Design Optimization of Steel Structures with Reused Components Using Generative Design

Golnaz Mirzaei[1], Amin Hammad[1] and Faraeen Homayounfard[2]

[1] Gina Cody School of Engineering and Computer Science, Concordia University, Canada
[2]School of Architecture and Urban Planning, University of Science & Technology, Iran
golnaz.mirzaei@mail.concordia.ca, amin.hammad@concordia.ca, faraeenhomayounfard@gmail.com

Abstract –
In recent years, there has been an increasing focus on adopting circular approaches within the construction sector, particularly reusing building components in new projects. Facilitating design for reuse can significantly expand the scope of deconstruction and reuse efforts. Unlike conventional structural design, which assumes an unlimited supply of standardized components and follows a straightforward process of geometric design, structural analysis, and member sizing, reusing structural components introduces unique challenges. With limited component availability, conventional design methods often fall short, leading to time-consuming trial-and-error processes or non-viable solutions. Despite growing interest, research in this area remains limited, focusing primarily on isolated criteria like minimizing material waste or embodied energy, without offering a comprehensive framework that balances environmental and economic considerations. Additionally, conventional approaches rely on traditional mathematical optimization methods, restricting the exploration of complex design spaces. To address these challenges, this research proposes a novel optimization framework that leverages generative design using genetic algorithms to streamline the design of steel structures with reused components. The framework uses the Non-Dominated Sorting Genetic Algorithm II to refine the geometry and topology of steel structures, minimizing environmental impacts and costs. A case study on optimizing a steel truss design using reused components demonstrates the framework's effectiveness.

Keywords –
Optimization; Steel Structures; Reuse; Generative Design; Circular Construction

1 Introduction

In recent decades, global population growth, urbanization, and industrialization have triggered significant environmental challenges, including global warming, resource depletion, and pollution in air, water, and soil. The construction, renovation, and demolition sector has emerged as a major contributor to these issues. This sector is a major energy consumer and greenhouse gas emitter, contributing nearly 30% to global energy usage and one-third of greenhouse gas emissions [1]. Consequently, construction industry has become a focal point in global sustainability initiatives, pivoting towards innovative approaches grounded in the principles of the circular economy.

Circular construction aims to minimize environmental impacts through the principles of reducing, reusing, recycling, and recovering building components throughout the entire lifecycle [2]. The focus is on strategies that keep materials in use, reducing the need for new resource extraction, energy consumption, and CO_2 emissions [3, 4]. This can occur either through extending the service life of a building, or the reuse and recycling of building components at the end of their service life. Reuse is a more valuable option than recycling because it preserves existing components, giving them a new life and adding value. Reusing building components also reduces energy and embodied carbon more effectively than recycling, as reuse typically requires only minor modifications for the components to be incorporated into new structures. This approach aligns with circular economy practices in construction by emphasizing the importance of retaining and repurposing components to minimize waste and maximize resource efficiency [5–7]. In contrast, recycling typically involves breaking down the product or component into secondary materials, resulting in a loss of quality, value, and energy [3, 8].

Among the four stages of the building life cycle—production, construction process, use, and end of life—the first stage (i.e., production), which includes raw material supply, transport, and manufacturing, can account for up to 50% of total embodied impacts [9]. Therefore, structural engineers can make the most significant reductions in embodied impacts by focusing on designing with reclaimed components [10]. Also, according to Webster [11], load-bearing structures contribute 20-70% of a building's embodied impacts, depending on factors like building type, size, and used components. By incorporating reused primary components into the design of load-bearing structures, structural designers can further reduce embodied impacts [10, 12]. This is particularly important for steel components, where reuse significantly lowers embodied carbon by avoiding the energy-intensive production of steel components made of virgin or recycled steel. Brütting et al. [13] demonstrated the efficacy of this approach in a real-world application, designing the truss for the main station roof in Lausanne using reclaimed components from electric pylons, resulting in a 63% reduction in embodied energy compared to newly fabricated components.

