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Guiding early building design towards lower carbon emissions through set-based design and genetic algorithm optimisation

Smart and Sustainable Built Environment

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Abstract

Purpose – The materials used in the structural system account for a significant share of a building's total embodied carbon emissions. Thus, to mitigate the climate impact of construction projects, it is essential to consider carbon emissions in early conceptual design and understand how structural decisions affect costs. Therefore, this study explores integrating set-based design with genetic algorithm optimisation to evaluate a wide range of building designs in terms of cost and carbon performance.

Design/methodology/approach – First, databases of structural building assemblies, including their capacities, costs, and embodied carbon, were developed. The NSGA-II algorithm, combined with set-based design, was then applied to a reference building to minimise its cost and carbon emissions.

Findings – The genetic algorithm alone identified solutions that reduced carbon emissions by 35% but with a 9% increase in cost. When set-based design was incorporated, carbon emissions were reduced by up to 42% with a comparable increase in cost. The findings demonstrate that integrating set-based design offers comparative advantages over using genetic algorithms alone, providing valuable insights for early-stage building design practice.

Originality/value – This paper proposes a novel design approach that combines genetic algorithm optimisation with set-based design to explore a broader solution space and support data-informed decision-making to reduce carbon emissions in buildings.

Keywords Carbon emission reduction, Data-driven optimisation, Artificial intelligence, Genetic algorithms, Set-based design

Paper type Research article

1. Introduction

The construction industry strives to reduce its climate impact, not only by lowering the operational energy use of buildings but also by reducing embodied carbon emissions from the construction phase (Röck *et al.*, 2020; Eisazadeh *et al.*, 2025). As a consequence, climate

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declarations that report carbon emissions from the raw materials used in the structure, the transportation of raw materials, and the construction and assembly processes are becoming mandatory in many countries (Song *et al.*, 2023; Boverket, 2024b). Although climate declarations are usually required in late project stages, carbon emission calculations should inform decision-making already during the conceptual design phase, when the potential to influence the project outcome is high (Liu *et al.*, 2015; Song *et al.*, 2023). The conceptual design process in itself does not induce high environmental impacts, but the decisions made in this phase determine approximately 80% of the project cost (Tempelmans Plat and Deiman, 1993; Rafiq *et al.*, 2009) and 70% of the building's lifetime environmental impact (Rebitzer, 2002; Liu *et al.*, 2015). Common structural designs are often cost-efficient, but since the transition to more sustainable building design may be associated with increased costs (Ekung *et al.*, 2022), it is important to have data-informed decision-making in the early project stages to minimise both cost and carbon emissions (Dunant *et al.*, 2021; Fathalizadeh *et al.*, 2022; Kamari *et al.*, 2022; Tumpa and Naeni, 2025).

The traditional conceptual design process often involves optimising costs and then calculating the solutions' corresponding carbon emissions. Such an approach risks generating solutions with too high carbon emissions, leading to costly and time-consuming rework as the design team needs to restart the design process to find an alternative solution that fulfils both cost and carbon requirements (Castañeda *et al.*, 2023). Therefore, it would be beneficial to explore multiple design solutions in parallel, highlighting the trade-offs between cost and carbon emissions to support informed decision-making.

Two possible approaches for solving such multi-optimisation problems and exploring a broader solution space are Set-Based Design (SBD) and Genetic Algorithms (GA). SBD is a design strategy within lean thinking, where sets of solutions are investigated in parallel, and the consequences of solution choices guide the pursuit of feasible design solutions (Bernstein, 1998). GA is a branch of population-based search algorithms that takes inspiration from natural selection and evolutionary strategies (Eiben and Smith, 2015). This research assesses how SBD and GA can be examined both individually and in combination to highlight cost and carbon trade-offs, thereby helping the design team make more sustainable design decisions.

1.1 Background

The conceptual design process typically begins with problem definition and brainstorming, followed by the selection and development of a single design concept (Bernstein, 1998). The concept is then iteratively refined and optimised (Ward *et al.*, 1995; Toche *et al.*, 2020). If the concept fails to meet requirements, the iterative design process restarts. As only one solution is explored at a time, this approach is known as Point-Based Design (PBD) (Ward *et al.*, 1995).

PBD becomes inefficient when new design requirements are introduced, as extensive redesign is often required (Castañeda *et al.*, 2023). Thus, introducing a carbon-emissions limit as a new requirement increases the risk of design rework if the chosen solution later proves to have excessively high emissions, necessitating a climate assessment early in the project design process. The PBD process also offers limited opportunities for trade-off visualisations, as few design concepts are investigated and can be compared.

1.2 Aim and contribution

Since previous research has identified limitations in the PBD approach, this underscores the need for design approaches that allow many alternatives to be evaluated in parallel, thereby providing a better understanding of how design choices influence production costs and embodied carbon outcomes. In this context, this paper investigates two such approaches—SBD and GA—as well as a combined method.

While SBD has primarily been applied in infrastructure projects, its suitability for building design remains underexplored. Genetic algorithms, on the other hand, have shown promise as an optimisation method in the construction sector, but existing structural optimisation studies

have primarily focused on load-bearing capacity. Limited attention has been given to functional requirements such as fire resistance and sound reduction, despite their substantial impact on both cost and carbon emissions.

These limitations highlight a gap in current research: a lack of integrated design approaches that enable parallel exploration of design alternatives while simultaneously addressing cost, carbon emissions, and essential functional requirements. This paper aims to address this gap by evaluating SBD, GA, and a combined SBD–GA approach for more data-informed early-stage building design, focussing on the building structure and envelope.

1.3 Set-based design

One method that explores multiple solutions simultaneously is Set-Based Design (SBD). SBD is a key principle of lean thinking, widely applied in industries such as automotive, aerospace, defence, and naval sectors (Bernstein, 1998; Toche *et al.*, 2020). The method begins with each engineering discipline independently developing sets of design alternatives (Liker *et al.*, 1996). The sets are then compared and integrated across disciplines, forming a solution space of feasible designs. Optimisation occurs through progressive narrowing of this space as new information or requirements emerge. An essential aim of SBD is to delay final design decisions until sufficient information is available or to generate more information earlier in the design process (Ward *et al.*, 1995).

