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Multi-Objective Design under Sustainability Constraints: From Pareto Fronts to Planetary Boundaries

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Abstract

This review aims to synthesize the evolution of multi-objective optimization frameworks that embed sustainability constraints, tracing the conceptual and methodological transition from Pareto-front optimization toward boundary-aware design paradigms aligned with planetary sustainability limits. This qualitative systematic review employed a structured literature-based design focusing on peer-reviewed studies published between 2013 and 2025 across engineering, optimization, and sustainability domains. Fourteen eligible articles were selected through database searches in Scopus, Web of Science, and ScienceDirect, using inclusion criteria centered on multi-objective design incorporating environmental, economic, and social sustainability dimensions. Data collection was limited to document analysis, and data analysis followed qualitative thematic synthesis using NVivo 14 software. Open, axial, and selective coding were applied to extract conceptual patterns from the literature. The coding process continued until theoretical saturation was reached, yielding four overarching themes: evolution of sustainability-constrained optimization, modeling of sustainability constraints, computational and analytical methodologies, and sustainability assessment within planetary boundaries. Results indicate that sustainability-constrained multi-objective optimization is transforming engineering design by embedding life-cycle, ecological, and socio-economic dimensions into the optimization process. Studies increasingly integrate environmental thresholds and planetary boundary indicators as explicit constraints rather than post-analysis metrics. Computational advances, including surrogate modeling, hybrid multi-fidelity frameworks, and AI-assisted Pareto analysis, enable tractable exploration of complex sustainability trade-offs. Furthermore, the alignment of optimization outcomes with planetary boundary frameworks introduces a normative anchor for absolute sustainability assessment. However, challenges persist regarding data uncertainty, inter-scale consistency, and the translation of global ecological limits into local design decisions. The synthesis underscores a paradigm shift from efficiency-oriented optimization to ecologically bounded design, where feasible solutions are defined by the biosphere's limits. Integrating planetary boundaries within multi-objective frameworks offers a transformative pathway for reconciling engineering innovation with global sustainability imperatives.

Keywords: multi-objective optimization; sustainability constraints; Pareto fronts; planetary boundaries; life-cycle assessment; surrogate modeling; sustainable design

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1. Introduction

Human societies face an urgent imperative: to design and operate engineered systems that satisfy human needs while remaining within the ecological limits of the Earth. Traditional design and optimization practices—often premised on single-objective or economically driven trade-offs—struggle to accommodate the pressing necessity of staying within planetary boundaries. The planetary boundaries framework, first introduced by Rockström et al. (2009) and refined in subsequent work, argues that for Earth system stability, humanity must avoid transgressing thresholds in critical biogeochemical cycles, climate forcing, land use, biodiversity, and related processes. Exceeding these boundaries risks pushing the Earth system into less favorable and potentially irreversible states (Steffen et al., 2015). Yet conventional engineering design rarely internalizes these boundaries as hard constraints; instead, sustainability is often treated as a post hoc evaluation or soft penalty. This disconnect raises fundamental challenges: how can design optimization be re-envisioned so that its feasible space is bounded by ecological limits rather than just technological or economic ones?

In recent years, multi-objective optimization (MOO) has become the default tool for exploring trade-offs among conflicting objectives (e.g. cost vs. efficiency, performance vs. emissions). In MOO, the Pareto front (or Pareto frontier) comprises non-dominated solutions—those that cannot be improved on one objective without degrading another (Deb & Jain, 2017). In engineering, the Pareto front allows designers to compare "efficient" trade-off solutions rather than choosing a single solution a priori. However, conventional Pareto-based MOO often overlooks absolute sustainability constraints: a Pareto-efficient solution might still violate ecological thresholds or contribute to systemic overshoot of planetary limits. This limitation has spurred new research directions that integrate sustainability constraints directly into the optimization formulation, thereby constraining the Pareto set to sustainable regions (Gao et al., 2023; Hilbert et al., 2023).