However, reuse is not yet widely considered in the architecture, engineering and construction field. For instance, stakeholders in construction projects often avoid reuse due to economic uncertainties [14, 15]. Designers are also concerned that the use of reusable components, which are often limited in shape and quantity, could complicate the design process [14, 16]. Additionally, the lack of accessible information on available reusable components poses a significant challenge [14, 15, 17]. The primary goal of this research is to develop a comprehensive optimization framework that uses advanced computational methods to streamline the design of steel structures with reused components. By utilizing generative design, the framework will address challenges related to designing with components with limited availability while minimizing cost and environmental impacts.

2 Literature Review

2.1 Optimization of Structures Made from Reused Components

Brütting et al. [13] introduced a novel framework for designing truss systems using reused components. Their approach formulates the problem as a mixed-integer linear programming (MILP) model to minimize mass and cut-off waste, while meeting structural safety and serviceability requirements. The framework begins by defining a stock of reusable components characterized by their material properties, geometric attributes, lengths, and available quantities. Through discrete structural optimization, the proposed framework iteratively optimizes the topology and geometry of the truss to align with the available stock. Structural constraints, such as equilibrium, stress, and serviceability, are integrated to ensure compliance with performance standards. A two-step process is employed, first solving the assignment problem to allocate stock components optimally and then adjusting the geometry to reduce cut-off waste. Brütting et al. [13] expanded their work to propose a *kit-of-parts* approach, enabling the reuse of components across multiple structural configurations. This method integrates two optimization problems: one for assigning stock components to predefined layouts and another for designing a shared stock inventory. The iterative process optimizes both individual structures and the shared inventory to reduce waste and minimize unique component requirements. De Boer [10] further advanced the optimization of reusable structures by incorporating connection design into the process. Recognizing the importance of connections for enabling reuse, the study developed a parametric design tool using Grasshopper for Rhino to automate the design process. By integrating connection length as a variable, the methodology optimizes both structural layouts and bolted steel connections.

2.2 Using Generative Design for Structural Design and Reuse

The complexity of optimizing structures for reuse, especially when dealing with diverse components, has made traditional design and optimization methods impractical. In other words, if the types of reusable components vary or large quantities of components are needed, the large number of alternatives will make it impossible to find the optimal solution using traditional design methods. Therefore, a metaheuristic approach is necessary to tackle such complex problems [18]. One effective metaheuristic approach is generative design, which generates, evaluates, and selects multiple potential solutions based on their effectiveness. This approach often relies on genetic algorithms (GAs) for optimization. GAs are powerful tools that have gained attention in structural design and other engineering domains due to their ability to solve complex optimization problems [18]. As defined by Koza [19], a GA is a sequence of mathematical operations that transforms individual objects within a population into a new population by selecting a subset based on fitness criteria. This process mimics natural selection, where the fittest individuals are chosen to pass on their traits to the next generation. GAs are particularly effective in solving problems with discrete variables, such as the selection of structural components, and are valuable for exploring optimal combinations of structural components under specific constraints in vast solution spaces [20].

Building on the capabilities of generative design and GAs, Kim & Kim [18] explored the structural reuse in modular construction with a novel method that leverages GAs to minimize both CO_2 emissions and costs. Their study focuses on noise barrier tunnel (NBT) construction. NBTs are modular structures installed along highways or railways to reduce noise pollution. The research integrates Building Information Modelling (BIM) with a multi-objective optimization framework using Non-Dominated Sorting Genetic Algorithm II (NSGA-II). The process begins with a BIM model providing detailed attributes of reusable components, such as shape, length, cross-sectional properties, curvature, and remaining life. This data forms the foundation for optimization, aligning the reuse strategy with structural and environmental constraints. Also, Van Marcke et al. [21] introduced a framework that leverages GAs to optimize the reuse of partially disassembled triangular components from steel trusses. Unlike previous approaches, which emphasized full disassembly and reuse at the component level, this method minimizes the labour-intensive and costly aspects of complete disassembly by leveraging partially intact structural components. The methodology consists of two main components: an aggregation engine for generating initial truss designs and a GA for optimizing these designs. The aggregation engine arranges reclaimed triangular subassemblies row by row to fit the desired truss geometry, allowing for cutting or the addition of new components when necessary. Once an initial design is created, the GA optimizes it by minimizing the total length of new components and reducing the amount of cutting required for reclaimed components.