In construction, SBD has mainly been applied to bridge design. Mathern *et al.* (2018) introduced a parametric SBD method for bridge design, which was later used by Rempling *et al.* (2019) to analyse costs and carbon emissions across three bridge types. Other studies explored SBD for soil-steel composite bridges (Lagerkvist *et al.*, 2022) and frame bridges (Löfgren, 2020; Bergenram and Ulander, 2023). Although less common, SBD has been applied in building design. Chuquín *et al.* (2021) assessed high-rise building designs; Wong *et al.* (2009) developed an SBD tool for shear wall design; and Wang *et al.* (2024) created an SBD tool to support early architectural design. Despite these efforts, using SBD for entire building structures remains largely unexplored, making it the focus of this study.

1.4 Genetic algorithms

Genetic Algorithms are a branch of population-based search algorithms, first introduced by Holland (Holland, 1975; Eiben and Smith, 2015). The algorithms draw inspiration from the principles of natural selection and utilise evolutionary strategies to iteratively improve a population of solutions. The GA process begins with an initial population, where each individual represents a potential solution encoded as a chromosome—a set of variable genes. The fitness of each solution is evaluated based on a predefined objective, typically to maximise or minimise a given function. The fittest individuals are selected for reproduction through crossover, which combines genetic material from two parents to produce new offspring. To ensure diversity and innovation in new solutions, mutation operators are applied to the offspring, allowing offspring to differ from their parents. The process repeats over multiple generations until a termination criterion, often a maximum number of generations, is met (Eiben and Smith, 2015).

Early applications of GA in construction focused on detailed design, such as steel plates, trusses, and reinforced concrete optimisation (Jenkins, 1991; Kousmoussis and Arsenis, 1994; Rafiq, 1995), while more recent research focuses on more complex structural designs (Rafiq *et al.*, 2003, 2009; Alanani and Elshaer, 2024). GA has also been used for optimising daylight and energy performance (Allam *et al.*, 2023; Nazari *et al.*, 2023).

1.5 Structural design optimisation, minimising costs and carbon emissions

Exploring a broader design solution space can reveal key cost-carbon trade-offs and support data-informed decision-making. However, it requires a larger design effort and

cross-disciplinary collaboration to avoid suboptimisation. The increased design complexity, design time, and costs are common barriers to carbon reduction (Smith *et al.*, 2024). Thus, there is a need for more automated methods to explore and evaluate multiple design solutions in parallel without increasing design time. Fang *et al.* (2023) identified that the most effective strategies for reducing structural carbon are applying optimisation techniques, comparing design concepts, selecting low-carbon materials, or reducing material use.

Several researchers have studied cost and carbon optimisation. Kanyilmaz *et al.* (2023) developed a design tool using genetic algorithms to optimise various building configurations in terms of both cost and carbon emissions. Gauch *et al.* (2022) developed a decision-support tool for cost and carbon optimisation of concrete, steel, and timber frames, various floor types, and foundations, with a focus on structural capacity. Dunant *et al.* (2021) highlighted the impact of early-stage design decisions and proposed a database to optimise layout grids and decking in steel structures. In contrast, several studies have applied cost-carbon GA optimisation to concrete structures. Gan *et al.* (2019) optimised high-rise concrete buildings, Lee *et al.* (2020) focused on office slabs, and Eleftheriadis *et al.* (2018) focused on column and slab sizing. Camp and Huq (2013) proposed a big-bang big-crunch algorithm for optimising reinforced concrete frames, and Mathem *et al.* (2021) applied Bayesian and GA optimisation for multi-objective bridge design. For timber, Nesheim *et al.* (2022) applied mixed-integer linear optimisation, accounting for serviceability factors like deflection and acceleration.

Some researchers have expanded their scope, including time, as an optimisation objective. For example, Behera *et al.* (2024) used genetic algorithms to optimise a building's time, cost, and carbon emissions. Huynh *et al.* (2021) proposed a multi-objective social group optimisation approach for optimising time, cost, carbon, and quality in generalised construction projects and applied it to office projects. Using GA, Oluyale (2024) optimised a two-story family house with respect to cost, time, and carbon. Ozcan-Deniz *et al.* (2012) used genetic algorithms to optimise a two-story residential building in China, focussing on time, cost, and carbon emissions. Instead of time, Choi *et al.* (2024) proposed a method for incorporating serviceability aspects as an optimisation factor alongside cost and carbon for high-rise buildings.

A summary of research conducted over the last ten years, with a focus on cost and carbon-emission optimisation in building projects, is presented in Table 1. The table presents each study's optimisation objectives, algorithms used, and case study approaches.

2. Methodology

The study followed a five-step methodology, visualised in Figure 1, to test a new design approach. The process included (1) creating assembly databases, (2) selecting a reference building, (3) developing a GA design prototype, (4) developing an SBD prototype, and (5) analysing the reference building using both prototypes. The GA and SBD prototypes in Steps 3 and 4 were developed as separate methods and applied to the same reference building to compare their outputs and assess their respective strengths. However, insights from the GA were used to guide the design space explored in the SBD analysis. The GA prototype was designed to enable individual optimisation of many building elements and to search a vast solution space. The results from the GA analysis were subsequently used to inform the set reductions applied before running the SBD prototype.