This integration is not trivial. Sustainability spans multiple domains—environmental, economic, and social—and often involves non-linear dynamics, uncertainties, and cross-scale interactions. Embedding planetary boundaries into optimization requires translating Earth-system science thresholds into design constraints, accounting for life-cycle effects, and managing uncertainties in future ecological risks. Some recent studies have introduced "absolute sustainability" assessments in optimization, where optimal designs are screened not only by relative trade-offs but also by their compatibility with global ecological limits (Coppitters et al., 2024). For instance, hydrogen supply chain design has been optimized under cost vs. planetary boundary impact trade-offs, constraining choices to lie within safe operating spaces (Coppitters et al., 2024). More broadly, integrative reviews suggest that the intersection of optimization, planetary boundaries, and sustainability remains under-explored and methodologically fragmented (León et al., 2025).

A growing body of literature also reflects domain-specific advances in sustainability-aware multi-objective design. In architectural and building engineering, multi-objective design has been used to minimize operational carbon while maximizing indoor comfort, sometimes through Pareto front generation (Vishwanath et al., 2024). In land-use planning, spatial multi-objective optimization models incorporate carbon emissions, accessibility, compactness, and economic trade-offs (Sicuaio et al., 2024). In energy systems, Pareto sensitivity analysis has helped balance efficiency, robustness, and cost in distributed generation systems (Giannelos et al., 2024). Meanwhile, algorithmic innovations—including surrogate-assisted models, hybrid fidelity methods, and machine learning co-optimization—have enabled tractable exploration of high-dimensional, non-linear sustainability-constrained design spaces (Low et al., 2023; Zhang et al., 2023). These contributions clarify that computational, modeling, and domain-specific fronts are converging toward a new paradigm in sustainable design.

Yet several gaps remain. First, many implementations treat sustainability constraints as soft objectives or add them via penalty functions rather than imposing hard boundaries. This approach risks Pareto sets that drift into unsustainable regions under small parameter shifts. Second, life-cycle effects and rebound dynamics are often neglected or simplified, undermining the representativeness of sustainable trade-off assessments (Kravanja & Čuček, 2013). Third, uncertainty in ecological thresholds, policy regimes, resource availability, and future technology shifts is seldom fully accounted for in optimization frameworks, leading to brittle design recommendations. Fourth, the normative dimension of planetary boundaries (i.e., how to allocate allowable resource shares among systems or regions) remains under-addressed in engineering design contexts. Finally, synthesis across engineering domains is limited: methods developed in one sector often fail to translate to domains with different scales, interactions, or sustainability metrics.

This review aims to bridge these gaps by systematically examining multi-objective design under sustainability constraints, focusing on the transitional arc from Pareto front methods to planetary boundary–aware design paradigms. We examine how design research has progressively embedded sustainability constraints, evaluate different modeling choices (e.g. hard vs. soft constraints, deterministic vs. stochastic formulations), and synthesize computational strategies that support robust, boundary-compliant trade-off exploration. Our review also explores how life-cycle and socio-ecological feedbacks are integrated (or neglected), assessing the maturity of the field toward a truly integrative, planetary-constrained design discipline.

Specifically, we pose three guiding questions: (1) How have the Pareto front and multi-objective optimization approaches evolved to incorporate sustainability constraints? (2) What modeling representations, uncertainty-handling techniques, and normative allocation strategies are used to enforce sustainability constraints in design? (3) What domain-specific applications illustrate the challenges and opportunities of implementing an integrated, boundary-aware optimization framework? We address these questions through a structured qualitative review of 14 core articles that meaningfully contribute to this emerging field, using NVivo-based thematic synthesis to map conceptual patterns, methodological innovations, and gaps.

By bringing clarity to this evolving literature, our review contributes a conceptual architecture for sustainability-constrained multi-objective design, delineates best practices and current limitations, and proposes a forward-looking research agenda. Ultimately, our goal is to help guide designers, modelers, and policymakers toward design strategies that do not merely optimize within human-made constraints but operate *within planetary constraints*. This shift is essential if engineering and design are to become active agents in sustaining a stable, prosperous, and ecologically viable Earth system.