2.3 Research Gaps

Existing research on structural design optimization with reused components has made valuable contributions but remains limited in scope. Most studies focus on specific criteria, such as minimizing material waste, reducing embodied energy, or optimizing connections, without providing a comprehensive framework that integrates environmental sustainability, economic efficiency, and the maximization of reused components. Moreover, many approaches rely on traditional optimization methods, which restrict the exploration of complex design spaces.

To address these gaps, this research introduces a framework that leverages generative design to explore a broader range of criteria. By considering material waste, energy consumption, CO_2 emission, and cost as a weighted multi-objective optimization problem, the framework achieves a balance between environmental and economic considerations.

3 Proposed Framework

As shown in Figure 1, the proposed framework employs a seven-step computational approach to optimize the geometry and topology of steel structures by reusing predefined stock components, with a focus on minimizing cut-off waste, cost, energy and CO_2 emission. This framework systematically integrates reusable components while ensuring structural integrity and economic feasibility. The process begins with designing an initial structure (topology and geometry) using new components to ensure feasibility, followed by an iterative process of replacing them with suitable reusable components. Each design alternative is generated and evaluated using GA. The key steps are outlined as follows:

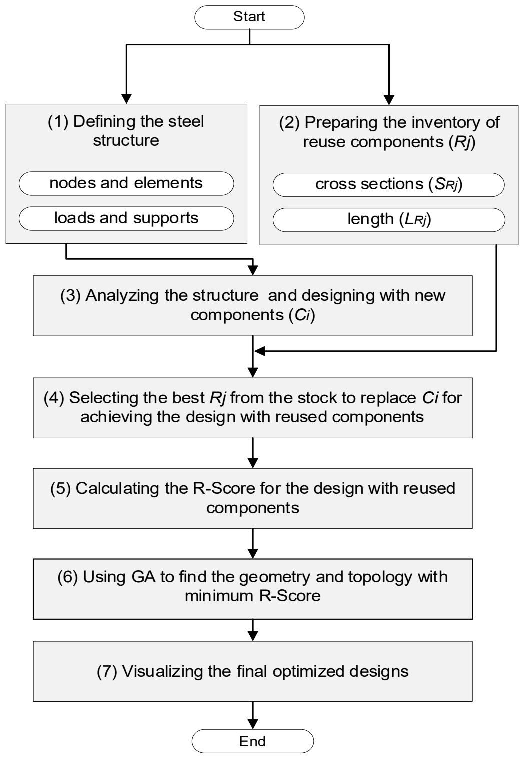

Figure 1. Proposed Framework

(1) Defining the steel structure by specifying its geometry and topology, including nodes and components, along with boundary conditions such as supports and applied loads, to ensure the design accounts for all relevant factors. This step provides a clear starting point for the optimization process.

(2) Preparing an inventory of reusable components ($\boldsymbol{R_j}$) based on their dimensions and properties, including lengths L_{R_j} and cross-sections S_{R_j}, which provides the required data to match components

(3) Analysing the structure to evaluate its performance under specified conditions from Step 1 and **designing the**

initial structure by assigning new components (C_i), which provides a baseline for comparison when incorporating reused components.

(4) Selecting the best match from reused components. This step involves replacing each initial design component C_i with a reusable component R_j from the inventory. The process compares the initial assigned components C_i with inventory components based on two key properties: length and cross section. For R_j to be suitable for C_i, it must meet the following conditions:

$$Match\,(C_i,\, R_j) = \begin{cases} 1 & if\; L_{R_j} \geq L_{C_i}\; and\; S_{R_j} \geq S_{C_i} \\ 0 & otherwise \end{cases} \tag{1}$$

where L_{R_j} and L_{C_i} are the lengths of the inventory component R_j and the design component C_i, respectively; S_{R_j} and S_{C_i} are the cross-sections of the inventory component R_j and the design component C_i, respectively.

After identifying all suitable matches, each initial design component C_i is replaced with the best match from the inventory. The best match, R_j, is the component that is closest in length (L_{R_j}) and cross-section (S_{R_j}) to C_i. If no suitable R_j is available in the inventory, a new component N_i is used to fulfil the requirements of the initial design component C_i.

This approach ensures that the final design uses the lightest and most appropriate reusable components, maximizing material efficiency, while ensuring feasibility and structural performance are not compromised.

