Advancing Sustainability Through Structural Optimization: Innovations in Material Efficiency and Environmental Impact Reduction

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Contents

1 Introduction

Concrete stands as not only the most utilized building material globally but also ranks second in overall material usage, following only water—an unsurprising status given its abundance, affordability, and widespread availability. Its versatility allows for a myriad of applications, rendering it indispensable in various construction projects. Cement serves as a binding agent utilized in concrete and other construction materials. The total volume of cement production worldwide amounted to an estimated 4.1 billion metric tons in 2022 [1]. At present, China stands as the foremost producer of cement globally, with an output of approximately 2.1 billion

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tons in 2022 (more than half of the global production) [2]. Following behind, India emerges as the second-largest producer of cement with its production reaching 370 million tons. Vietnam secures the third position, with 120 million tons in 2022. Among the remaining cement-producing countries, none surpasses the threshold of 100 million tons.

Steel, as a construction material, offers advantages in sustainability when compared to concrete. While both materials are widely used in construction, steel's recyclability stands out as a key factor contributing to its sustainability. Unlike concrete, which relies heavily on cement production—a process associated with significant carbon emissions—steel can be recycled infinitely without loss of quality, reducing the need for raw material extraction and minimizing environmental impact. On the other hand, the production of crude steel also has a significant cost to the environment. One of the primary contributors to environmental degradation is the extraction and processing of raw materials, particularly iron ore and coal, which are essential inputs in steelmaking. Moreover, the manufacturing process itself involves high energy consumption and emissions of greenhouse gases, such as CO_2 and CH_4. Overall, the environmental cost of steel production underscores the urgent need for sustainable practices and technological innovations to mitigate its adverse impacts [3]. In 2022, global crude steel production reached nearly 1.89 billion tons [4]. China emerged as the largest steel-producing country, contributing approximately 1 billion tons, accounting for approximately 54% of the world's production.

Figure 1 illustrates the annual cement and steel production worldwide from 1995 to 2022. Comparatively, in 1995, global cement output was a modest 1.39 billion tons, or 34% of the 2022 production. Similarly, crude steel production in 1995 totaled 753 million tons, representing 40% of the output witnessed in 2022. These statistics underscore the recent expansion experienced in the construction sector globally.

Despite the finite nature of the planet's resources, both concrete and steel production continue to escalate annually. This trend underscores the urgent need for responsible resource management and sustainable construction practices. In the face of burgeoning demand, it becomes imperative to utilize these materials efficiently and judiciously, avoiding wastage wherever possible. Furthermore, it is

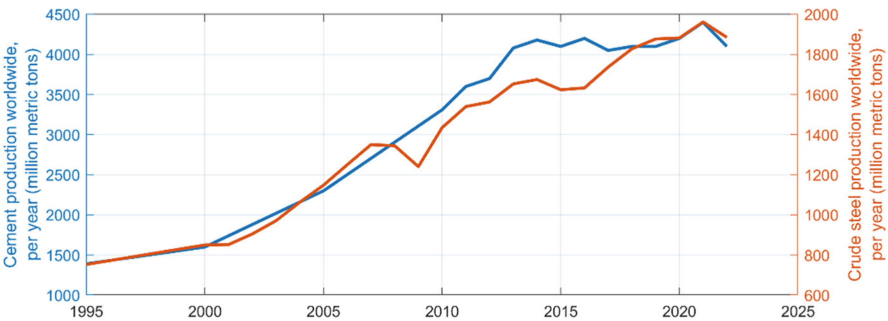

Fig. 1 Cement and steel production worldwide, per year (1995–2022) [1, 4]

essential to acknowledge that the building sector in general consumes approximately 40% of the world's energy, 25% of its water, and 40% of its resources, while also serving as the leading contributor to global greenhouse gas (GHG) emissions, accounting for 30%. Additionally, the construction industry is a significant source of waste generation [5].

2 Structural Optimization and Sustainability

Structural optimization emerges as a vital tool in the quest for sustainability in our constructions, offering a pathway toward constructing structures that maximize efficiency while meeting stringent safety standards. Structural optimization involves applying optimization techniques to the design of load-bearing engineering structures such as buildings, bridges, and others. Before the adoption of computer-assisted optimization procedures, structural elements like beams and plates were designed optimally using manual trial-and-error methods, which were time-consuming. Today, by leveraging advanced optimization techniques, engineers can design buildings and infrastructures that require minimal material inputs without compromising structural integrity or performance. In doing so, structural optimization paves the way for a more sustainable future, where our constructions are not only resource-efficient but also resilient and environmentally conscious.

