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Lifecycle Assessment of Sustainable Construction Materials in Green Buildings: A Multi-Objective Optimization Model

Arthur J. Sterling, Marcus P. Thorne, Julian T. Harrow

Department of Architecture and Civil Engineering, University of Bath, Bath BA2 7AY, United Kingdom

Abstract

The construction sector remains one of the largest contributors to global energy consumption and greenhouse gas emissions, precipitating an urgent shift toward sustainable development practices. Green buildings aim to mitigate these environmental impacts through the adoption of eco-friendly materials and energy-efficient designs. However, the selection of sustainable materials often presents a complex decision-making problem characterized by conflicting criteria, primarily the trade-off between initial construction costs and long-term environmental benefits. This paper presents a comprehensive framework that integrates Lifecycle Assessment with a Multi-Objective Optimization model to assist decision-makers in selecting optimal construction materials. By utilizing a non-dominated sorting genetic algorithm, the study simultaneously minimizes lifecycle cost and lifecycle environmental impact, specifically embodied carbon and operational energy. The proposed model is applied to a mid-rise commercial building case study, evaluating a wide range of material alternatives for structural and envelope systems. The results demonstrate that while sustainable materials may incur a higher upfront cost, optimization can identify Pareto-optimal solutions that significantly reduce environmental footprints with marginal economic premiums. This research contributes to the body of knowledge by providing a quantitative tool that bridges the gap between economic constraints and environmental stewardship in the built environment.

Keywords

Lifecycle Assessment, Multi-Objective Optimization, Sustainable Construction, Green Buildings.

1 Introduction

The built environment is a dominant force in the global economy, yet it exerts a profound pressure on the natural environment. Recent statistics indicate that the construction and operation of buildings account for nearly forty percent of global energy-related carbon dioxide emissions. As urbanization accelerates and the demand for infrastructure grows, the imperative to decouple construction activities from environmental degradation has never been more critical. This context has given rise to the green building movement, which seeks to minimize the ecological footprint of structures throughout their lifecycle, from raw material extraction to demolition and disposal. However, the transition to green buildings is frequently hindered by perceived and actual financial barriers. Stakeholders often face a difficult dichotomy: choosing conventional materials that are economically favorable in the short term but environmentally detrimental, or selecting sustainable alternatives that offer long-term ecological benefits but require higher initial capital investment.

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The complexity of material selection is further exacerbated by the multifaceted nature of environmental impacts. A material that is energy-efficient during the operational phase, such as high-performance insulation, may possess a high embodied energy due to intensive manufacturing processes. Therefore, a holistic approach is required to evaluate the true sustainability of construction materials. Lifecycle Assessment has emerged as the standard methodology for quantifying environmental impacts associated with all the stages of a product's life. Despite the robustness of Lifecycle Assessment as an evaluative tool, it is traditionally used for post-design verification rather than as an active design support tool. This retrospective application limits its potential to influence early-stage design decisions where the greatest opportunities for sustainability improvements lie.To address these challenges, there is a growing need for decision support systems that can handle high-dimensional design spaces and conflicting objectives. Multi-objective optimization offers a mathematical framework to resolve such conflicts by identifying a set of optimal trade-off solutions, known as the Pareto frontier. Unlike single-objective optimization, which might focus solely on minimizing cost or maximizing energy efficiency, multi-objective approaches allow for the simultaneous consideration of economic and environmental performance. This paper proposes a novel integrated model that combines Lifecycle Assessment with evolutionary optimization algorithms to navigate the complex landscape of sustainable material selection.The primary objective of this research is to develop a computational model capable of automatically selecting material combinations that minimize both total lifecycle cost and global warming potential. By incorporating a cradle-to-grave perspective, the study ensures that impacts occurring at the end-of-life stage, such as recyclability and landfill disposal, are not overlooked. As noted in foundational research on sustainable infrastructure [1], the failure to account for the full lifecycle often leads to burden-shifting, where environmental savings in one phase are negated by increased impacts in another. Furthermore, the integration of economic analysis through Lifecycle Costing ensures that the proposed solutions are financially viable, addressing the hesitation of investors to commit to green building projects [2]. The study builds upon the premise that sustainability is not merely an environmental constraint but a multi-faceted optimization problem that requires rigorous quantitative analysis to solve effectively [3].