(5) Evaluating each design by calculating a Reuse Score (R-Score), which integrates energy consumption (E), CO_2 emissions (G), cost (C), and material waste (W). This provides a quantitative method for comparing different designs, not only minimizing the cost but also environmental impact indicators.

Each parameter is derived from the specific characteristics of *n* new and *m* reused components within the design. As part of this process, a Life Cycle Assessment (LCA) is conducted to evaluate CO_2 emissions and energy consumption. The LCA focuses on a part of the lifecycle of components, beginning with their supply and ending with their transport to the site. Construction-related energy consumptions, CO_2 emissions, and costs are excluded, as they are identical for all reuse-based designs. The detailed steps for these calculations are outlined below:

- **Energy Consumption (E):** The energy consumption for *n* new components (E_N) includes production and transportation:

$$E_N = \sum_{i=1}^{n} \left(E_{product(N_i)} + E_{transport(N_i)} \right) \tag{2}$$

The energy consumption for *m* reused components (E_R) includes deconstruction, modification, and transportation:

$$E_R = \sum_{j=1}^{m} \left(E_{decon.(R_j)} + E_{modify(R_j)} + E_{transport(R_j)} \right) \tag{3}$$

The total energy consumption (E_T) for the design is:

$$E_T = E_N + E_R \tag{4}$$

- **CO_2 Emissions (G):** The total CO_2 emissions are calculated similarly to energy consumption:

$$G_N = \sum_{i=1}^{n} \left(G_{product(N_i)} + G_{transport(N_i)} \right) \tag{5}$$

$$G_R = \sum_{j=1}^{m} \left(G_{decon.(R_j)} + G_{modify(R_j)} + G_{transport(R_j)} \right)$$

$$G_T = G_N + G_R \tag{7}$$

- **Cost (C):** The total cost is calculated by summing the production and transportation costs of new components, as well as the deconstruction, modification, and transportation costs of reused components.

$$C_N = \sum_{i=1}^{n} \left(C_{product(N_i)} + C_{transport(N_i)} \right) \tag{8}$$

$$C_R = \sum_{j=1}^{m} \left(C_{decon.(R_j)} + C_{modify(R_j)} + C_{transport(R_j)} \right) \tag{9}$$

$$C_T = C_N + C_R \tag{10}$$

- **Waste (W):** Material cut-off waste is calculated as the total mass (M) of excess material removed from reused components:

$$W = \sum_{j=1}^{m} \left(M_{R_j} - M_{C_j} \right) \tag{11}$$

- **R-Score:** The R-Score is computed as a weighted sum of these four parameters:

$$RS = \alpha \times E_T + \beta \times G_T + \gamma \times C_T + \delta \times W \tag{12}$$

where $\alpha, \beta, \gamma, \delta$ are weights assigned based on project priorities, satisfying:

$$\alpha + \beta + \gamma + \delta = 1 \tag{13}$$

(6) Implementing GA for minimizing the R-Score, balancing components cut-off waste, environmental impact and cost by exploring a wide range of design possibilities. The optimization process utilizes NSGA-II to explore various design alternatives, applying genetic operators such as crossover and mutation to iteratively refine solutions. The key steps include **(a) Generating initial designs** to form the population of alternatives; **(b) Calculating fitness value** by evaluating the R-Score, where designs with lower waste, energy use, CO_2

emissions, and cost achieve a higher fitness value; **(c) Applying genetic operations**, such as crossover and mutation, to create new design alternatives; and **(d) Iteratively refining the geometry and topology** to minimize environmental impact and cost.
For each design alternative, steps 1, 3, 4, and 5 of the proposed framework are repeated to ensure that the optimization process considers all relevant factors and continuously improves the design until the most efficient and sustainable solution is identified.

(7) Visualizing the final optimized design with the highest fitness value, which allows designers to better understand the structural configurations, as well as their cost and environmental impact, leading to better decision-making.

4 Implementation and Case Study

To demonstrate the practical application of the proposed framework, a case study was conducted using Grasshopper [23] and Rhinoceros [24] to optimize the topology and geometry of a 10-meter-long two-dimensional Warren steel truss.