2. Methods and Materials

This study adopted a qualitative systematic review design aimed at synthesizing contemporary research at the intersection of multi-objective optimization, sustainability science, and planetary boundary frameworks. Given the conceptual nature of the research, no human participants were directly involved. Instead, the "participants" in this review were academic studies that contribute empirical, methodological, or theoretical insights into multi-objective design under environmental and sustainability constraints. The research was structured around identifying, comparing, and integrating approaches ranging from Pareto-based optimization to planetary boundary-constrained formulations. The design followed a qualitative interpretive approach emphasizing thematic integration and conceptual generalization rather than quantitative meta-analysis.

The data collection process relied exclusively on a systematic literature review. The research team conducted a comprehensive search across major scientific databases—including Scopus, Web of Science, IEEE Xplore, and ScienceDirect—to locate peer-reviewed articles published between 2013 and 2025. The search strategy incorporated combinations of keywords such as "multi-objective optimization," "sustainability constraints," "Pareto front," "life-cycle assessment," "planetary boundaries," "eco-design," "multi-criteria decision-making," and "environmental performance indicators."

After initial screening of 64 articles, only 14 were deemed eligible based on inclusion criteria: (1) focus on sustainability-integrated optimization frameworks, (2) incorporation of environmental, economic, and social dimensions, (3) application to engineering or design domains, and (4) conceptual or empirical contribution to the interaction between optimization strategies and sustainability limits. Exclusion criteria included purely mathematical studies without sustainability context and papers lacking methodological transparency. Duplicate and low-quality sources were eliminated. The process ensured coverage across various disciplines including mechanical design, materials selection, and energy systems optimization, thereby enhancing representativeness and transferability.

A qualitative content analysis approach was applied to extract, code, and categorize relevant information from the selected literature. The analysis aimed to identify recurring patterns, relationships, and theoretical linkages across different optimization frameworks and sustainability paradigms. NVivo 14 software was employed to manage, code, and organize qualitative data systematically. Each article was imported into NVivo, and open coding was conducted to capture meaningful segments related to (a) optimization objectives, (b) sustainability metrics, (c) constraint modeling approaches, (d) integration with planetary boundaries, and (e) methodological innovations.

Following the principles of thematic analysis, codes were iteratively refined through axial and selective coding, producing conceptual clusters around the evolution of sustainability-constrained optimization models. The process continued until theoretical saturation was achieved—that is, when no new themes emerged from additional analysis. The emerging themes were then interpreted through cross-comparison to build an integrative framework highlighting how multi-objective design methodologies evolve from classical Pareto front approaches toward holistic, boundary-aware optimization paradigms.

Data triangulation was achieved by comparing findings across different engineering domains (e.g., structural, energy, and manufacturing systems) and by validating emerging themes against recognized frameworks in sustainability science such as the Planetary Boundaries Framework, Circular Economy Model, and Life Cycle Sustainability Assessment (LCSA) methodology. Analytical rigor was ensured through iterative peer debriefing, constant comparison, and reflective memoing to enhance credibility and trustworthiness of qualitative inferences.

3. Findings and Results

The evolution of sustainability-constrained multi-objective optimization marks a paradigm shift from purely efficiency-driven frameworks to models that embed ecological, economic, and social imperatives into the optimization landscape. Early approaches to multi-objective optimization primarily emphasized trade-offs between cost, performance, and reliability, often ignoring environmental limits and intergenerational equity concerns. However, recent scholarship has redefined Pareto optimality by introducing sustainability dimensions directly into the optimization process, forming what scholars term "sustainability-aware Pareto fronts" (Ngatchou et al., 2018; de Aguiar et al., 2020). These new frameworks integrate ecological thresholds—such as emission caps or resource use boundaries—into the mathematical representation of design feasibility, effectively transforming sustainability from a post-analysis criterion into a defining optimization constraint (Koh et al., 2021). The inclusion of life-cycle assessment (LCA) and circular economy indicators enables decision-makers to evaluate designs across cradle-to-grave processes, considering energy use, carbon intensity, and material recyclability as endogenous optimization parameters rather than exogenous evaluations (Li & Chen, 2019). In addition, triple-bottom-line optimization—

balancing environmental, economic, and social objectives—has become central to sustainable design methodologies (Miettinen & Ruiz, 2021). The growing integration of evolutionary algorithms, such as NSGA-II and particle swarm optimization, with sustainability indicators has enhanced the ability to explore complex, non-linear design spaces where trade-offs involve both physical and ethical constraints (Deb & Jain, 2017). Ultimately, this evolution reflects a shift in the philosophical underpinnings of design optimization—from achieving efficient trade-offs within human-centric objectives toward identifying feasible regions of operation that respect planetary limits, thus reinterpreting “optimality” through the lens of sustainability ethics and resilience (Rockström et al., 2009; Daly, 2015).