2.1 Step 1: creating assembly databases

This study used a building assembly-based approach, linking costs and carbon emissions to components such as floor slabs, columns, and walls. The approach was chosen because it aligns with the practice of standard BIM, cost estimation, and design software. Thus, there was a need to create databases with building assembly properties. In this paper, the term 'assembly' refers to a complete building component, encompassing both structural materials and

Table 1. Summary of relevant research on cost and carbon emission optimisation in the construction industry in the scope of building design

Authors and year	Optimisation objectives	Algorithm/method	Case study
Kanyilmaz <i>et al.</i> (2023)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	NSGA-II	9-,6- and 3-storey office buildings
Oluyale (2024)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input checked="" type="checkbox"/> Time	NSGA-II	Two-storey family house in wood
Huynh <i>et al.</i> (2021)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input checked="" type="checkbox"/> Time +Quality	Multiple objective social group optimisation	Six-storey office building
Behera <i>et al.</i> (2024)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input checked="" type="checkbox"/> Time	NSGA-III	Case study with 13 project activities
Gauch <i>et al.</i> (2022)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	Traditionell dimensionering av många olika kombinationer	Complex four-storey building
Dunant <i>et al.</i> (2021)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	Rule-based	Floors from 19 different buildings
Eleftheriadis <i>et al.</i> (2018)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	NSGA-II	Two residential buildings
Gan <i>et al.</i> (2019)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	Genetic algorithm combined with optimality criteria	High-rise reinforced concrete building
Choi <i>et al.</i> (2024)	<input checked="" type="checkbox"/> Cost <input type="checkbox"/> Carbon <input type="checkbox"/> Time +energy	NSGA-II	270-m-tall high-rise building in Korea
Lee <i>et al.</i> (2020)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	NSGA-II	Office building slabs
Nesheim <i>et al.</i> (2022)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	Mixed-integer sequential linear optimisation technique	Timber floor elements
Camp and Huq (2013)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input type="checkbox"/> Time	Big-bang big-crunch optimisation algorithm	Reinforced concrete frames
Ozcan-Deniz <i>et al.</i> (2012)	<input checked="" type="checkbox"/> Cost <input checked="" type="checkbox"/> Carbon <input checked="" type="checkbox"/> Time	NSGA-II	2-storey residential building in China

Source(s): Authors' own work

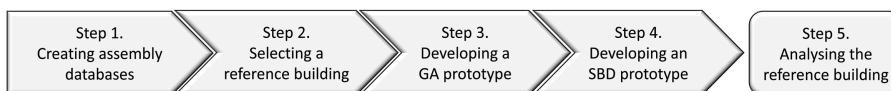


Figure 1. The five-step methodology used in the research. Source: Authors' own work

supplementary layers, such as gypsum boards or step-sound mats. Seven databases were developed for commonly used floors, roofs, inner walls, façade walls, gable walls, columns, and beams. Each database includes parameters like maximum span length, load capacity, fire

resistance, sound reduction, carbon emissions, cost, height, and weight. [Table 2](#) provides an overview of the databases and the materials and parameters included in each.

For each assembly in the databases, its sound class and fire resistance were defined in the database metadata. Three sound reduction classes, A (60 dB), B (56 dB), and C (52 dB), and five fire resistance classes, R0, R15, R30, R90, and R120 (i.e. 120 min) were used according to the Swedish standards SS25267 ([Swedish Institute for Standards, 2024](#)), BFS 2019:1 ([Boverket, 2019](#)), respectively.

The maximum floor and roof loads were calculated using Load Case 6.10a in Eurocode ([European Committee for Standardization, 2002](#)). The deflection limitations for roof elements were set to $L/300$, and for floor elements to $L/450$. The structural capacity of all elements was calculated in accordance with Eurocode ([European Committee for Standardization, 2002](#)), for both the ultimate and service limit states, using standard structural software and supplier guidelines ([VM Civil, 2025](#); [Strusoft, 2025](#)). For all concrete assemblies, both conventional concrete and climate-improved concrete were represented in the database. All load-bearing walls were assumed to be used for stabilisation.

Table 2. Summary of database content

Database	Number of variations	Parameters	Main structure
Floors	159	Min span, max span, sound class, fire class, kgCo ₂ e, cost, height, weight	<i>In situ</i> cast concrete, prefabricated concrete, filigree slabs, prestressed filigree slabs, hollow core elements with concrete topping, hollow core elements with installation floor, prestressed prefabricated elements, CLT with concrete topping, CLT with installation floor
Roofs	47	Min span, max span, snow zone 1–5.5, sound class, fire class, kgCo ₂ e, cost, height, weight	<i>In situ</i> cast concrete with pitched timber, hollow core slabs with pitched timber, CLT with pitched timber, timber trusses, prefabricated timber elements, filigree slabs with pitched timber, glulam girders, prestressed prefab slabs with pitched timber
Inner walls	30	Sound class, fire class, kgCo ₂ e, cost, thickness, weight	<i>In situ</i> cast concrete, semi-prefabricated concrete, prefabricated concrete, CLT double, CLT + girders
Non-load bearing facade	22	U-value, sound class, fire class, kgCo ₂ e, cost, thickness, weight	Lightweight timber, lightweight steel, CLT, <i>in situ</i> concrete, prefabricated concrete, prefabricated sandwich
Load bearing gables	22	Max load, U-value, sound class, fire class, kgCo ₂ e, cost, thickness, weight	Lightweight timber with columns and beams, lightweight steel with columns and beams, CLT, <i>in situ</i> concrete, prefabricated concrete, prefabricated sandwich
Columns	94	Cross-section area, mass, max load capacity, kgCo ₂ e, cost	VKR, circular steel profiles, glulam, rectangular <i>in situ</i> concrete, circular <i>in situ</i> concrete, rectangular prefabricated concrete, circular prefabricated concrete
Beams	92	Cross-section area, mass, max moment capacity, max shear capacity, kgCo ₂ e, cost	IPE, HEA, HSQ, glulam, prefabricated concrete

Source(s): Authors' own work

Carbon emissions were calculated in accordance with the guidelines from Sweden's National Board of Housing, Building and Planning, using generic emission factors from their Open Climate Database (Boverket, 2024a, b). The assessment covers stages A1–A5, reflecting current Swedish practices (Boverket, 2024b), and is given in units of equivalent carbon emissions (kgCO₂e). The stages include carbon emissions from the following.

- (A1) Raw materials
- (A2) Raw material transport
- (A3) Production
- (A4) Transport to the site
- (A5) Construction and assembly

Construction costs for the building assemblies were based on data from a Swedish contractor, supplemented by input from suppliers and purchasing specialists. All prices reflect complete building parts, including additional materials to meet fire and sound requirements, and cover both material and labour costs. For example, the cost of a concrete wall per square metre includes concrete, reinforcement, formwork, stop-ends, patching, and recesses. Prefabricated element costs cover the unit itself, transportation, assembly, assembly materials, lifting equipment, joint grouting, and concrete topping. The cost of steel columns and beams includes materials, assembly, and required fire protection. No common costs were included in the cost estimation, meaning, for example, site office rent, various common equipment costs, and scaffolding and construction crane rent were neglected.