Grasshopper, a visual programming tool within Rhinoceros3D CAD, was selected for its parametric modelling and generative design capabilities. This tool is widely used by architects and engineers for algorithm-driven design through graphical elements. Additionally, the study integrates plugins such as Karamba [25] for structural analysis and Galapagos [26] for GA optimization. The implementation process consists of the following steps of the proposed framework:

(1) Defining the steel structure: The first step involved modelling the truss geometry and topology (Figure 2) in Grasshopper by defining its nodes, elements, and structural boundary conditions, including loads and supports. A Warren truss configuration with verticals was selected, with a fixed overall span of 10 meters and three bays, with a 5 kN load applied along the lower chord nodes. To explore design flexibility, the allowable movement of the upper chord nodes (0, 2, 4, 6) was constrained to ±0.80 meters in both horizontal and vertical directions as shown in Figure 2. Additionally, to ensure the generated design alternatives remain practical, symmetry constraints were applied to upper nodes so that nodes 0 and 6, as well as nodes 2 and 4, move together. The truss height was set at 2 meters, adjustable within a range of 1.2 meters to a maximum of 2.8 meters. Furthermore, the horizontal positions of nodes 0 and 6 were further restricted to +0.8 meters and -0.8 meters, respectively, so that the length of the upper cord will not exceed 10 meters. In addition to geometry, six different topology configurations, defining how nodes are connected, were incorporated to explore alternative structural layouts. These constraints were integrated as adjustable sliders to explore different design alternatives.

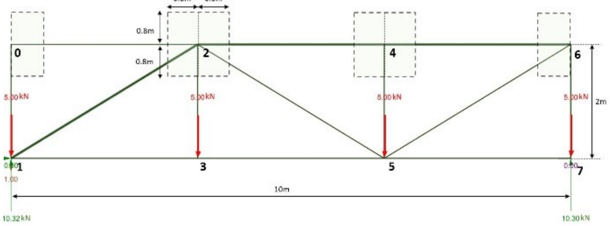

Figure 2. Modelling the geometry of the truss

(2) Preparing the inventory of reusable components: An inventory of reusable steel components (Figure 3) was prepared, consisting of circular hollow sections (CHS) selected from the EN 10219 standards. The cross-sections and lengths of the inventory components were chosen to ensure they are not too large, which would waste material without structural benefits, or too small, which would not properly replace the initial design components. All steel bars are assumed to have a yield strength of 235 MPa, a Young's modulus of 210 GPa, and a density of 7,850 kg/m³. The inventory specifies the types, quantities, and lengths of the available components, ensuring compatibility with the design optimization process.

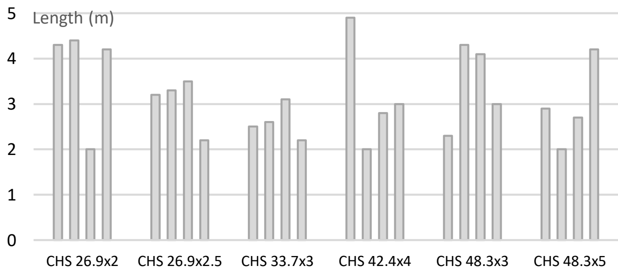

Figure 3. Inventory of reusable components

(3) Analysing the structure and designing with new components: The *Assemble Model* component in the *Karamba* plugin was used to prepare the truss model for structural analysis. This process included defining the cross-section library, loads, joints, and supports. The structural performance of the initial design was then assessed to ensure it met the criteria for stress, displacement, and buckling constraints in accordance with Eurocode 3 (EN 1993-1-1). To achieve this, the *Karamba CroSec Optimizer* was used to determine the lightest cross-sections that satisfied the structural performance requirements while considering stress limits, displacement constraints, and local buckling checks. Specifically, the maximum axial stress in any truss element was limited to 0.9 × yield strength (235 MPa) to maintain a safety margin, while the maximum vertical deflection of any upper chord node was restricted to L/250 (e.g., 40 mm for a 10 m span) to comply with serviceability criteria. Additionally, local buckling checks were incorporated to prevent instability in slender elements.

