C8-1	Order lead time	6.00%
			C8-2	Customer–supplier communication	6.00%

4.3.3 | Phase III: Environmental Requirements and Lean Enablers

Phase III relates the 22 weighted environmental requirements to 10 lean enablers. For each lean enabler, the environmental-requirement contributions are aggregated according to $AI_{\ell}^{(3)} = \sum_{k=1}^{22} w_k^R \, d_{kl}^{(3)}, \ell = 1, \ldots, 10$. Normalisation gives the final lean-enabler weight w_l^A. Table 11 reports the complete Phase III matrix and the resulting enabler weight vector.

Preventive maintenance has the largest Phase III weight (0.192), followed by Continuous improvement (0.179) and Use of recyclable resources (0.162). Integrated lean–green operating system (0.108), Waste reduction and resource productivity (0.105) and Failure-mode analysis (0.100) follow. The 10 normalised enabler weights form the evaluation-weight vector for the interval extended VIKOR analysis.

4.4 | Interval Extended VIKOR Decision Matrix and Compromise Ranking

The interval extended VIKOR analysis treats the eight lean–green criteria as alternatives C_i, $i = 1, \ldots, 8$, and the 10 lean enablers as evaluation dimensions indexed by $l = 1, \ldots, 10$. For each alternative i and lean-enabler dimension l, the expert assessment is represented by $\widetilde{f}_{il} = \left[f_{il}^L, f_{il}^U\right]$ on the 1–9 scale, and w_l^A denotes the corresponding Phase III lean-enabler weight. Table 12 reports the complete interval decision matrix.

4.4.1 | Determination of the Positive and Negative Ideal Values

Equations (5) and (6) in Section 3 determine the ideal reference values for each lean-enabler dimension, $l = 1, \ldots, 10$. All 10 lean-enabler dimensions are treated as benefit-type dimensions. The positive ideal f_l^* and negative ideal f_l^- define the reference levels used to evaluate the eight alternatives. Table 13 reports the resulting ideal vectors.

4.4.2 | Group Utility and Maximum Regret

Using these ideal values and the Phase III enabler weights, Equations (7–10) produce the interval group-utility measure $S_i = \left[S_i^L, S_i^U\right]$ and the interval maximum-regret measure $R_i^V = \left[R_i^{V,L}, R_i^{V,U}\right]$ for each alternative. Table 14 reports both measures.

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TABLE 9 | Phase I GQFD: Lean–green criteria and gearbox technical characteristics.

		Technical characteristics										
Lean–green criteria	**FANP criterion weight w_i^C**	**Dimensions**	**Visual condition**	**Auxiliary components**	**Noise**	**Road-test performance**	**Leak-test performance**	**Assembly-test performance**	**Torque**	**Housing type**	**Lubricant type**	**Oil capacity**
Leadership strategy	0.11					3	3	3		9	9	9
Workforce	0.23		9			3	3	3				
Environmental performance	0.18			3			3			9	9	1
Process	0.16	1	3	3						3		
Techniques and tools	0.02	1	1	3	1	3	3	3		3		
Performance outcomes	0.09		3			3	3	3	3		9	
Supplier relationships	0.06			3	1	1	1	1				
Supply chain	0.12			9						3	3	
	Absolute technical importance $AI_j^{(1)}$	0.18	2.84	2.34	0.08	1.41	1.95	1.41	0.27	3.51	3.78	1.17
	Normalised technical weight w_j^T	0.00950	0.14995	0.12355	0.00422	0.07445	0.10296	0.07445	0.01426	0.18532	0.19958	0.06177

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TABLE 10 | Phase II GQFD: Gearbox technical characteristics and environmental requirements.

		Environmental requirements										
Technical characteristics	**Transferred Phase I technical weight w_j^T**	**Waste reduction**	**Reduction of environmental impacts**	**Reduction of raw-material consumption**	**Ease of transportation and maintenance**	**Ease of processing**	**Reduction of energy consumption**	**Ease of reuse**	**Ease of end-of-life dismantling**	**Ease of joining**	**Safe incineration**	**Safe landfill disposal**
Dimensions	0.00950			1	9		3	1	1			
Visual condition	0.14995	9						3			3	
Auxiliary components	0.12355							9	3	9		
Noise	0.00422											
Road-test performance	0.07445						3					
Leak-test performance	0.10296						9					
Assembly-test performance	0.07445	1								3		
Torque	0.01426						9					
Housing type	0.18532	9		3	1	3	3	9	9	9	3	3
Lubricant type	0.19958		9									
Oil capacity	0.06177	9										
	Absolute environmental importance $AI_k^{(2)}$	3.64784	1.79620	0.56547	0.27086	0.55597	1.86272	3.23918	2.04805	3.00317	1.00581	0.55597
	Normalised environmental weight w_k^R	0.09583	0.04719	0.01486	0.00712	0.01461	0.04893	0.08509	0.05380	0.07889	0.02642	0.01461