For both *in situ* and prefabricated concrete products, the database includes a baseline with standard concrete and climate-improved alternatives with 10% and 20% emission reductions. Although concretes with up to 40% reduction are available, their costs vary significantly depending on supplier and production method, making generalised assumptions unreliable. Therefore, they were excluded from the study.

2.2 Step 2: selecting a reference building

A reference building was used for quantity take-offs of floors, roofs, and inner and outer walls. The building was a four-storey, lamella-shaped apartment building with a required structural fire safety classification of 60 min and a sound class of level B according to the Swedish standard SS25267 (Swedish Institute for Standards, 2024).

The reference building's load-bearing inner walls were semi-prefabricated shell walls consisting of two 50 mm prefabricated concrete layers and a 100 mm *in situ* cast concrete core. The façade walls were made of a cement exterior board, lightweight steel girder with a 600 mm spacing, insulation, plastic foil, an internal 45 mm timber girder with insulation, and a 13 mm gypsum board. Floors were filigree slabs with a 50 mm prefabricated concrete base and a 200 mm *in situ* cast top layer. The roof used the same slab system, topped with insulation and an elevated timber structure. A floor plan for the reference building is presented in Figure 2.

2.3 Step 3: developing and implementing the GA prototype

The GA prototype was developed in Python using the DEAP toolkit (Fortin et al., 2012). Since the prototype was intended to support a contractor's conceptual design, the floor plan was treated as fixed, reflecting common tendering scenarios where architectural plans are predefined. User input included free room height, number of floors, snow zone, required sound and fire classes, span lengths, and material quantities. The tool supported user-defined floor, roof, and wall zoning to enable individual optimisation (Klasson and Kärvegård, 2024). The chosen floor zoning and wall division for the reference building are presented in Figure 2.

The databases created in Step 1 were then filtered to include only building assemblies with sufficient capacities and properties to meet the project requirements. Next, the building was

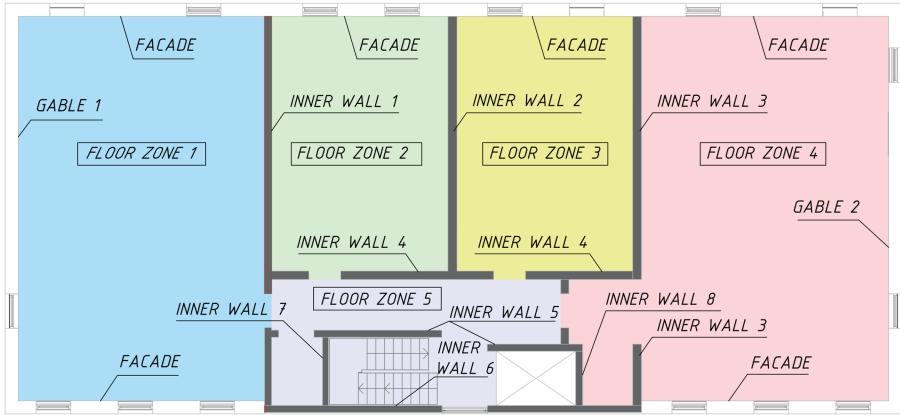


Figure 2. Zoning and element division for the reference building used in the GA prototype. The floors (and roof) were divided into five zones; load-bearing inner walls into eight elements; non-load-bearing façade on the long sides into one element; and gable walls into two elements. Source: Authors' own work

assigned a chromosome of 25 gene positions, numbered (1)–(25), where each position represents a specific structural component as follows.

- | | |
|-------------------|-------------------------|
| (1) Floor zone 1 | (14) Roof zone 1 |
| (2) Floor zone 2 | (15) Roof zone 2 |
| (3) Floor zone 3 | (16) Roof zone 3 |
| (4) Floor zone 4 | (17) Roof zone 4 |
| (5) Floor zone 5 | (18) Roof zone 5 |
| (6) Inner wall 1 | (19) Façade |
| (7) Inner wall 2 | (20) Gable wall 1 |
| (8) Inner wall 3 | (21) Gable wall 2 |
| (9) Inner wall 4 | (22) Columns in Gable 1 |
| (10) Inner wall 5 | (23) Columns in Gable 2 |
| (11) Inner wall 6 | (24) Beams in Gable |
| (12) Inner wall 7 | (25) Beams in Gable 2 |
| (13) Inner wall 8 | |

During the optimisation, each gene position is assigned an assembly index from the filtered database, meaning that the chromosome encodes one complete combination of building assemblies for the reference building. Given the number of genes and available items in the databases, the total search space was approximately 1.2×10^{43} possible design combinations.

Each chromosome was evaluated based on its cost and carbon footprint. The cost was calculated as:

$$C = \sum (A_i c_i + L_n c_n)$$

where A_i is the area of surface elements (e.g. floors, roof, walls) with the cost c_i (SEK/m²), and L_n is the length of linear elements (e.g. columns, beams) with cost c_n (SEK/m).

The carbon emissions were calculated as:

$$E = \sum (A_i e_i + L_n e_n)$$

where e_i and e_n represent carbon emissions (kgCO₂e) per m² and metre, respectively, for the corresponding elements.

Some gable walls and floor combinations required columns and beams. In these cases, four columns and one beam were added per gable wall and storey. These elements were included in the chromosome, allowing optimisation of their material and size. However, their costs and carbon emissions were only accounted for when needed. Since their required load resistance varies by design, a penalty function was applied to solutions with insufficient column or beam capacity. These were assigned a cost of 4 million SEK and 300,000 kgCO₂e, effectively excluding them from crossover selection.