2. Literature Review

2.1 Lifecycle Assessment in Construction

Lifecycle Assessment methodology has evolved from simple energy analysis to a comprehensive environmental management tool standardized by international protocols. In the context of construction, it involves compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential impacts associated with identified inputs and releases, and interpreting the results to make informed decisions. The construction industry has traditionally focused on operational energy—the energy used for heating, cooling, lighting, and ventilation—as it historically represented the largest portion of a building's carbon footprint. However, as energy codes have become stricter and building envelopes more efficient, the relative significance of embodied carbon—the emissions associated with material extraction, manufacturing, and transport—has increased.Recent studies emphasize that for near-zero energy buildings, embodied carbon can account for up to half of the total lifecycle carbon emissions. This shift necessitates a rigorous evaluation of construction materials. For instance, concrete is the most widely used construction material globally, yet its production is responsible for a significant share of industrial carbon emissions. Research into alternative binders, such as fly ash and slag, has shown potential for reducing these impacts. Similarly, the use of bio-based materials like cross-laminated

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timberhas gained traction due to their carbon sequestration capabilities. However, the variability in Lifecycle Assessment data and the lack of interoperability between assessment tools and building information modeling software remain significant hurdles. Previous reviews have highlighted the need for dynamic assessment frameworks that can adapt to changing design parameters in real-time [4].

2.2 Sustainable Material Alternatives

The market for sustainable construction materials has expanded rapidly, offering architects and engineers a plethora of choices. In the structural domain, high-strength recycled steel and geopolymer concrete are being investigated for their mechanical properties and environmental profiles. In the building envelope sector, innovations in glazing technologies, such as aerogel insulation and electrochromic glass, promise superior thermal performance. Nevertheless, the adoption of these materials is often slow due to the lack of long-term performance data and higher upfront costs.Literature suggests that the environmental benefits of these materials are highly context-dependent. A material that performs well in a cold climate may not be suitable for a tropical region due to different thermal mass requirements. Furthermore, the transportation distance of materials plays a crucial role; a sustainable material imported from a great distance may have a higher carbon footprint than a locally sourced conventional material due to transport emissions. Therefore, material selection cannot be based on generic attributes alone but must be evaluated within the specific context of the project. Studies have demonstrated that integrating local availability constraints into the selection process is essential for realistic sustainability assessments [5].

2.3 Optimization in Building Design

Optimization techniques have been applied to building design for decades, initially focusing on structural weight minimization and cost reduction. With the advent of the sustainability agenda, the scope of optimization has broadened to include energy performance and environmental impacts. Traditional linear programming methods often struggle with the non-linear and discontinuous nature of building design variables. Consequently, meta-heuristic algorithms, particularly genetic algorithms, have become the preferred method for solving building optimization problems.Genetic algorithms mimic the process of natural selection, evolving a population of candidate designs over multiple generations to converge on optimal solutions. In the context of multi-objective optimization, these algorithms are particularly powerful because they generate a set of non-dominated solutions rather than a single optimal point. This allows stakeholders to visualize the trade-offs between conflicting objectives. For example, a study might reveal that a twenty percent reduction in embodied carbon can be achieved with only a two percent increase in cost, whereas further reductions require exponentially higher investments. While numerous studies have applied optimization to specific building subsystems, such as HVAC or envelope design, fewer have attempted a holistic optimization of the entire building material palette [6]. Existing models often simplify the lifecycle stages, neglecting maintenance and end-of-life scenarios, which can significantly alter the optimization results [7].

3. Methodology

3.1 Framework and System Boundaries

The proposed methodology is structured around a closed-loop integration of a parametric building model, a Lifecycle Assessment database, and an optimization engine. The system boundary for the assessment is defined as "cradle-to-grave," encompassing four distinct stages: product stage, construction process stage, use stage, and end-of-life stage. The product

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stage includes raw material supply, transport to the manufacturer, and manufacturing. The construction process stage covers transport to the building site and installation. The use stage accounts for maintenance, repair, replacement, and operational energy use over the building's lifespan, assumed to be fifty years. Finally, the end-of-life stage includes deconstruction, transport to waste processing, and disposal or recycling.To ensure consistency, the functional unit is defined as one square meter of gross floor area for the entire building service life. This normalization allows for the comparison of different design configurations. The inventory analysis relies on established databases for environmental inputs and outputs. Cost data is derived from national construction cost guides and supplier quotations, adjusted for regional variations. The framework operates by iteratively selecting material combinations for various building elements—such as columns, beams, floors, walls, and windows—and calculating the cumulative environmental and economic impacts [8].