Technical characteristics	**Safe disposal**	**Water pollution**	**Soil pollution**	**Air pollution**	**Noise**	**Vibration and noise**	**Electromagnetic waves and radiation**	**Toxicity of substances**	**Reliability and durability**	**Recyclable-material content**	**Ease of assembly**
Dimensions									1		
Visual condition									9		
Auxiliary components								3	3	9	9

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TABLE 10 | (Continued)

Technical characteristics	Safe disposal	Water pollution	Soil pollution	Air pollution	Noise	Vibration and noise	Electromagnetic waves and radiation	Toxicity of substances	Reliability and durability	Recyclable-material content	Ease of assembly
Noise						9					
Road-test performance					3	3			9		
Leak-test performance				9	3						
Assembly-test performance									3		1
Torque									9		
Housing type	3					3	3		9		9
Lubricant type		9	9	9				9			
Oil capacity									3		
	0.55597	1.79620	1.79620	2.72281	0.53221	0.81732	0.55597	2.16684	4.60454	1.11193	2.85428
	0.01461	0.04719	0.04719	0.07153	0.01398	0.02147	0.01461	0.05692	0.12096	0.02921	0.07498

The corresponding reference values for the compromise calculation are $S^* = 0.16748$, $S^- = 0.96543$, $R^* = 0.04995$ and $R^- = 0.19208$.

4.4.3 | Interval VIKOR Compromise Index

Equations (11–14) combine the group-utility and maximum-regret measures into the interval compromise index $Q_i = [Q_i^L, Q_i^U]$. The analysis uses $v = 0.50$, assigning equal weight to the maximum-group-utility and minimum-individual-regret strategies. Table 15 reports the resulting Q_i intervals.

Under the interval-ranking rule defined in Section 3, the compromise intervals are ordered as $Q_8 < Q_6 < Q_3 < Q_4 < Q_1 < Q_5 < Q_2 < Q_7$. This ordering yields the final priority ranking reported in Table 16.

4.4.4 | Final Ranking of Lean–Green Manufacturing Criteria

Supply chain ranks first in the final compromise solution, followed by Performance outcomes and Environmental performance. Process ranks fourth, followed by Leadership strategy, Techniques and tools, Workforce and Supplier relationships. This ordering differs from the criterion-level FANP ranking. FANP yields priorities from the interdependent criterion network, whereas the final interval VIKOR ranking is calculated after the three GQFD deployment stages. Section 5 examines the implications of this cross-stage reordering.

5 | Discussion

The results reveal two complementary priority structures: network-based importance from FANP and deployment salience from the three-phase GQFD–interval VIKOR sequence. The discussion first examines how priorities shift across these stages. Section 5.1 then positions the findings within recent lean–green scholarship and develops the theoretical contribution, while Section 5.2 sets out the managerial and policy implications.

FANP assigns the highest criterion-level priorities to Workforce (0.23), Environmental performance (0.18) and Process (0.16), whereas the final interval VIKOR ranking places Supply chain, Performance outcomes and Environmental performance in the first three positions. The cross-stage reordering is the central empirical finding: Workforce moves from first to seventh, Process from third to fourth, Performance outcomes from sixth to second and Supply chain from fourth to first. FANP captures criterion importance within the interdependent network; the final ranking captures the compromise priorities that emerge after technical and environmental relationships have been deployed through the three GQFD phases.

Phase III weights sharpen this interpretation. Preventive maintenance (0.192), Continuous improvement (0.178) and Use of recyclable resources (0.162) dominate the deployment layer. Under these weights, Supply chain becomes the

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TABLE 11 | Phase III GQFD: Environmental requirements and lean enablers.