The NSGA-II algorithm, originally developed by [Deb et al. \(2002\)](#), was selected for optimisation. Known for balancing convergence and diversity, NSGA-II is widely used for multi-objective problems. The algorithm identifies a set of optimal solutions, where no solution is better than another across all objectives. The algorithm uses a non-dominated sorting technique, in which it first determines which solutions dominate others. A solution A is said to dominate another B if A is no worse than B in all objectives and better in at least one objective. The algorithm then assigns a rank to each solution based on the level of non-domination. The first non-dominated front consists of solutions that are not dominated by any other solution. The second front consists of solutions dominated only by those in the first front, and so on. Within each front, crowding distance is calculated to maintain diversity by favouring solutions in less crowded regions. Parent selection is performed through tournaments, where the solution with the better rank or higher crowding distance (in the event of equal ranks) is chosen.

The GA algorithm was set to minimise both cost and carbon emissions, and the two objectives were given equal importance. The mutation and crossover operators were selected through parameter tuning, in which their values were adjusted, and the impact on the optimisation results was analysed. The GA process used in this study, along with the final choice of mutation and crossover operators, is presented in [Figure 3](#).

2.4 Step 4: developing and implementing the SBD prototype

The SBD prototype was developed in Python and was designed to be as similar to the GA prototype as possible, utilising identical cost and carbon evaluation functions. However, while the GA script optimised 25 components, the SBD script used a single solution for each building part, reducing computational time and limiting optimisation to five components.

Another difference was material flexibility for beams and columns. The GA prototype allowed columns and beams to be optimised in steel, concrete, or timber, whereas the SBD script used only steel, assigning the smallest suitable dimension. For instance, steel columns were added when filigree slabs were paired with lightweight façade walls. Similarly, steel beams and columns were added when hollow-core elements were combined with lightweight façade walls. This approach was justified by the GA results, which often favoured steel, and by the significant reduction in the number of possible combinations and runtime.

A set reduction was performed to reduce the number of feasible assemblies in the databases. The set reduction was performed as follows.

- (1) Filtering assemblies with sufficient structural capacity
- (2) Filtering assemblies with sufficient fire resistance

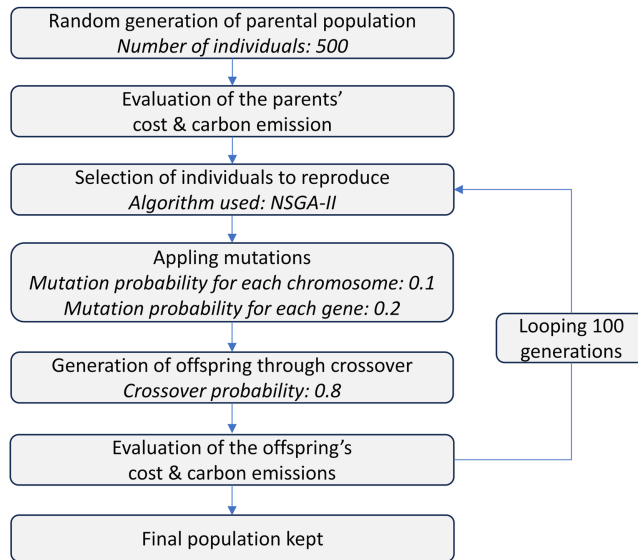


Figure 3. The GA optimisation process. A parental population of 500 individuals was generated by randomly assigning an assembly index to each gene on the chromosome. The cost and carbon performance of these individuals were evaluated, and the best-performing individuals were selected for crossover. After the crossover, mutations were applied, and the new individuals' cost and carbon performance were evaluated. The process was repeated for 100 generations. Source: Authors' own work

- (3) Filtering assemblies with sufficient sound reduction
- (4) Removing assemblies of the same type with excessive fire and sound resistance
- (5) Removing infeasible assemblies identified with the GA approach

After the set reduction, approximately 37% of the database items remained. Given that there were only five optimisation components in the SBD setup, this reduced the search space to 1.44 million possible design combinations.

2.5 Step 5: analysing the reference building

In the GA analysis, the solutions in the final population were represented as chromosomes with gene indices, which were mapped to the database assemblies. Since the solutions contain extensive information, they were grouped into six performance regions based on cost and carbon emissions, as visualised in Figure 4. The solutions in each performance region were statistically analysed by primary structural material (*in situ* cast concrete, timber, prefabricated concrete, and steel), and the resulting distributions are presented in Figure 5.

The SBD results were presented as assembly combinations. The SBD solutions were plotted and compared to the most optimal GA suggestions.

3. Results

3.1 GA results and design trend visualisation

The GA prototype took about a minute to run, and its results were used to identify design trends. Solutions with penalties due to insufficient structural capacity were excluded before plotting cost and carbon emissions. The best solutions had a cost of just above 3 million SEK and climate emissions of around 150,000 kgCO₂e, and are found in Region 1 in Figure 4. At the time the research was conducted, the exchange rate of 1 Euro was 11.0 Swedish Krona (SEK).

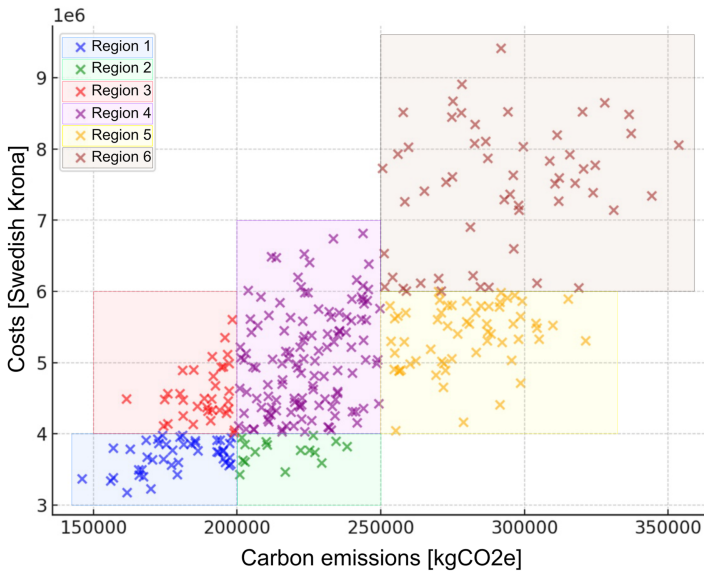


Figure 4. Cost and carbon emissions of design solutions in the final population from the genetic algorithm optimisation. Source: Authors' own work