3.2 Objective Functions

The optimization problem is formulated with two minimization objectives. The first objective is the Total Lifecycle Cost. This is an economic metric that aggregates all costs incurred during the building's life. It is calculated as the sum of the initial capital cost, the present value of recurring maintenance and replacement costs, and the present value of operational energy costs. The calculation utilizes a discount rate to convert future costs into present value terms, reflecting the time value of money. The initial capital cost is determined by multiplying the quantity of each material by its unit price. Operational energy cost is derived from energy simulation results multiplied by the projected unit price of energy.The second objective is the Total Lifecycle Carbon, expressed in kilograms of carbon dioxide equivalent. This environmental metric sums the embodied carbon of all materials used in the initial construction and subsequent replacements, the operational carbon emitted due to energy consumption, and the carbon emissions associated with demolition and disposal. The Global Warming Potential factors for each material are drawn from Environmental Product Declarations and generic Lifecycle Assessment databases. Importantly, the model accounts for the recycling potential of materials at the end of life, crediting the system for avoided burdens where applicable [9].

3.3 Optimization Algorithm

The study employs the Non-dominated Sorting Genetic Algorithm II, a popular evolutionary algorithm known for its efficiency in handling multi-objective problems. The algorithm initiates by generating a random population of design variants, where each variant represents a specific combination of materials. These variants are then evaluated against the two objective functions. The core mechanism of the algorithm involves sorting the population into different ranks based on dominance. A solution is said to dominate another if it is better in at least one objective and not worse in any other.The first rank consists of the non-dominated solutions, forming the current Pareto frontier. The algorithm then applies genetic operators—selection, crossover, and mutation—to create a child population. Selection favors higher-ranked individuals, ensuring that better traits are passed to the next generation. Crossover combines the genetic information of two parents to produce offspring, while mutation introduces random changes to maintain diversity and prevent premature convergence. This process repeats for a specified number of generations until the population converges to a set of optimal solutions. The variables in this study are discrete, representing a catalog of distinct material choices for each building element [10].

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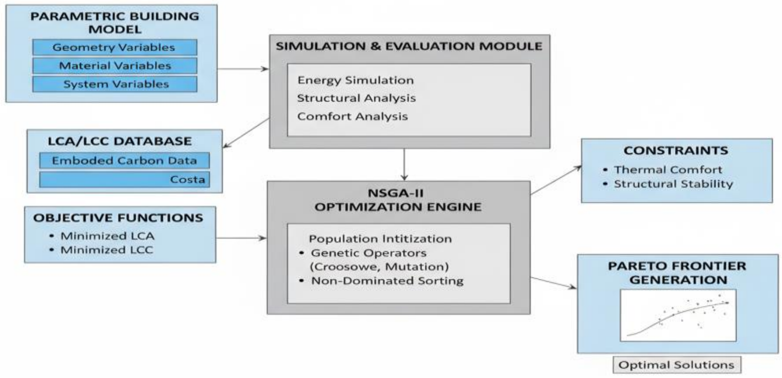

Figure 1: Optimization Framework

4. Case Study Application

To validate the proposed model, a case study of a five-story commercial office building is conducted. The building is located in a temperate climate zone, requiring both heating and cooling. The structure is a reinforced concrete frame with a gross floor area of approximately four thousand square meters. The design variables selected for optimization include the type of concrete mix for structural elements, the type of insulation material for the exterior walls and roof, the glazing specifications for windows, and the type of floor covering.For the concrete mix, alternatives range from standard Portland cement concrete to mixes with varying percentages of fly ash and ground granulated blast-furnace slag substitution. Insulation options include expanded polystyrene, mineral wool, cellulose, and polyurethane rigid foam. Glazing alternatives vary by U-value and solar heat gain coefficient, ranging from double-glazed air-filled units to triple-glazed argon-filled units with low-emissivity coatings. Floor coverings include ceramic tiles, carpet tiles, vinyl, and linoleum. In total, the combination of these variables results in a search space exceeding one million potential design solutions, making manual evaluation impossible and justifying the use of the optimization algorithm. The operational energy demand for each design variant is estimated using a simplified thermal model calibrated against standard energy simulation software.