2.1 Literature Review

Structural optimization has emerged as an innovative technology in recent decades, as demonstrated by the wealth of research articles dedicated to the subject in the literature. A search on Scopus conducted on March 16, 2024, using the query "TITLE-ABS-KEY ("structural optimization") "AND PUBYEAR>1994 AND PUBYEAR<2024" yielded a total of 52,404 published documents from 1995 to 2023. By limiting the search to engineering only, using the additional instruction "AND (LIMIT-TO (SUBJAREA, "ENGI"))" we similarly get 33,670 published documents. Figure 2 depicts the trend of published papers on structural optimization according to Scopus for the period 1995–2023, both overall and within the engineering field. Within the engineering domain, the figure reveals a consistent increase in the number of papers published each year, from 117 papers in 1995 to 1365 papers in 2009 and 3439 papers in 2023.

Lagaros [6] sought to demonstrate the profound environmental benefits and economic advancements achievable through the adoption of optimization-based design procedures within the construction industry. Russo and Rizzi [7] introduced a computer-aided methodology, which integrates Structural Optimization and Life Cycle Assessment (LCA) tools. They used optimization strategies that convert environmental objectives and constraints into structural and geometrical parameters, enabling the generation of alternative green scenarios based on shape, material, and

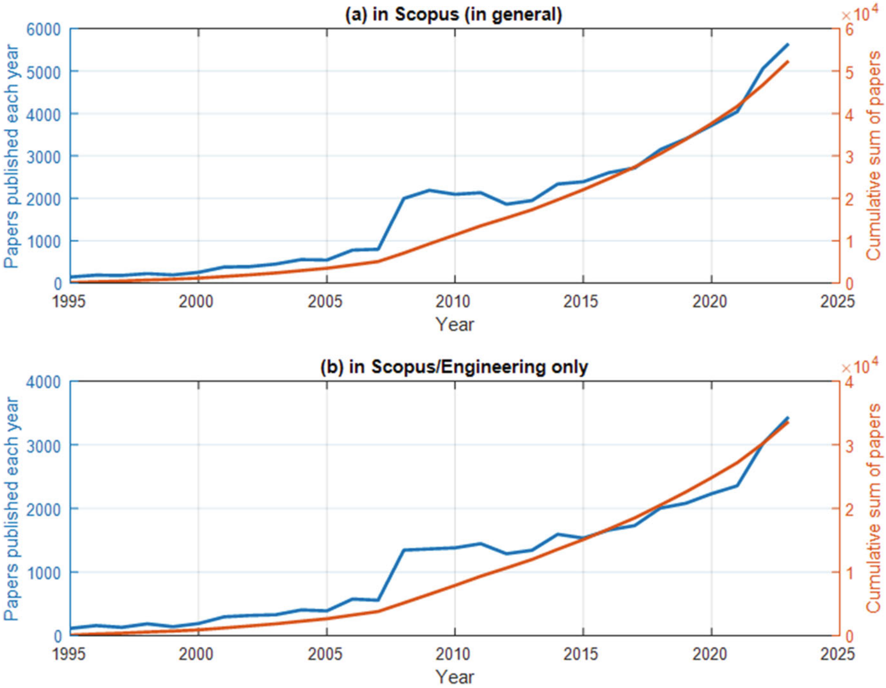

Fig. 2 Published papers in "Structural Optimization," according to Scopus (1995–2023)

production. Rempling et al. [8] attempted automatic structural design by combining set-based design, parametric design, finite element analysis (FEA), and multi-criteria decision analysis. The method was tested on three existing bridges. Tien and Van Tung [9] used building information modeling (BIM) for the multidisciplinary design optimization of sustainable structures, employing the Non-dominated Sorting Genetic Algorithm II. Islam et al. [10] described an optimization approach for balancing life cycle cost and environmental impacts for typical Australian houses, employing single- and multi-objective optimization techniques. Afzal et al. [11] investigated the potential of BIM and optimization algorithms to optimize structural systems and improve design outcomes, following the PRISMA systematic review methodology.