(4) Selecting the best match from inventory: To incorporate reusable components into the design, each truss components of the design were compared to the available inventory based on two key properties: length and cross-section area. For a component from the inventory to be a suitable replacement, its length had to be equal to or greater than the required length of the design component, and its cross-section area had to meet or exceed the design requirements. Among the suitable options, the component closest in length and cross-section was chosen. If no matching component was found in the inventory, a new steel component was introduced to meet the design specifications.

(5) Calculating the R-Score for the design with reused components: The evaluation of each truss design alternative is conducted by calculating the R-Score, as described in Section 3.

To simplify the analysis, the environmental impacts from modifications are considered negligible. Only components incorporated into the final structure contribute to environmental impacts, as leftover materials are assumed to be reused elsewhere. For new components, it is assumed that they are produced to exact lengths, resulting in no additional waste.

The energy consumption in MJ/Kg and CO_2 emissions in $kgCO2\ eq/Kg$ for a new component, with a transport distance of 70 km are:

$$E_N = 13.227\ M_{N_i} \tag{16}$$

$$G_N = 0.925\ M_{N_i} \tag{17}$$

where M_{N_i} is the mass of the new component. The energy consumption and CO_2 emissions of a reused component are calculated using the following equations, based on transport distances of 200 km [12]:

$$E_R = 3.245\ M_{R_j} + \ 3.235\ \Delta M_{R_j} \tag{14}$$

$$G_R = 0.277\ M_{R_j} + \ 0.276\ \Delta M_{R_j} \tag{15}$$

where M_{R_j} and ΔM_{R_j} are the masses of the reused component and the material waste from cutting it, respectively.

The cost estimation for a new component of the truss is calculated by multiplying the unit costs, as shown in Table 1, by its mass (Eq. 18). The cost estimation for the reused components is calculated in a similar way, but it considers both the mass of the uncut component and the cut-off part, as shown in Eq. 19. It is assumed that components are transported between locations at a speed of 40 km/h using a 25-ton truck. The unit cost for purchasing new CHS components is assumed to be 1.25 USD/kg [27], and for this study, the unit cost of reused components is assumed to be half that of new components (i.e., 0.625 USD/kg), and the cut-off waste is assumed to be sold as scrap steel. Consequently, the total costs for new and reused components are estimated using the following equations:

$$C_N = 1.256\ M_{N_i} \tag{18}$$

$$C_R = 1.313\ (M_{R_j} + \Delta M_{R_j}) - 0.325\ \Delta M_{R_j} \tag{19}$$

Table 1. Cost estimation assumptions [18, 22, 27]

Component type	Work	Unit price (US$/kg)
Reuse	Deconstruction	0.383
	Purchase	0.625
	Modification	0.289
	Transportation (200 km)	0.016
	Scrap steel sales	0.325
New	Purchase	1.250
	Transportation (70 km)	0.006

Also, material waste for each design alternative in the case study is calculated based on the material cut-off during the modification process, as mention in Section 3.

For calculating the R-Score, since all factors in this case study are considered equally important, a uniform weighting of 0.25 is applied to each factor (i.e. $\alpha = \beta = \gamma = \delta = 0.25$).

(6) Using GA to find the geometry with minimum R-Score: The Galapagos solver in Grasshopper was then used for generative design to optimize the truss's geometry and topology. Galapagos iteratively refined the design by exploring different configurations of variables (nodes' position and connection) to minimize the R-Score while ensuring structural performance. The GA was tested with two different population sizes of 20 and 50 individuals, both using an elitism ratio of 5%, where the top-performing individuals were carried forward to the next generation. The search space consisted of both discrete and continuous variables, including continuous adjustments in node positions, six discrete topological configurations, and discrete inventory component replacements using a combination of new and reused components. The termination criterion was set to stop the optimization when the improvement in the R-Score is below 1% over 5 consecutive generations. As shown in Figure 4, the GA with a population size of 50 (P50) achieved a lower final R-Score compared to the population size of 20 (P20). The process for the P50 case stopped after 32 generations and took a total of 68 minutes and 17 seconds, including 5 minutes and 28 seconds for the initial design phase.