5. Results and Analysis

5.1 Pareto Optimal Solutions

The optimization process was executed over one hundred generations with a population size of fifty, resulting in the evaluation of five thousand design variants. The convergence of the algorithm was monitored, and the final set of non-dominated solutions was extracted to form the Pareto frontier. The results reveal a clear conflict between lifecycle cost and lifecycle carbon. Solutions that achieved the lowest possible carbon footprint typically involved high-performance materials such as triple glazing and high-volume fly ash concrete, which commanded a premium price. Conversely, the most economical solutions utilized standard materials but resulted in higher operational energy consumption and embodied carbon.The Pareto frontier provides a range of optimal choices. At one extreme, the "Greenest" solution achieved a thirty-five percent reduction in total carbon emissions compared to the baseline

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design (which used standard industry practices) but incurred a twelve percent increase in lifecycle cost. At the other extreme, the "Cheapest" solution reduced costs by five percent compared to the baseline but increased carbon emissions by eight percent. Interestingly, the optimization identified "Knee Point" solutions—designs that offer a balanced compromise. One such solution achieved a twenty-five percent reduction in carbon emissions with only a two percent increase in cost. This demonstrates that significant environmental gains can be made with minimal economic impact if materials are selected strategically [11].

Table 1 presents a comparative analysis of three distinct design configurations: the Baseline Design (representing standard practice), the Cost-Optimized Design (minimizing economic impact), and the Carbon-Optimized Design (minimizing environmental impact).

Table 1: Comparison of Lifecycle Performance for Selected Design Configurations

Design Configuration	Initial Cost ($/m2)	Lifecycle Cost ($/m2)	Embodied Carbon (kgCO2e/m2)	Operational Carbon (kgCO2e/m2)	Total Carbon (kgCO2e/m2)
Baseline Design	1250	2800	450	1800	2250
Cost-Optimized	1180	2650	510	1920	2430
Carbon-Optimized	1450	3150	320	1150	1470

5.2 Material Selection Patterns

Analysis of the optimal solutions reveals specific patterns in material selection. For the structural system, concrete mixes with forty to fifty percent cement replacement by industrial by-products were frequently selected in the balanced and carbon-optimized solutions. While these mixes are slightly more expensive due to supply chain constraints in the specific region of the case study, the reduction in embodied carbon is substantial. In terms of the building envelope, mineral wool insulation appeared in the majority of Pareto-optimal solutions. It offers a favorable balance between thermal performance, cost, and embodied impact compared to petroleum-based foams.Regarding glazing, triple glazing was dominant in the carbon-optimized solutions due to its ability to significantly reduce heating and cooling loads. However, in the cost-optimized solutions, double glazing with a high solar heat gain coefficient was preferred, as it lowered initial costs and utilized passive solar heating to offset some heating demand, albeit less effectively than the triple glazing options. The choice of floor covering showed that linoleum and bamboo were preferred in environmental optimizations due to their rapid renewability and low manufacturing intensity, whereas vinyl remained the choice for pure cost minimization [12].The interaction between embodied and operational phases was particularly evident. For example, increasing insulation thickness yields diminishing returns. The optimization model successfully identified the tipping point where the embodied carbon of the additional insulation material outweighed the operational carbon savings it provided. This highlights the capability of the multi-objective approach to avoid over-engineering, a common pitfall in green building design where more technology is assumed to always be better [13].

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6. Discussion

6.1 Economic and Environmental Trade-offs

The findings of this study underscore the existence of a "Green Premium," but also suggest that it is often lower than perceived. The identification of solutions that drastically reduce carbon for a marginal cost increase implies that the barrier to sustainable construction is often informational rather than purely economic. Stakeholders lack the visibility of these trade-offs during the early design stages. The Pareto frontier serves as a powerful communication tool, allowing clients to make value-based decisions. For instance, a client might be willing to pay an extra one percent in total cost to achieve a ten percent reduction in carbon, but might reject a solution requiring a ten percent cost increase for a twelve percent carbon reduction.The analysis also highlights the sensitivity of the results to external economic factors. The lifecycle cost is heavily influenced by the discount rate and energy price projections. A sensitivity analysis conducted as part of this research indicates that if energy prices rise faster than inflation, the Pareto frontier shifts, making energy-efficient, high-embodied-cost solutions more economically attractive. Conversely, a high discount rate prioritizes low initial costs, penalizing investments in longevity and efficiency. This suggests that financial incentives or carbon taxation policies could effectively shift the optimal design choices toward the greener end of the spectrum.