3 Optimization Problems, Algorithms, and Objectives

3.1 Types of Structural Optimization Problems

The basic types of structural optimization problems encompass topology, shape, and sizing optimization, as shown in Fig. 3. Topology optimization is a computational method that aims to determine the optimal distribution of material within a given

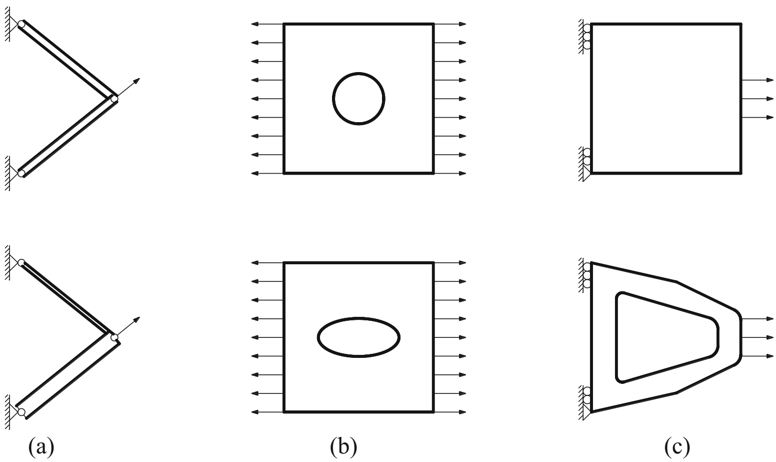

Fig. 3 Basic types of structural optimization problems [16] (Top: Original structure, Bottom: Optimized structure): (**a**) Sizing, (**b**) Shape, and (**c**) Topology optimization

design space to achieve predefined performance objectives while minimizing material usage [12]. By iteratively removing unnecessary material and redistributing load paths, topology optimization enables the creation of structurally efficient designs with optimized strength-to-weight ratios. This approach allows engineers to explore unconventional complex geometries, leading to the development of lightweight and resource-efficient structures that can meet stringent sustainability criteria.

Shape optimization focuses on refining the geometry of structural components to improve their performance characteristics, such as stiffness, strength, or aerodynamic efficiency [13]. By adjusting the shape of individual elements or entire structures, engineers can achieve desired functional requirements while minimizing material usage and environmental impact. Shape optimization techniques often involve parametric modeling and FEA to explore a vast design space and identify the most efficient geometric configurations. This approach facilitates the creation of streamlined and aerodynamic structures that enhance sustainability by reducing energy consumption and material waste.

Sizing optimization involves determining the optimal dimensions of structural members, such as beams, columns, or trusses [14, 15], to maximize performance while minimizing material usage and cost. By systematically adjusting the cross-sectional properties of components based on loading conditions and design constraints, engineers can achieve optimal structural efficiency. Sizing optimization techniques consider factors such as strength, stiffness, and stability to ensure that the resulting structures meet safety standards and functional requirements. This approach allows for the creation of lightweight and resource-efficient designs that contribute to overall sustainability by reducing material consumption and carbon emissions.

3.2 Optimization Algorithms

Optimization algorithms can be broadly categorized into mathematical and metaheuristic ones. *Mathematical algorithms*, also known as deterministic algorithms, are systematic procedures that rely on mathematical principles to find optimal solutions. One of the most widely used mathematical optimization techniques in structural optimization is the gradient-based optimization method. Gradient-based algorithms, such as the method of steepest descent and Newton's method, iteratively update the design variables in the direction of the gradient of the objective function to converge toward the optimal solution. These algorithms are efficient for convex optimization problems with smooth, continuous objective functions.

On the other hand, *metaheuristic algorithms* [17] are stochastic search techniques inspired by natural phenomena or human behavior [18]. These algorithms explore the solution space using randomized search strategies, making them well-suited for non-convex, multimodal optimization problems commonly encountered in structural optimization. They can be broadly classified into the categories shown in Table 1 which also includes some example algorithms for each class. The list is not exhaustive.

In structural optimization, mathematical algorithms are often preferred for problems with well-defined objectives and constraints which can be often expressed analytically. Gradient-based methods are particularly effective for problems with smooth, continuous objective functions and explicit constraints. However, for more complex, non-convex optimization problems with discontinuous or non-smooth objective functions, metaheuristic algorithms offer a more robust and versatile solution approach due to their ability to effectively handle non-convex, multimodal

Table 1 Categories of metaheuristic optimization algorithms

Category	Examples and related works
Evolution-based algorithms	Genetic algorithms (GA) [19, 20]
	Differential evolution (DE) [21, 22]
Swarm intelligence-based algorithms	Particle swarm optimization (PSO) [23]
	Firefly algorithm (FA) [24]
	Grasshopper optimization algorithm (GOA) [25]
	Cuckoo search (CS) [26]
	Whale optimization algorithm (WOA) [27]
Physics-based algorithms	Simulated annealing (SA) [28]
	Lightning search algorithm (LSA) [29]
	Gravitational search algorithm (GSA) [30]
	Electromagnetic field optimization (EFO) [31]
Human-related algorithms	Teaching-based learning optimization (TBLO) [32]
	Sharing knowledge-based algorithm (GSKA) [33]

objective functions and complex design spaces. Hybrid methods can also be employed, aiming to harness the strengths of both categories. Typically, these methods utilize a metaheuristic algorithm for global exploration, followed by a mathematical optimizer for fine-tuning through localized search around the global optimum [23].