(7) Visualizing the final optimized truss and results: The final optimized design was visualized in Rhinoceros3D, with detailed structural analysis performed using *Karamba*. Figure 5 shows the final optimized design, which includes 13 reused and 0 new components. Table 2 compares the criteria considered in this design with those of the initial design, which has the same geometry but uses only new components. The final design reduced energy consumption and CO_2 emissions by approximately 64% and 56%, respectively, while increasing the cost by about 47%. These results show that incorporating reused components in the design can have significant positive environmental impacts that could justify the increase in the cost.

Table 2. Comparing the initial and final designs

Criteria	Initial design	Final design	Change (%)
Energy (MJ)	958.61	589.31	63.73 ↓
CO_2 ($kgCO2\ eq$)	66.78	45.08	55.56 ↓
Cost ($US\$$)	90.68	128.99	-47.24 ↑
Weight (kg)	55.03	62.93	-14.35↑

5 Conclusions and Future Work

This paper proposed a framework using generative design to streamline the design process of steel structures with reused components. It introduces a systematic seven-step framework, leveraging the NSGA-II to iteratively refine structural geometry and topology, enabling efficient matching of limited sets of stock components to the desired design. This framework is able to minimize cut-off waste, energy consumption, and CO2 emissions, highlighting its potential for sustainable design practices aligned with circular economy principles and evolving sustainability regulations. Additionally, it enhances the financial viability of structural reuse by reducing costs in two key areas: (1) material procurement by utilizing existing components instead of new ones and (2) waste management by lowering disposal and handling costs. By demonstrating that reuse can be both environmentally responsible and economically feasible, this study contributes to the broader adoption of sustainable structural design practices.

While the proposed framework offers significant advancements, the case study introduced several simplified assumptions when calculating the R-Score. Future research should aim to improve the framework to enhance the R-Score by incorporating additional criteria and utilizing Pareto optimization. Furthermore, future work would benefit from integrating material passports and Environmental Product Declarations (EPDs) to provide more comprehensive data on the sustainability and lifecycle impacts of reuse. To further validate the framework's robustness, future research will also extend its application to seismic and wind load considerations, ensuring its suitability for a broader range of structural conditions. Additionally, the framework will be applied to three-dimensional space trusses, allowing for a more complex and realistic evaluation of its effectiveness in optimizing material reuse.

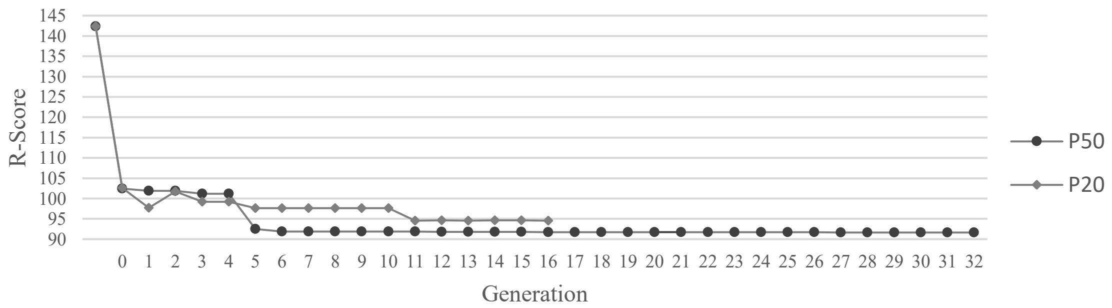

Figure 4. R-Score minimization during the optimization process

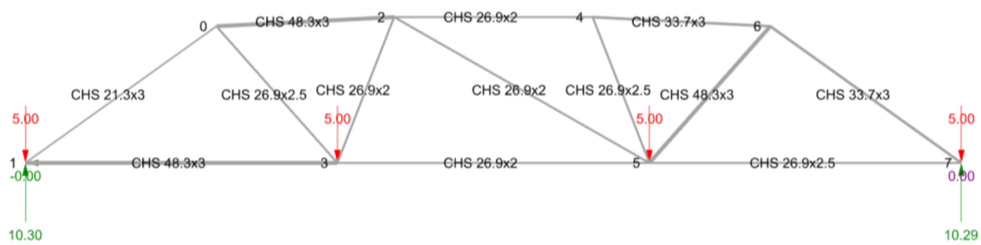

Figure 5. Final optimized design with reused components

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