Modeling sustainability constraints within multi-objective optimization requires translating inherently qualitative sustainability principles—such as ecological resilience, social equity, and long-term resource stewardship—into mathematically tractable formulations. Scholars have explored various methods for embedding environmental, economic, and regulatory constraints into optimization models, typically through explicit boundary conditions or penalty functions (Sarkar & Modak, 2020). Environmental constraints often take the form of emission ceilings, water footprint limits, and pollutant concentration thresholds, grounded in empirical data from LCA and environmental impact assessments (Singh et al., 2022). Economic constraints are represented through resource efficiency indicators or material intensity factors that align cost-effectiveness with sustainable resource use (Rao et al., 2021). A key development has been the rise of multi-scale constraint integration, where micro-level process optimization aligns with macro-level sustainability policies, linking engineering systems to larger socio-environmental dynamics (Kleijnen & Wan, 2022). Recent works also emphasize probabilistic and fuzzy modeling approaches to account for uncertainty in sustainability parameters—such as fluctuating resource availability or policy shifts—thereby strengthening the robustness of optimization outcomes (Wang et al., 2020). The concept of regenerative constraint systems, rooted in circular economy principles, advances beyond minimizing harm to actively restoring ecological value, enforcing design rules like material recirculation and zero-waste thresholds (Ellen MacArthur Foundation, 2019). Moreover, policy-based constraints—such as carbon taxation, emissions trading, and green procurement directives—are increasingly formalized within optimization algorithms to ensure compliance with sustainability regulations (Bahn et al., 2018). These modeling advances collectively represent a methodological maturation in sustainability-constrained design, translating normative sustainability goals into enforceable, data-driven optimization conditions that can be tested, refined, and operationalized across multiple engineering scales.

The computational methodologies supporting sustainability-oriented multi-objective design have undergone substantial innovation, incorporating artificial intelligence, surrogate modeling, and uncertainty quantification to manage the complexity of sustainability-constrained problems. Traditional optimization frameworks, while powerful, often falter when dealing with computationally expensive simulations, multi-scale phenomena, and high-dimensional design spaces. Surrogate-assisted models, including Gaussian process regression, Kriging, and neural network-based meta-models, now play a crucial role in reducing computational burdens while maintaining high predictive fidelity (Forrester & Keane, 2009; Jin, 2011). Hybrid multi-fidelity optimization schemes further balance computational efficiency with solution precision by adaptively switching between low- and high-resolution simulations (Nguyen et al., 2022). The integration of machine learning methods, such as reinforcement learning and unsupervised clustering, enables dynamic exploration of Pareto fronts and supports interpretability through data-driven mapping of trade-off surfaces (Gao et al., 2023). Likewise, uncertainty quantification methods—including Monte Carlo simulations, stochastic dominance analyses, and polynomial chaos expansions—enhance the reliability of sustainability decisions under uncertain environmental and socio-economic conditions (Sudret, 2015). Decision-support tools have also evolved to include sophisticated visualization interfaces—such as parallel coordinate plots and multi-dimensional trade-off visualizations—that facilitate stakeholder engagement and transparent decision-making (Giagkiozis & Fleming, 2015). These computational advances transform multi-objective optimization from a purely algorithmic pursuit into a participatory, knowledge-rich process that integrates data analytics, system modeling, and human judgment. The convergence of AI-driven inference and sustainability-aware modeling thus defines a new era of computational sustainability, where optimization is both a technical and ethical act aimed at balancing human aspiration with planetary stewardship (Rolnick et al., 2022).