3.3 Optimization Objectives

Optimization criteria, also known as objective functions, play a critical role in structural optimization by defining the goals and performance metrics that guide the design process. In optimum structural design, these criteria typically encompass various factors such as structural efficiency, safety, cost-effectiveness, and environmental sustainability. Structural engineers often aim to maximize structural performance while minimizing material usage, weight, or construction costs. Additionally, considerations may include constraints related to permissible stress levels, deflection limits, and geometric configurations. By carefully selecting and formulating optimization criteria, engineers can effectively balance competing objectives and tailor designs to meet specific project requirements, ultimately yielding more sustainable structures.

In *single-objective optimization* (SOO) within structural engineering, the focus is on optimizing a single performance metric or objective function, such as minimizing material usage or cost, maximizing structural strength, or minimizing deflection under load. Engineers typically formulate the optimization problem as a mathematical function, seeking the optimal solution that satisfies predefined constraints while optimizing the chosen objective. SOO techniques, such as gradient-based methods or evolutionary algorithms, facilitate the exploration of design alternatives to achieve the desired performance targets. While SOO provides a straightforward approach for addressing specific design goals, it may overlook trade-offs between conflicting objectives and fail to capture the full spectrum of design possibilities.

In contrast, *multi-objective optimization* (MOO) considers multiple conflicting objectives simultaneously, aiming to identify a set of solutions that represent trade-offs between competing criteria [34]. These objectives often encompass diverse aspects such as structural performance, cost, sustainability, and aesthetic considerations. MOO techniques enable engineers to explore the trade-off space and generate a range of design alternatives known as the Pareto front [35]. By evaluating trade-offs between different objectives, MOO facilitates informed decision-making and helps identify design solutions that offer superior overall performance across multiple criteria. This approach is particularly valuable in complex design scenarios where conflicting objectives must be balanced to achieve optimal outcomes.

4 Benefits of Optimization in Structural Design

Optimization in structural design offers numerous benefits that contribute to the development of efficient, cost-effective, and sustainable structures. By leveraging advanced computational techniques and mathematical algorithms, engineers can systematically refine designs to enhance performance, reduce material usage, and minimize environmental impact. Optimization enables the exploration of a vast design space, leading to innovative solutions that prioritize structural integrity, safety, and functionality. It facilitates informed decision-making by quantifying trade-offs between conflicting objectives, allowing engineers to achieve optimal outcomes tailored to specific requirements. Ultimately, the adoption of optimization methodologies empowers engineers to push the boundaries of structural design, resulting in more resilient and resource-efficient built environments.

Efficiency Optimization improves the efficiency of structural systems by maximizing performance while minimizing resource consumption and waste. Through iterative refinement of designs, engineers can achieve higher structural efficiency, leading to lighter, more streamlined structures that require fewer materials and resources to construct. This enhanced efficiency translates to reduced construction time, lower energy consumption, and improved overall sustainability.

Cost Savings Optimization helps to reduce construction costs by optimizing material usage, minimizing the need for expensive materials, and streamlining construction processes. By identifying cost-effective design alternatives and eliminating unnecessary elements, engineers can realize significant savings in material procurement, labor costs, and project overheads. Furthermore, optimized designs often require less maintenance over their lifespan, further reducing life-cycle costs and enhancing long-term affordability.

Sustainability Optimization plays a crucial role in promoting sustainability in structural design by minimizing environmental impact and resource depletion. By optimizing material usage, structural configurations, and construction methodologies, engineers can reduce the carbon footprint of buildings and infrastructure projects. Additionally, optimization enables the integration of sustainable materials, renewable energy systems, and passive design strategies, further enhancing environmental performance and resilience to climate change.

Innovative Designs Optimization fosters creativity and innovation in structural design by pushing the boundaries of conventional practices and exploring new possibilities. By leveraging advanced computational tools and generative design techniques, engineers can generate novel structural forms and geometries that maximize performance and visual appeal. Optimization encourages experimentation with unconventional materials, fabrication methods, and construction techniques, leading to the realization of iconic and landmark structures that inspire future generations.

Safety Optimization can enhance structural safety by optimizing designs to withstand a wide range of loading conditions and environmental hazards. By conducting rigorous analysis and optimization iterations, engineers can identify potential weaknesses, improve structural robustness, and mitigate risks of failure. Optimization also allows for the incorporation of safety factors and design redundancies, ensuring that structures meet or exceed regulatory standards and withstand unforeseen challenges throughout their lifespan.

