

Article

Topology Optimization Approach to Reducing Carbon Emissions in Landscape Structures

Xiaoxu Su ¹, Zichang Xianyu ¹, Yijin Lian ¹, Ziyao Chang ¹, Zhuofan Li ² and Yukun Zhai ^{1,*} 

¹ School of Landscape Architecture, Beijing Forestry University, No. 35 Qinghua East Road, Haidian District, Beijing 100083, China; suxiaoxu1625@163.com (X.S.); xianyuzichang@163.com (Z.X.); lianyijin1230@163.com (Y.L.); changziyao0215@163.com (Z.C.)

² School of Materials Science and Engineering, Beijing Forestry University, No. 35 Qinghua East Road, Haidian District, Beijing 100083, China; zhuofanlin666@gmail.com

* Correspondence: archi_zhai@163.com

Abstract

Landscape structures generate significant life-cycle embodied carbon due to material redundancy and low structural efficiency. While topology optimization provides a scientific basis for material reduction, its resulting free-form surfaces and complex joints often hinder manufacturing and on-site assembly. This study introduces the Design for Manufacture and Assembly (DfMA) method to address these challenges, using landscape benches, pavilions, and bridges in the Beijing Olympic Forest Park as case studies. After data collection, we performed topology optimization via Autodesk Fusion and applied DfMA principles to simplify complex topological forms into standardized, modular structural systems. Life-cycle embodied carbon emissions were then compared across initial, topology-optimized, and DfMA-simplified designs. The results indicate that while topology optimization reduces material usage by 19–85%, it may increase total carbon emissions, especially in complex metal structures, due to higher construction energy demands and recycling difficulties. In contrast, DfMA simplification significantly improves manufacturing feasibility, cutting total carbon emissions by 33–64% compared to initial designs. The material production phase exhibited the most prominent carbon reduction, contributing an average of 60% to total emission savings. Ultimately, this study highlights that topology optimization alone is not universally carbon-reducing, and it requires DfMA-oriented simplification to achieve reliable low-carbon outcomes.

Keywords: landscape structures; topology optimization; DfMA; constructability; embodied carbon; low-carbon design



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1. Introduction

In the face of global warming, a low-carbon transition through emission reduction has become a global consensus [1]. The construction industry stands as a major consumer of energy and a primary source of carbon emissions, accounting for approximately 30% of the global total [2]. The global push towards climate neutrality has prompted leading nations to adopt distinct but overlapping approaches to net-zero carbon buildings [3]. In the UK, frameworks driven by organizations like the UK Green Building Council emphasize immediate action on both operational energy use and embodied carbon through stringent whole-life carbon assessments. The United States focuses on integrating passive envelope designs and active renewable energy systems to offset greenhouse gas emissions.

In recent years, as carbon emissions during the operational phase of buildings have been gradually controlled and mitigated, the proportion of embodied carbon of buildings has steadily risen, positioning it as a core target for low-carbon design [4,5]. Particularly during the materialization stage of construction, material production is typically the dominant contributor to embodied carbon emissions [6]. Consequently, optimizing structural efficiency to reduce material demand represents one of the critical pathways to lowering the embodied carbon emissions of landscape structures [7–9].

Topology optimization (TO), as a performance-driven structural design method, can identify the core load-bearing paths within a given set of loads, constraints, and design domains [10,11]. By redistributing material logically, it achieves the lightweight design of structures. However, in current architectural and landscape engineering practices, the outputs of topology optimization often feature free-form surfaces, complex joints, and non-standard components. These characteristics make it difficult to directly translate optimization results into physical structures that satisfy conventional manufacturing and on-site assembly requirements [12,13]. Therefore, bridging the gap between the scientific load-bearing logic of topology optimization and its practical constructability has emerged as a critical challenge.

Design for Manufacture and Assembly (DfMA) is an engineering methodology that integrates manufacturing capabilities and construction logic into the early design phase to minimize component complexity, reduce material waste, and improve assembly efficiency [14]. Currently, this method has been integrated into the Modern Methods of Construction (MMC) framework by the Royal Institute of British Architects (RIBA), serving as an important tool to promote standardization and modularization [15,16]. Existing research demonstrates that DfMA is highly effective in reducing construction complexity, minimizing material waste, and shortening on-site assembly schedules [17–19]. Nevertheless, regarding the complex forms generated by topology optimization, how DfMA can systematically guide their morphological simplification and further intervene in their life-cycle carbon emission evaluation remains an area requiring exploration.

To address the widespread material redundancy found in landscape structures and the practical challenges of implementing topology optimization results, this study introduces the DfMA method to reduce the geometric complexity of optimized structures, thereby lowering the embodied carbon emissions. Focusing on three typical landscape facilities—landscape benches, pavilions, and bridges—this study employs DfMA principles to simplify complex topological forms into standardized, modular, and assemblable structure systems. On this basis, the research compares the life-cycle embodied carbon emissions among the initial, topology-optimized, and DfMA-simplified designs. This approach aims to reveal the value of a synergistic topology optimization–DfMA strategy in achieving lightweight structures, enhancing constructability, and driving low-carbon design.

While previous studies have explored topology optimization for material reduction and DfMA for assembly efficiency, there remains a gap in synergizing these approaches to address the constructability of topology-optimized structures and their subsequent life-cycle carbon impacts. This study advances the current state of knowledge by proposing an integrated topology optimization–DfMA framework. By simplifying free-form topological outputs into standard, DfMA-compliant modules, this study provides a new pathway to evaluate and achieve low-carbon structural design.