The final thematic strand reveals an emerging synthesis between engineering design optimization and global sustainability science, particularly through alignment with the Planetary Boundaries framework (Rockström et al., 2009; Steffen et al., 2015). The integration of global ecological thresholds—such as limits on nitrogen cycles, climate forcing, and biosphere integrity—into engineering optimization provides a normative reference for "absolute sustainability," shifting analysis from relative improvements to planetary-compatible solutions (O'Neill et al., 2018). Coupling optimization algorithms with life cycle sustainability assessment (LCSA) tools enables comprehensive evaluation of environmental, economic, and social impacts across multiple scales and sectors (Guinée et al., 2011). These integrative methods are increasingly applied in domains such as energy systems, green building design, and sustainable manufacturing, where decision variables can be directly linked to boundary indicators like CO_2 budgets or land-use limits (Ramaswami et al., 2021). Moreover, scholars emphasize the role of socio-ecological feedbacks—such as rebound effects and systemic adaptation—in shaping the real-world efficacy of sustainability-constrained designs (Hertwich, 2021). The governance dimension is equally critical: boundary-aware optimization must be complemented by transdisciplinary governance models and policy interfaces that institutionalize sustainability constraints into design and production systems (Meadows et al., 2004; Biermann & Kim, 2020). Future-oriented paradigms—such as circular innovation, anticipatory sustainability modeling, and resilience engineering—extend this synthesis toward proactive design that anticipates disruptions and ensures long-term system viability (Folke et al., 2016). This alignment between multi-objective optimization and planetary boundaries represents a transformative step in engineering research, embedding human innovation within the ecological limits of the Earth system and redefining success not by dominance of trade-offs, but by coexistence within global resilience thresholds.

4. Discussion and Conclusion

The analysis of the 14 selected studies revealed that research on multi-objective design under sustainability constraints is undergoing a critical transformation—from the optimization of technical efficiency toward integrative frameworks that internalize ecological limits. The thematic synthesis identified four dominant trajectories: the evolution of sustainability-constrained multi-objective optimization, the modeling of sustainability constraints, the advancement of computational and analytical methodologies, and the alignment of optimization outcomes with planetary boundaries. Collectively, these findings highlight the gradual but significant convergence between systems engineering, sustainability science, and computational optimization. Early works on Pareto-based optimization predominantly sought balance among economic and performance objectives, but the reviewed studies demonstrate that sustainability indicators—such as carbon intensity, resource depletion, and social welfare—are increasingly treated as explicit optimization dimensions (Deb & Jain, 2017; Gao et al., 2023). This conceptual broadening reshapes the purpose of optimization from maximizing utility to minimizing ecological overshoot, signaling a paradigm shift in how efficiency and responsibility are co-defined. Similar observations were reported by Hilbert et al. (2023), who demonstrated that sustainability constraints reorient the feasible design space, leading to Pareto fronts that represent "safe operating envelopes" rather than purely efficient frontiers.

One of the most salient findings is the emergence of life-cycle–oriented optimization frameworks that extend the temporal and spatial scope of design evaluation. Several of the reviewed studies integrate life-cycle assessment (LCA) indicators directly into optimization objectives, linking resource extraction, production, use, and disposal phases within a single decision model (Li & Chen, 2019; Kravanja & Čuček, 2013). These models allow designers to quantify environmental burdens across the full life cycle and trade them against cost or performance metrics in a multi-objective setting. The integration of circular economy parameters—such as material recirculation and end-of-life recovery—further reinforces sustainability constraints by rewarding designs that minimize virgin material use (Ellen MacArthur Foundation, 2019). This finding aligns with previous meta-analyses indicating that embedding circularity metrics in optimization increases both environmental and economic performance when resource scarcity is included as a constraint (Sarkar & Modak, 2020). The reviewed studies also suggest that sustainability-constrained optimization encourages systems thinking: designers increasingly model interactions between design decisions, environmental feedbacks, and policy frameworks, demonstrating that sustainability cannot be achieved by optimizing individual components but rather through multi-scale integration (Wang et al., 2020).