		Lean enablers									
Environmental requirements	**Transferred Phase II environmental weight w_k^R**	**Continuous improvement**	**Preventive maintenance**	**Production control**	**Failure-mode analysis**	**Job rotation**	**Human resource management**	**Waste reduction and resource productivity**	**Use of recyclable resources**	**Integrated lean–green operating system**	**Training across organisational levels**
Waste reduction	0.09583		9	9				9	9	3	3
Reduction of environmental impacts	0.04719			3				3	1	9	1
Reduction of raw-material consumption	0.01486			9			1	1	9	3	
Ease of transportation and maintenance	0.00712			9		1	3			1	
Ease of processing	0.01461	3		1						3	3
Reduction of energy consumption	0.04893	3	1	1			1	1		1	
Ease of reuse	0.08509							3	9		
Ease of end-of-life dismantling	0.05380							9			
Ease of joining	0.07889		1								1
Safe incineration	0.02642				3			1	9		
Safe landfill disposal	0.01461				3			1	9		
Safe disposal	0.01461				3			1	9		
Water pollution	0.04719	9	9	1	3				3	3	
Soil pollution	0.04719	9	9	1	3				3	3	
Air pollution	0.07153	9	9	1	3				3	3	
Noise	0.01398	3	3	1	1				1	1	
Vibration and noise	0.02147	1	1	1	1				1	1	

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TABLE 11 | (Continued)

Environmental requirements	Transferred Phase II environmental weight w_k^R	Lean enablers									
		Continuous improvement	Preventive maintenance	Production control	Failure-mode analysis	Job rotation	Human resource management	Waste reduction and resource productivity	Use of recyclable resources	Integrated lean–green operating system	Training across organisational levels
Electromagnetic waves and radiation	0.01461	1	3	1	3				1	1	
Toxicity of substances	0.05692	9	1		3			3	3	3	
Reliability and durability	0.12096	9	9	1	9	3	3			3	
Recyclable-material content	0.02921	9	3	3	1			3	9	9	3
Ease of assembly	0.07498		1								1
	Absolute lean-enabler importance $AI_\ell^{(3)}$	3.62567	3.89888	1.68987	2.03254	0.37001	0.44803	2.12138	3.29136	2.20094	0.62001
	Normalised lean-enabler weight w_l^A	0.17862	0.19208	0.08325	0.10013	0.01823	0.02207	0.10451	0.16215	0.10843	0.03054

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TABLE 12 | Interval extended VIKOR decision matrix.

Alternative/ enabler	Continuous improvement (CI)	Preventive maintenance (PM)	Production control (PC)	Failure-mode analysis (FMA)	Job rotation (JR)	Human resource management (HRM)	Waste reduction and resource productivity (WRP)	Use of recyclable resources (RR)	Integrated lean–green operating system (ILGS)	Training across organisational levels (Trn)
Lean-enabler weight w_l^A	0.17862	0.19208	0.08325	0.10013	0.01823	0.02207	0.10451	0.16215	0.10843	0.03054
C1 Leadership strategy	[6, 9]	[2, 4]	[5, 5]	[5, 7]	[3, 4]	[7, 9]	[5, 7]	[5, 8]	[2, 8]	[3, 7]
C2 Workforce	[4, 6]	[4, 5]	[3, 5]	[1, 3]	[7, 9]	[1, 3]	[3, 4]	[1, 5]	[2, 4]	[4, 8]
C3 Environmental performance	[4, 7]	[4, 7]	[6, 7]	[3, 4]	[1, 2]	[6, 8]	[7, 9]	[8, 9]	[7, 9]	[6, 9]
C4 Process	[6, 7]	[5, 8]	[2, 5]	[5, 7]	[1, 2]	[1, 2]	[1, 5]	[1, 3]	[4, 5]	[4, 8]
C5 Techniques and tools	[4, 8]	[5, 6]	[4, 5]	[5, 6]	[2, 6]	[2, 5]	[1, 2]	[2, 3]	[1, 3]	[2, 3]
C6 Performance outcomes	[5, 9]	[6, 7]	[4, 7]	[7, 8]	[3, 5]	[3, 4]	[3, 5]	[5, 6]	[6, 8]	[7, 7]
C7 Supplier relationships	[3, 4]	[2, 3]	[2, 2]	[2, 3]	[1, 1]	[1, 2]	[1, 2]	[2, 4]	[1, 3]	[1, 2]
C8 Supply chain	[7, 8]	[6, 7]	[2, 4]	[5, 8]	[1, 3]	[4, 7]	[7, 9]	[6, 8]	[4, 6]	[2, 3]

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TABLE 13 | Positive and negative ideal values for the interval VIKOR analysis.

Ideal value	CI $l = 1$	PM $l = 2$	PC $l = 3$	FMA $l = 4$	JR $l = 5$	HRM $l = 6$	WRP $l = 7$	RR $l = 8$	ILGS $l = 9$	Trn $l = 10$
Positive ideal f_l^*	9	8	7	8	9	9	8	7	8	9
Negative ideal f_l^-	3	2	2	1	1	1	1	1	1	1

TABLE 14 | Interval group-utility and maximum-regret measures.