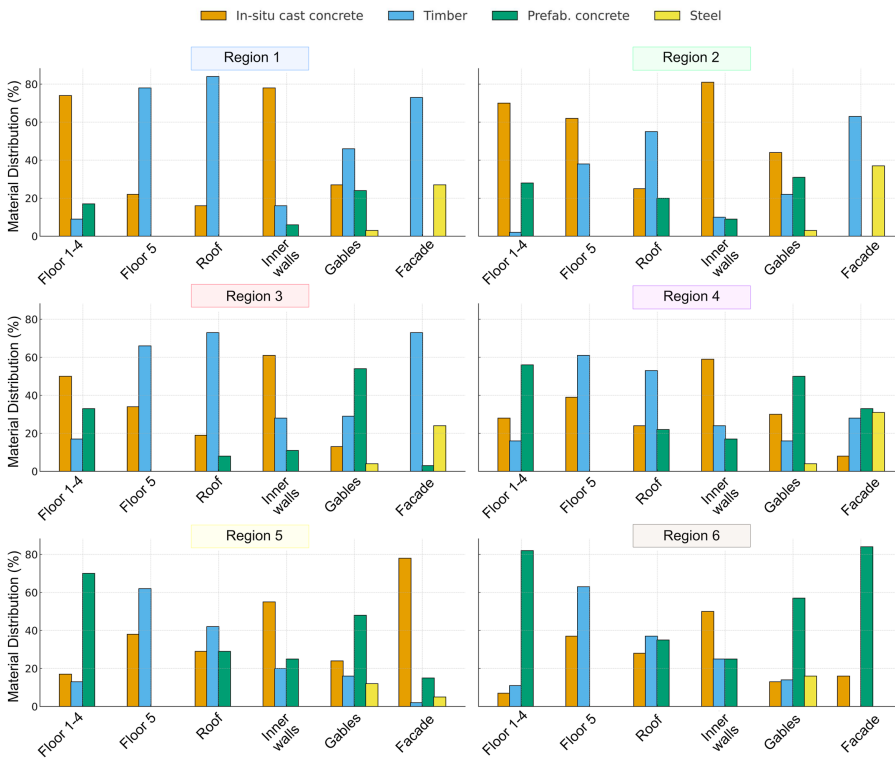


Figure 5. Material distribution in solutions for Regions 1–6 for floor slabs, roofs, inner walls, gable walls, and façade walls, as achieved through GA optimisation. Source: Authors' own work

The distribution of structural materials in floors, roofs, inner walls, gables, and façades across the six regions is presented in Figure 5. Region 1, shown in blue in Figure 4, contains the most optimal solutions in terms of both cost and carbon emissions. Most solutions in this region use climate-improved *in situ* cast or semi-prefabricated concrete for the floors. Region 2 lies to the right of Region 1 and includes solutions that remain cost-efficient but exhibit higher carbon emissions. Floors in this region are still primarily *in situ* cast concrete, although with a lower share of climate-improved concrete. A few prefabricated concrete alternatives also appear in this region. Moving upwards from Region 1 in Figure 4, Region 3 comprises solutions with similarly low carbon emissions but higher costs. Here, floors are typically made of timber or climate-improved prefabricated concrete. Region 4 has a higher proportion of prefabricated concrete solutions, a trend that becomes even more pronounced in Regions 5 and 6, where prefabrication dominates floor slab configurations.

For the façade walls, Region 1 is dominated by timber girder walls. The most common material for the gable walls is cross-laminated timber (CLT). In Region 2, the façade configuration remains largely the same, with timber girder walls still the dominant solution, though wall thicknesses tend to be larger and therefore more material-intensive. In Region 3, CLT becomes the most common façade wall material, while gable walls are typically prefabricated climate-improved concrete. Region 4, in contrast, is characterised by prefabricated concrete walls made of standard concrete, which are the most frequent materials for both façades and gables. Region 5 shows a shift towards *in situ* cast concrete façade walls using standard concrete, whereas Region 6 predominantly features prefabricated sandwich walls made of standard concrete.

3.2 SBD results and solution space exploration

The SBD script took 26 hours to run, and the results show that there are design solutions with even lower costs and carbon emissions than found using GA. The complete solution space is shown in Figure 6a, with the reference building marked with a red cross. For clarity, the figure displays only 0.5% of the solutions. The position of the reference building suggests it is well cost-optimised, but there are design solutions possible to reduce its carbon emissions without significantly increasing production costs. Figure 6b zooms in on the most optimal SBD solutions, with a cost of less than 4 million SEK and 170,000 kgCO₂e. The seven best GA solutions are marked as red dots in the same figure. The SBD results indicate that the GA

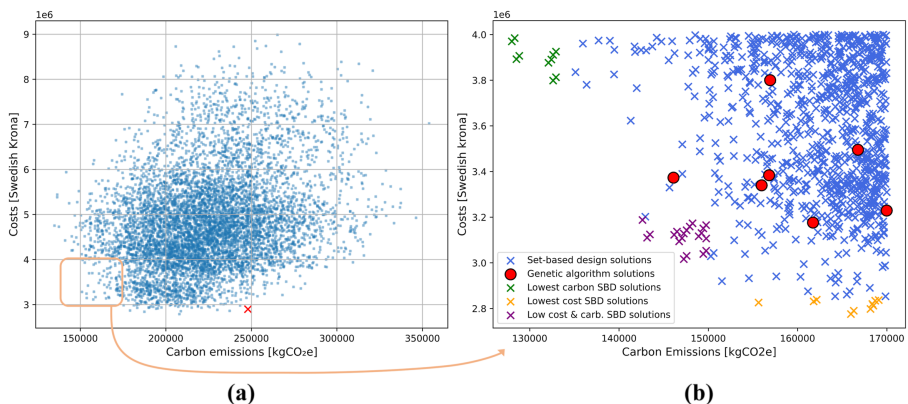


Figure 6. (a) Costs and carbon emissions for the full solution space, as found in the SBD analysis. The red cross shows the cost and carbon emissions for the reference building. (b) A zoom-in of the most cost- and carbon-efficient zone in Figure 6a. The SBD solutions are marked with crosses. For comparison, the best design solutions identified through GA optimisation are marked with red circles. Source: Authors' own work

results are satisfactory, but more optimal solutions can be found, albeit at the cost of longer computational time. The SBD results provide a broader solution space, enabling more effective trade-off visualisations.