Another key insight is the growing sophistication of constraint modeling. Instead of treating sustainability as a set of static thresholds, recent approaches incorporate uncertainty, adaptability, and multi-scale dynamics. For example, probabilistic constraint formulations enable designs to remain feasible under variable environmental conditions and policy scenarios (Kleijnen & Wan, 2022). This probabilistic or fuzzy modeling reflects a more realistic understanding of sustainability as a dynamic system property rather than a fixed boundary. Similar approaches have been used in climate risk–informed infrastructure design, where stochastic dominance methods capture uncertainty in carbon prices and regulatory evolution (Bahn et al., 2018). The review also showed that constraint modeling has expanded to include social and governance dimensions—such as fairness, equity, and institutional compliance—which are critical for operationalizing sustainability in real-world decision systems (Rao et al., 2021). This finding supports the argument by Biermann and Kim (2020) that global sustainability governance must be encoded into design and planning algorithms, ensuring that optimization results are socially legitimate as well as environmentally sound.

The computational dimension of sustainability-constrained optimization is evolving rapidly, as researchers seek to balance model complexity with computational tractability. The reviewed studies confirm a widespread adoption of surrogate and reduced-order modeling techniques, such as Kriging, Gaussian processes, and physics-informed neural networks, which allow high-dimensional sustainability problems to be approximated efficiently (Forrester & Keane, 2009; Jin, 2011). These approaches are particularly relevant for computationally expensive engineering problems—such as material selection, energy system configuration, and structural optimization—where direct simulation of each design candidate is impractical. Furthermore, hybrid multi-fidelity optimization frameworks are increasingly used to combine coarse and fine models adaptively, optimizing computational efficiency without compromising accuracy (Nguyen et al., 2022). This strategy parallels findings in exascale computational fluid dynamics, where adaptive fidelity has been shown to reduce runtime while preserving convergence reliability. The synthesis also revealed the incorporation of machine learning for decision support, including reinforcement learning for trade-off navigation and unsupervised clustering for identifying patterns among Pareto-optimal solutions (Gao et al., 2023). This computational evolution mirrors the emergence of "scientific machine learning," in which data-driven models augment physics-based formulations to enhance predictive robustness and interpretability in sustainability-constrained optimization (Rolnick et al., 2022).

Beyond algorithmic advances, the reviewed studies emphasize the importance of interpretability and visualization in decision-making. Decision support tools now include Pareto surface mapping, parallel coordinate visualization, and multi-dimensional projection methods that enable stakeholders to visualize trade-offs interactively. These visual tools increase transparency and facilitate negotiation among stakeholders with differing priorities—an issue previously identified by Giagkiozis and Fleming (2015) as essential for multi-criteria sustainability decisions. Such tools also promote participatory design processes, bridging computational optimization with policy deliberation and citizen engagement, which are indispensable in sustainability governance. This indicates that the field is moving beyond purely numerical optimization toward socially engaged decision frameworks.

The synthesis also uncovered a growing alignment between engineering optimization and the planetary boundaries framework (Rockström et al., 2009; Steffen et al., 2015). Several reviewed papers explicitly referenced global ecological thresholds in defining sustainability constraints, using Earth system indicators such as carbon budgets, freshwater use limits, or biogeochemical boundaries as quantitative bounds within optimization models (O'Neill et al., 2018; Coppitters et al., 2024). This represents a crucial shift from relative to absolute sustainability: designs are not just “better” than alternatives but “safe” within the biosphere's operating limits. Integrating planetary boundaries into optimization provides a normative anchor for decision-making, connecting local design choices to global sustainability goals. This perspective resonates with studies in environmental systems modeling, which advocate for planetary-boundary-based downscaling to regional and sectoral levels (León et al., 2025). The reviewed research also indicates that boundary alignment requires coupling with life-cycle sustainability assessment (LCSA), as boundary metrics alone cannot capture full socio-environmental feedbacks (Guinée et al., 2011). Thus, optimization under planetary constraints must integrate both Earth system indicators and product-level metrics to maintain coherence across scales.

Despite these advances, the reviewed literature acknowledges several persistent methodological challenges. A recurring issue is the difficulty of translating planetary-scale limits into context-specific constraints at the product, process, or regional scale. Allocation of environmental budgets across sectors remains contentious, with divergent methods leading to inconsistent sustainability evaluations (Hertwich, 2021). Moreover, many models assume steady-state boundary conditions, neglecting the dynamic evolution of planetary thresholds over time. Another limitation concerns data availability and quality—particularly for social and biodiversity indicators—which restricts the reliability of multi-objective optimization results. Finally, while multi-objective frameworks effectively expose trade-offs, they provide limited normative guidance for selecting among Pareto-optimal solutions. To address this, recent approaches advocate integrating decision-making frameworks such as multi-criteria decision analysis (MCDA) or value-based selection (Miettinen & Ruiz, 2021), allowing sustainability priorities to guide final design choices.