5 Challenges and Limitations

Optimization in structural design, while offering significant benefits, also presents various challenges and limitations that engineers must navigate to achieve successful outcomes. Below we examine and analyze some of these obstacles in detail.

Computational Intensity One of the primary challenges in optimization-driven structural design is the computational intensity required to solve complex optimization problems. The iterative nature of optimization algorithms and the need for detailed FEA in each step contribute to significant computational demands, requiring substantial computing resources and time. As a result, engineers must carefully manage computational resources, employ efficient algorithms, and leverage parallel computing techniques to overcome this challenge and expedite the optimization process without compromising accuracy. For instance, if a single FEA iteration of a building requires approximately 5 s to finish, and an optimization algorithm demands 10,000 iterations to reach convergence, then the optimization process could potentially consume up to 14 h to complete—a substantial duration of time.

Multiple Objectives Balancing multiple conflicting objectives and constraints poses a significant challenge in structural optimization, particularly in real-world construction problems. Engineers must navigate trade-offs between competing design criteria, such as performance, cost, sustainability, and aesthetics, to identify Pareto-optimal solutions that represent acceptable compromises. Achieving consensus among stakeholders and reconciling conflicting preferences can further complicate the optimization process, requiring robust decision-making frameworks and stakeholder engagement strategies to address diverse perspectives and priorities effectively.

Inherent Uncertainties The existence of uncertainties in material properties, loading conditions, and modeling assumptions introduces challenges to the accuracy and reliability of optimization results [36]. Sensitivity analysis techniques are essential for assessing the sensitivity of optimized designs to input parameters and identifying sources of uncertainty that may affect performance and safety. Engineers must employ robust probabilistic methods, such as Monte Carlo simulation [37] or stochastic optimization, to account for uncertainties and optimize designs that exhibit resilience and robustness [38] in the face of varying operating conditions and environmental factors. Consequently, this introduces further computational complexities to the optimization process [39].

Constraint Handling Handling constraints presents a significant challenge in optimization-driven structural design, as balancing optimization objectives with real-world constraints can be complex and difficult to fully automate. Structural engineers must navigate a diverse array of constraints, including fabrication limitations, regulatory requirements, material availability, and construction logistics, which can significantly impact the feasibility and practicality of designs. While optimization algorithms excel at finding solutions that optimize specified performance metrics, integrating constraints into the optimization process requires careful consideration and often involves trade-offs. Engineers must strike a delicate balance between achieving optimal performance and adhering to practical constraints, such as budgetary limitations, site-specific conditions, and safety standards. Furthermore, constraints may vary in nature and complexity across different projects, necessitating customized approaches and expert judgment while optimizing structural designs for sustainability, efficiency, and safety. Despite these challenges, advancements in constraint handling techniques, continue to enhance the capabilities of optimization algorithms to accommodate diverse constraints and facilitate the development of innovative and practical structural solutions.

6 Conclusions

In conclusion, structural optimization emerges as a pivotal asset in contemporary engineering, offering a pathway toward the creation of stronger, more efficient, and sustainable structures. By harnessing the power of optimization algorithms and computational tools, engineers can unlock innovative design solutions that maximize performance while minimizing environmental impact. Optimization techniques enable the strategic allocation of materials and resources, resulting in structures that exhibit superior resilience, structural integrity, and resource efficiency. Moreover, optimization has the potential to revolutionize the construction industry by streamlining design processes, reducing material waste, and enhancing project cost-effectiveness.

With advancements in technology, hardware, and software, coupled with the increasing availability of computational resources, the field of structural optimization is poised for significant expansion. The integration of cutting-edge computational methods and predictive modeling techniques promises to propel structural design into a new era of unprecedented creativity and efficiency. By leveraging these technological advancements, engineers can explore complex design spaces, optimize structural configurations, and push the boundaries of conventional construction practices. As a result, the forthcoming era of structural design holds the promise of seamlessly blending artistic ingenuity with scientific precision, yielding structures that not only meet functional requirements but also embody ecological mindfulness and cost-efficiency.

In essence, structural optimization represents a transformative paradigm shift in the built environment, offering a harmonious convergence of engineering excellence and sustainable design principles. By embracing optimization methodologies, engineers can catalyze positive change in the construction industry, fostering the development of resilient, adaptable, and environmentally conscious structures. As we embark on this journey toward a more sustainable future, structural optimization stands as a beacon of innovation, driving the evolution of architectural design toward a greener, more efficient, and harmonious built environment.

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