The green crosses in Figure 6b represent the ten SBD solutions with the lowest carbon emissions. They have emissions ranging from 121,000 to 128,000 kgCO₂e, costing between 4.1 and 5.0 million SEK. As floors, climate-improved hollow core elements of prefabricated concrete with a concrete topping were the most common building assembly. All other building components, except the floors, were made of timber as the primary material. Inner walls were made of cross-laminated timber, the roof of prefabricated timber elements, the façade of lightweight timber, and the gables of insulated cross-laminated timber. The high presence of timber assemblies indicates that timber is climate-efficient but more costly than concrete solutions. Even though the assembly type is the same for all green-crossed solutions, the cost and carbon differences between them stem from slight variations in the thickness or size of the structural component.

The yellow crosses in the lower-right corner of Figure 6b indicate the ten SBD solutions with the lowest costs. These solutions cost around 2.7 million SEK and have carbon emissions between 186,000 and 200,000 kgCO₂e. For these solutions, the floor assemblies consist of filigree slabs combined with an *in situ* cast concrete topping. The inner walls are made of *in situ* cast concrete, prefabricated timber elements dominate the roof, and lightweight timber assemblies are found in the external walls.

Another group of interesting SBD solutions is marked in purple in Figure 6b. This group comprises 20 solutions with costs of less than 3.2 million SEK and carbon emissions of less than 150,000 kgCO₂e. For these solutions, climate-improved *in situ* cast concrete is the dominant material for both floors and inner walls. Prefabricated timber elements dominate the roof, and lightweight timber is used for the non-load-carrying façade. For gable walls, 65% of all solutions use lightweight steel or timber combined with steel columns, and 35% use insulated cross-laminated timber walls.

Figure 7 presents density plots for all solutions. For the carbon emissions presented in Figure 7a, most solutions emitted around 220,000 kgCO₂e. Looking instead at costs in Figure 7b, most solutions were found to be around 4.5 million SEK.

3.3 Comparisons with the reference building

The structure and envelope of the reference building had a production cost of 2.9 million SEK and emissions of 248,000 kgCO₂e. The best GA solution increases costs by 9% but reduces carbon emissions by 35%. The second-best GA solution increases the costs by 15% but reduces carbon emissions by 41%. The GA-suggested building assemblies are very similar to the original assemblies of the reference building, but use climate-improved concrete instead of

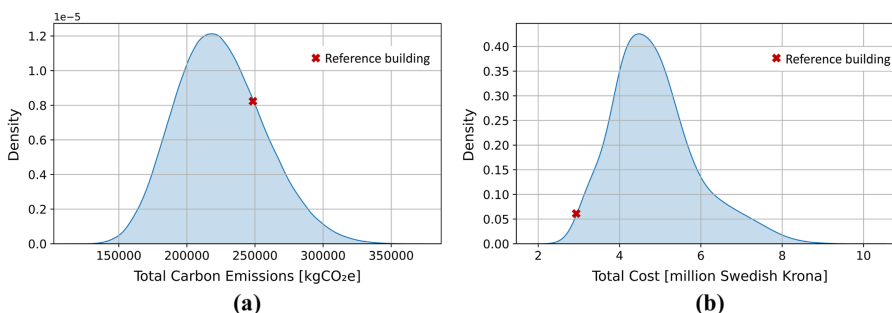


Figure 7. (a) and (b) Density of the design solution space. Most solutions had carbon emissions of around 220,000 kgCO₂e and a cost of around 4.5 million Swedish Krona. Source: Authors' own work

standard concrete. There are three main differences between the best GA solutions and the original building parts of the reference building, specifically regarding the gable walls, roof structure, and floor in the corridor. While the reference building used lightweight steel walls combined with steel columns in the gables, the GA tool suggests CLT walls. The original roof structure was a filigree slab with *in situ* cast topping, combined with an elevated timber roof. The GA prototype instead recommended prefabricated timber elements. For the corridor, shown as Floor Zone 5 in Figure 2, the GA recommended timber solutions due to the short span.

The SBD analysis could identify solutions that performed better on both objectives than those identified by GA. Compared to the GA solution with the lowest cost increase, the SBD results yielded solutions with a similar 9% cost increase but achieved a 42% reduction in carbon emissions, corresponding to an additional 7% carbon emission savings. When focussing on reducing carbon emissions, the SBD identified solutions achieving around 50% carbon reduction compared to the reference building. However, the costs increased by more than 60%. These solutions consist of climate-improved hollow-core concrete floor elements and utilise timber as the primary material for walls and roofs.

Some solutions slightly reduce production costs compared to the original reference building design. The most cost-efficient solutions cost 7% less than the reference building. Interestingly, these solutions also reduced climate emissions by approximately 25%. To achieve such reductions, the reference building's floor and inner wall materials should remain the same; the façade should be slightly modified by replacing lightweight steel with timber; and the roof structure should be replaced with prefabricated timber elements.

The SBD approach offers good compromise solutions that are, from a climate perspective, slightly better than those obtained using GA. These solutions reduce the climate emissions of the reference building by approximately 40% at a cost increase of 3%. These SBD solutions require replacing the filigree floor system with climate-improved *in situ* cast concrete, using climate-improved *in situ* cast concrete for the inner walls, replacing the roof structure with prefabricated timber elements, and replacing the gable walls with a CLT structure.

4. Discussion

The largest assembly quantity for the reference building was the floor assemblies, which consequently greatly impacted the overall cost and carbon performance. This study showed that climate-improved concrete was the most cost- and carbon-effective solution. With this solution, the results indicated carbon savings of 35–40% and a cost increase of 3–9% for the reference building. Jayasinghe *et al.* (2021) optimised various concrete slabs with similar results. Their research shows that flat concrete slabs are the most cost- and carbon-efficient structure for spans of 5–7 m, whereas hollow-core elements are more efficient for spans of 7 m or more. Their results suggest that prefabricated hollow-core slabs would likely be more competitive if the analysis presented in this paper were extended to other building types with larger spans, such as commercial buildings.