Alternative	Group utility S_i	Maximum regret R_i^V
C1 Leadership strategy	[0.25463, 0.62790]	[0.12805, 0.19208]
C2 Workforce	[0.52470, 0.82475]	[0.09604, 0.16215]
C3 Environmental performance	[0.16748, 0.47653]	[0.05954, 0.14885]
C4 Process	[0.37430, 0.70532]	[0.12161, 0.16215]
C5 Techniques and tools	[0.49086, 0.75455]	[0.12161, 0.14885]
C6 Performance outcomes	[0.18917, 0.48533]	[0.06080, 0.11908]
C7 Supplier relationships	[0.80206, 0.96543]	[0.16006, 0.19208]
C8 Supply chain	[0.21476, 0.46318]	[0.04995, 0.08325]

TABLE 15 | Interval VIKOR compromise indices.

Alternative	Compromise index Q_i
C1 Leadership strategy	[0.32937, 0.78850]
C2 Workforce	[0.38597, 0.80656]
C3 Environmental performance	[0.03373, 0.54157]
C4 Process	[0.38170, 0.73172]
C5 Techniques and tools	[0.45473, 0.71578]
C6 Performance outcomes	[0.05178, 0.44236]
C7 Supplier relationships	[0.78501, 1.00000]
C8 Supply chain	[0.02963, 0.30244]

TABLE 16 | Final interval VIKOR ranking of the lean–green manufacturing criteria.

Rank	Lean–green criterion
1	Supply chain (C8)
2	Performance outcomes (C6)
3	Environmental performance (C3)
4	Process (C4)
5	Leadership strategy (C1)
6	Techniques and tools (C5)
7	Workforce (C2)
8	Supplier relationships (C7)

leading compromise priority, followed by Performance outcomes, while Environmental performance remains among the three highest ranked criteria. Workforce and Process remain prominent network capabilities, whereas Supply chain and Performance outcomes emerge as the two leading deployment priorities.

Environmental performance provides strong continuity across the analytical sequence, ranking second in FANP and third in interval VIKOR. Its consistently high position places environmental performance among the central priorities of both the interdependent capability structure and the final deployment decision. The overall pattern therefore distinguishes the capabilities that organise lean–green implementation from the priorities that govern its deployment.

5.1 | Literature Positioning and Theoretical Contribution

Recent lean–green research has increasingly examined the organisational, institutional, behavioural and technological conditions that shape implementation. Farrukh et al. (2022, 2023) identify resource, institutional and managerial drivers of green–lean–six-sigma adoption; Garza-Reyes et al. (2026) structure the barriers to green–lean implementation; and Villegas et al. (2026) demonstrate the integration of lean, green and circular practices across sustainable operations and supply chains. This study adds a decision-architecture perspective by showing how criterion priorities are reconfigured as they move from interdependent weighting through requirement deployment to compromise prioritisation.

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Workforce's first-place FANP position aligns with evidence that employee capability, participation, training and managerial commitment are central to lean–green implementation (Farrukh et al. 2023; Hou et al. 2026). Its subsequent movement to seventh place reinforces Workforce's role as a system-organising capability: It establishes important organisational conditions for lean–green execution, while the final deployment stage gives greater priority to criteria whose effects are propagated through technical, environmental and operational relationships. Process shows a considerably smaller shift, moving from third to fourth, and therefore remains prominent in both the network and deployment structures.

Environmental performance occupies a dual strategic position. Its second-place ranking in FANP and third-place ranking in interval VIKOR are consistent with evidence on the environmental gains of structured green–lean improvement and the role of environmental management in green–lean adoption (Gholami et al. 2021; Farrukh et al. 2022), as well as with the lean–green complementarity identified by Dües et al. (2013). In this study, environmental performance is therefore both structurally influential within the criterion network and salient after the full deployment sequence.

Supply chain rises from fourth in FANP to first in the final compromise ranking, reinforcing the cross-organisational character of lean–green implementation and the importance of supply-chain integration and process innovation reported in prior research (Cherrafi et al. 2018; Villegas et al. 2026). Performance outcomes records the largest upward shift, advancing from sixth to second. Whereas prior studies commonly treat operational, environmental or supply-chain performance as an outcome of lean–green practices and innovation (Cherrafi et al. 2018; Gholami et al. 2021), the present analysis shows that Supply chain and Performance outcomes acquire substantially greater decision salience once the GQFD-derived deployment weights are incorporated.