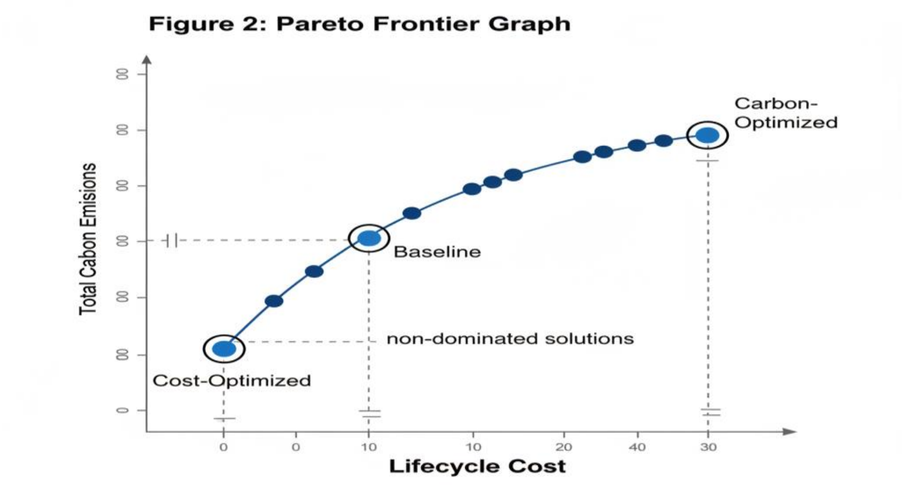

Figure 2: Pareto Frontier Graph

6.2 Limitations and Model Constraints

While the proposed model provides robust insights, it is subject to certain limitations. The accuracy of the Lifecycle Assessment is contingent on the quality of the underlying databases. Generic data may not perfectly reflect the specific supply chains of a local project. Furthermore, the model assumes a static building usage pattern over fifty years, which does not account for potential changes in occupancy or function. The social aspects of sustainability, such as occupant comfort and indoor air quality, were not explicitly quantified as objective functions, although they are implicitly addressed through material standards.Another limitation lies in the scope of the structural optimization. The study focused on material substitution within a fixed geometric frame. It did not explore topological optimization or changes to the structural grid, which could yield further material savings.

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Additionally, the end-of-life scenarios are based on current recycling technologies and market conditions, which are likely to change over the building's lifespan. Future iterations of the model should incorporate probabilistic methods to account for these uncertainties.

Conclusion

This paper presented a Multi-Objective Optimization model for the Lifecycle Assessment of sustainable construction materials in green buildings. By integrating parametric modeling, environmental databases, and evolutionary algorithms, the research demonstrated a viable pathway for reconciling the often-conflicting goals of cost minimization and environmental protection. The application of the model to a generic office building revealed that significant reductions in total carbon footprint—up to thirty-five percent—are achievable through intelligent material selection. Crucially, the study identified "compromise solutions" capable of delivering substantial environmental benefits with negligible increases in lifecycle cost, challenging the narrative that green buildings are prohibitively expensive.The research confirms that a holistic view, considering both embodied and operational impacts, is essential. Focusing solely on operational energy can lead to sub-optimal decisions where the embodied carbon of high-tech materials negates their operational savings. The use of fly ash concrete, mineral wool insulation, and optimized glazing emerged as key strategies for sustainable design in the studied context.Future research will focus on expanding the model to include social sustainability indicators and extending the system boundaries to include community-scale impacts. Furthermore, the integration of this optimization framework directly into Building Information Modeling software is a critical next step to facilitate its adoption by industry practitioners. By empowering designers with real-time data on the consequences of their material choices, the construction industry can move closer to achieving its sustainability targets and mitigating its contribution to climate change [14]. The transition to a circular economy in construction requires not just new materials, but new methods of evaluation and decision-making, for which this study provides a foundational blueprint [15].

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