Kanyilmaz *et al.* (2023) found that shorter column spacing reduced both costs and carbon emissions across all building types. Such an effect is more significant when only structural capacity is considered, neglecting sound reduction and fire safety requirements. For example, using a reinforced concrete slab in an apartment building in sound class B requires a minimum thickness of 240 mm, making it impossible to reduce the thickness even though the span length is short.

This study focused on optimising the structural systems and the building envelope. In practice, design choices – such as the type and placement of the ventilation system – can significantly impact structural optimisation. For instance, embedding ventilation channels within the floor structure may limit design flexibility. In the database created for this study, such limitations were highlighted, enabling possible future integration of these buildability factors.

In this study, cost and carbon were treated as equally important objectives in the GA optimisation process. However, the research by [Klasson and Kärvegård \(2024\)](#) indicates that designers often wish to adjust the weighting of objectives based on project phase and priorities. For example, during a bidding phase with strict cost constraints, designers may prioritise cost at 80% and carbon at 20%. This balance might shift later through dialogue with the client. Unlike single-objective genetic algorithms that use weighted sums, the NSGA-II algorithm is a Pareto-based algorithm that does not consider the magnitude of weights, making such adjustments less straightforward. To address this, the Pareto solutions generated by the NSGA-II algorithm can be normalised (scaled to 0–1), allowing a combined fitness value to be computed.

The study presented in this paper focused on building assemblies rather than construction activities, offering advantages when leveraging BIM as a data source. For instance, [Huynh et al. \(2021\)](#) showed that quality can be integrated into optimisation, and digital issue reporting tools now allow linking quality issues to BIM objects ([Cusumano et al., 2024](#)). This streamlines the mapping process and enables GA optimisation to account for quality. However, this assembly-based approach has limitations, for example, regarding the inclusion of time as an optimisation objective. Linking production time to building assemblies is complex; therefore, most studies employ work activity-based approaches ([Huynh et al., 2021](#); [Behera et al., 2024](#); [Oluyale, 2024](#)). The research by [Ljung and Tallgren \(2024\)](#) indicates that mapping production time and building assemblies is feasible, although it requires conceptual development and effort.

5. Conclusions

This paper proposes a combined SBD-GA approach for identifying cost- and carbon-effective building designs. The results demonstrate that genetic algorithms can rapidly guide the design team towards promising regions of the solution space, while set-based design enables a deeper exploration of feasible alternatives and can reveal solutions that outperform those found by the GA. Together, the approaches facilitate a more transparent and data-driven decision-making process during conceptual design.

Beyond the methodological contribution, the findings carry several practical implications for industry implementation. Because the workflow is based on building assemblies, no existing design software needs to be replaced; instead, the method can be used as an add-on to the current tendering process. Including functional aspects such as fire resistance and sound reduction makes the method directly applicable within the industry. The required change lies in creating the databases, which demand that parts of the tender design work be prepared before the tendering phase itself, as different element types and their maximum spans, load capacities, and related parameters need to be defined in advance. The assembly-database approach also increases transparency in the optimisation process, which is advantageous in light of emerging regulatory frameworks such as the EU AI Act that emphasise traceability, explainability, and verifiable decision-support systems.

The GA approach enables designers to rapidly evaluate millions of combinations of structural alternatives, while additional calculation time can be invested in SBD to explore a wide range of variants within selected regions of the solution space. This combination helps contractors reduce tender-phase risks of exceeding expected costs or carbon emissions. Moreover, the method provides value in later design stages, where it can serve as an effective communication tool in design meetings, enabling practitioners to visually compare design regions, assess trade-offs, and justify decisions to clients. The method further supports early alignment between cost managers, structural engineers, and sustainability specialists by providing a shared quantitative basis for decision-making.

The assembly-based nature of this work creates promising opportunities for integration with BIM platforms. Linking optimisation outputs directly to BIM objects could support automated quantity take-offs, visualisation of carbon hotspots, and dynamic updating of cost-

carbon charts as the model evolves. Future research should investigate workflows in which BIM serves both as a data source and as a real-time interface for interacting with optimisation results.

Although this study focused on a residential reference building, the methodology has strong potential to be applied to other building types. However, because the allowable spans and capacities of floor elements are dependent on building function and associated loads, the underlying datasets would need to be updated to reflect the characteristics of each building type. Applying the approach across multiple building typologies could also generate a more generalisable understanding of cost-carbon trade-offs within the broader building sector.

The results have relevance for emerging carbon policies and building regulations. As national climate targets increasingly require reductions in embodied carbon, optimisation tools that quantify trade-offs across materials and design strategies can support compliance and scenario testing. The ability to rapidly assess the carbon implications of thousands of design combinations may also inform regulatory development, for example, by highlighting which structural choices offer the greatest decarbonisation potential. Moreover, visualising the extent to which emissions can be reduced using current construction methods—and the associated cost implications—can support policymakers in evaluating realistic pathways to meet carbon targets. The approach also enables the exploration of how changes in functional requirements, such as acoustic performance classes, influence both carbon outcomes and material demands. By identifying the full solution space, the method further clarifies how many—and which—design options are excluded when stricter CO₂e limits are imposed, thereby offering valuable insights for both regulatory decision-making and industry compliance.

Foundation materials and costs represent a substantial share of overall project impacts, yet they were not included in this study. To extend the method's applicability, future research should explore how to integrate foundation design. Two approaches appear feasible: incorporating foundation parameters directly into the GA chromosomes—though this may increase the number of penalised solutions—or developing a separate foundation design module that builds on the outputs of the current tools. Such a module would allow foundation-related cost-carbon trade-offs to be visualised alongside the conceptual building design, providing a more holistic basis for early decision-making.

Another limitation of the study was the exclusion of production time as an optimisation parameter. This was due to the absence of sufficiently detailed data that could be linked directly to specific building assemblies. More research is required to determine how production time can be mapped to assemblies instead of being based on traditional activity-oriented work structures, and how such mappings can be generated and validated in practice.

Statements and declarations

No humans or animals were involved in the study presented in this paper.

Language editing support was provided using Grammarly.

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