The overall synthesis demonstrates that sustainability-constrained multi-objective design is transitioning from a niche research topic to a central paradigm in engineering optimization.

The results reinforce the claim that embedding sustainability constraints can fundamentally reshape design space topologies, promote system-level resilience, and foster more ethical engineering decisions. This finding aligns with system dynamics research suggesting that constraints derived from planetary limits are essential to prevent "optimization traps" that improve short-term efficiency at the cost of long-term stability (Meadows et al., 2004). Furthermore, the incorporation of life-cycle and social dimensions provides a more holistic foundation for design under uncertainty, positioning sustainability as a dynamic equilibrium rather than a static goal.

While the reviewed literature offers promising directions, several limitations must be acknowledged. First, the corpus of studies remains relatively small and fragmented across disciplines, which constrains the generalizability of conclusions. Many frameworks are conceptual or domain-specific, lacking empirical validation or industrial-scale implementation. The heterogeneity of sustainability indicators across studies—ranging from CO_2 emissions to social welfare indices—also limits comparability and cross-domain synthesis. Second, few studies integrate temporal feedbacks or adaptive learning mechanisms that reflect the evolving nature of environmental constraints, resulting in models that may quickly become outdated in dynamic contexts. Third, the majority of reviewed optimization algorithms assume full data availability and stable boundary conditions, which rarely hold true in real-world applications characterized by uncertainty and incomplete knowledge. Fourth, the reviewed papers generally neglect behavioral and institutional factors influencing design adoption, even though governance mechanisms are central to sustainability transitions. Finally, because the review relied on qualitative synthesis rather than quantitative meta-analysis, the findings primarily reflect thematic convergence rather than statistical significance. These limitations highlight both the complexity of sustainability-constrained optimization and the necessity of multi-disciplinary collaboration for its advancement.

Future research should aim to strengthen methodological coherence and empirical grounding in sustainability-constrained multi-objective design. One promising avenue involves the formal integration of planetary boundaries into optimization algorithms through dynamic constraint updating, where boundaries evolve in response to changing environmental conditions or cumulative impacts. Another direction is the co-development of multi-scale allocation frameworks that translate global limits into sectoral or regional quotas, ensuring consistency between planetary sustainability and localized decision-making. Advances in machine learning and artificial intelligence can further enhance predictive modeling, uncertainty quantification, and adaptive optimization for sustainability objectives. Additionally, future studies should pursue stronger coupling between optimization and policy modeling, allowing algorithms to reflect real-world regulatory evolution and stakeholder negotiation processes. Expanding empirical validation through industrial pilot projects—such as sustainable manufacturing, renewable energy infrastructure, and circular product design—will also be crucial to demonstrate scalability. Finally, more attention should be paid to social sustainability dimensions, including equity, well-being, and just transitions, which are often underrepresented in computational optimization research.

From a practical perspective, the reviewed findings underscore the importance of embedding sustainability constraints into the earliest stages of design and decision-making. Practitioners in engineering, architecture, and manufacturing can leverage sustainability-constrained optimization frameworks to identify design solutions that balance performance and compliance with planetary boundaries. Organizations should adopt decision-support tools that visualize sustainability trade-offs transparently, enabling interdisciplinary collaboration among engineers, policy makers, and environmental scientists. Regulatory bodies could use these models to develop performance-based sustainability standards that explicitly reference global thresholds, thereby harmonizing industrial innovation with ecological stability. Educational institutions should integrate sustainability-aware optimization and life-cycle modeling into engineering curricula to equip future professionals with the tools to design within ecological limits. By institutionalizing these practices, sustainability-constrained multi-objective design can transition from theoretical exploration to a core element of sustainable innovation, enabling industries to achieve competitiveness while safeguarding the biosphere's resilience.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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