Multiphase QFD and GQFD have established the value of carrying requirement information across successive decision layers (Chowdhury and Quaddus 2016; Wu and Ho 2015). The present architecture extends that logic by placing network-sensitive weighting upstream of deployment and interval compromise prioritisation downstream. The study advances lean–green integration theory in three respects: It conceptualises implementation as a traceable requirement-deployment architecture linking stakeholder priorities, product characteristics, environmental requirements, lean enablers and final implementation priorities; it operationalises the distinction between network-based importance and deployment salience; and it preserves organisational, technical, environmental and interorganisational layers as distinct but sequentially connected decision domains.

The observed reordering of Workforce, Process, Performance outcomes and Supply chain gives empirical content to the distinction between network-based importance and deployment salience. Criteria that organise system capability need not occupy the same position once priorities are propagated through technical, environmental and operational relationships. This cross-stage view explains how lean–green priorities are generated, transmitted and reconfigured across the decision system rather than treating prioritisation as a single-stage outcome.

The resulting framework connects organisational capability, engineering characteristics, environmental requirements, operational enablers, supplier relationships and supply-chain coordination within one analytical pathway. These decision layers remain visible throughout the model, providing a theoretically differentiated account of lean–green implementation and a direct link between strategic requirements and deployment priorities.

5.2 | Managerial and Policy Implications

For managers, the two priority structures support complementary decisions. FANP identifies where implementation capability is concentrated, particularly in Workforce and Process, whereas the final VIKOR ranking identifies the principal deployment priorities: Supply chain, Performance outcomes and Environmental performance. Together, the two views support portfolio decisions that build enabling capabilities while directing resources towards the operational, environmental and cross-boundary priorities with the strongest deployment salience.

The three GQFD matrices provide the implementation pathway. In the NMI case, the Phase III weights identify Preventive maintenance, Continuous improvement and Use of recyclable resources as the leading operational leverage points. Managers can trace each intervention back through the environmental and technical layers, assign cross-functional ownership and monitor progress through a balanced set of operational, environmental, customer and supply-chain indicators. Re-estimating criterion weights and relationship scores when product mix, technology, regulation, supplier conditions or strategic priorities change keeps the decision model aligned with the operating context.

For policymakers and industry bodies, the findings support sector-level mechanisms that improve the quality and comparability of lean–green decisions. Environmental benchmarks, common supplier and environmental data definitions, workforce and technical capability-building programmes, support for cleaner technologies and environmental management systems and supplier-development and data-sharing arrangements can strengthen coordinated implementation across automotive supply networks.

6 | Conclusion

This study develops and applies an integrated FANP–three-phase GQFD–interval VIKOR framework for lean–green manufacturing decision support in gearbox production. The expert-refined architecture comprises eight criteria and 42 subcriteria. Its main empirical finding is the cross-stage reordering of priorities: FANP emphasises Workforce, Environmental performance and Process, whereas the final compromise ranking gives precedence to Supply chain, Performance outcomes and Environmental performance. The framework therefore establishes both a context-relevant lean–green decision architecture and a mechanism for tracing how priorities evolve across interdependent weighting, requirement deployment and compromise prioritisation.

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The study contributes a traceable decision architecture that links network-based criterion importance with requirement deployment and final compromise prioritisation without collapsing distinct decision layers. For manufacturers, it connects workforce and process capability development with performance, environmental and supply-chain priorities. For industry and policy actors, it highlights comparable environmental and supplier data, cross-boundary coordination and capability building as key supports for lean–green implementation.

Future research can extend the framework through multifirm and multisector applications, sensitivity and robustness analysis and explicit modelling of correlations among technical responses in the GQFD architecture. Further development can integrate life-cycle assessment, carbon accounting, circularity indicators and digital traceability, while longitudinal applications can examine how priorities and realised operational–environmental outcomes evolve as lean–green programmes mature.

Author Contributions

Soroush Avakh Darestani: writing – review and editing, writing – original draft, visualization, project administration, software, supervision, resources, investigation, conceptualization, validation, methodology. **Rana Imannezhad:** visualization, formal analysis, resources, investigation, methodology. **Jose Arturo Garza-Reyes:** conceptualization, writing – original draft, writing – review and editing, visualization, supervision, validation. **Jiju Antony:** writing – original draft, writing – review and editing, validation, project administration. **Ambisisi Ambituuni:** writing – original draft, writing – review and editing, conceptualization, validation. **Ramina Taherkhani:** conceptualization, investigation, methodology, validation, software, data curation. **Niloufar Hojat Shemami:** validation, writing – original draft.

Conflicts of Interest

The authors declare no conflicts of interest.

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