2. Literature Review

Embodied carbon emissions generally refer to the greenhouse gas emissions associated with buildings and structures throughout their life cycles, excluding the operational

phase. This encompasses all stages, including raw material extraction, material production, logistics and transportation, construction, routine maintenance, and demolition and disposal [20]. Among these, the material production phase is typically the primary source of embodied carbon [11]. Therefore, reducing material consumption can simultaneously lower carbon emissions across transportation, processing, and waste disposal. Within the overall landscape structure, structural components typically account for the majority of embodied carbon [21], with emission levels closely tied to total material consumption, component morphology, and structural load-bearing efficiency [22]. Consequently, performance-driven structural design methods, such as topology optimization, can reduce embodied carbon emissions through lightweight design [23].

Topology optimization is a method that seeks the optimal material distribution within a given design space, subject to specific loads and boundary conditions. In recent years, common methods have included the Solid Isotropic Material with Penalization (SIMP), Evolutionary Structural Optimization (ESO), the Level-set Method (LSM), and the Moving Morphable Component (MMC) [24,25]. To achieve weight reduction in architectural applications, scholars have further proposed various modified optimization algorithms tailored to building mechanics, such as Generalized SIMP (GSIMP) and Bi-directional Evolutionary Structural Optimization (BESO) [12]. Regarding building structural components, practical studies by Mavroudis et al. have demonstrated that topology optimization of steel purlin cross-sections can reduce material mass by 25% to 30% [26]. Furthermore, topology-optimized beam modules manufactured via 3D printing technology can achieve over 40% weight reduction, effectively avoiding the embodied carbon increments caused by traditional construction formwork waste and concrete over-pouring [27]. Xie Yimin's team utilized the BESO algorithm to dynamically "delete" inefficient materials and "add" highly efficient ones, generating biomimetic structures that balance mechanical logic with esthetic form. This approach drastically reduces the material consumption of the main structure while satisfying performance requirements, thereby lowering life-cycle embodied carbon emissions [11,28,29].

However, transitioning topology optimization methods from theoretical algorithms to architectural and landscape engineering practices still faces constructability challenges. On the one hand, high computational costs and complex nonlinear iterations constrain the large-scale application of this method to massive structures or multi-objective synergistic optimization [25,30]. On the other hand, the organic load-bearing forms generated by optimization algorithms often feature free-form surfaces, irregular holes, and complex joints. Their high geometric complexity inherently conflicts with traditional industrialized construction methods, which can easily lead to surging costs for customized molds, increased manufacturing difficulties, and compounding on-site assembly errors [27]. As a result, topology optimization outputs often lean more toward early-stage conceptual design and require geometric simplification and topological reconstruction before they can smoothly transition into the detailed design and construction phases [11,31]. Currently, existing studies have attempted to introduce density filters [32], structural grammars [33], human-informed optimization [34], and artificial intelligence (AI) [35] to enhance the constructability of optimization results at the computational logic aspect.

The application of DfMA in architecture can reduce costs, shorten schedules, and minimize construction waste by reducing the number of components, simplifying joints, and increasing prefabrication efficiency. Compared to traditional cast-in-place construction, applying DfMA principles can cut material waste by 15% to 25% and shorten the on-site assembly period by approximately 30% [17]. Furthermore, the integration of DfMA with Building Information Modeling (BIM) helps to further lower on-site labor requirements, material consumption, and waste generation [36,37]. Currently, many countries are pro-

moting DfMA methods at the policy level. For example, Singapore’s Building and Construction Authority (BCA) has formulated systematic DfMA guidelines for Prefabricated Prefinished Volumetric Construction (PPVC), precast concrete structural systems, and Mechanical, Electrical, and Plumbing (MEP) systems. Nevertheless, there remains a relative lack of research on how to systematically conduct DfMA for irregular structural systems generated by topology optimization, as well as how to perform the life-cycle sustainability evaluations [38]. In a few pioneering explorations, a team from ETH Zurich applied DfMA principles to spatial timber grid structures, significantly simplifying complex multidirectional intersections [39]. Rausch et al. improved material utilization through panel unfolding and nesting algorithms [40]. These studies illustrate that DfMA can serve as a crucial technical mediator, guiding the transformation of topology optimization results to feasible systems.

Furthermore, the integration of DfMA within the context of the Modern Methods of Construction (MMC) and industrialized construction has begun to transform traditional building paradigms [15,16]. Recent advancements in BIM-Based DfMA have introduced assessment logics to enable precise constructability evaluations during the early design phase [41]. BIM-Based DfMA workflows are critical for systematically evaluating manufacturing complexity, modularization, and assembly efficiency, bridging the gap between digital design and physical fabrication. Despite these advancements, applying BIM-Based DfMA to the complex geometric outputs of topology optimization remains an underexplored domain.

3. Materials and Methods

This study focuses on landscape structures (benches, pavilions, and bridges) within the Beijing Olympic Forest Park as specific research subjects. It establishes a systematic research framework encompassing “case investigation–initial carbon emission accounting–topology optimization–DfMA simplification–structural verification–post-optimization carbon emission accounting–emission reduction comparison” (Figure 1).

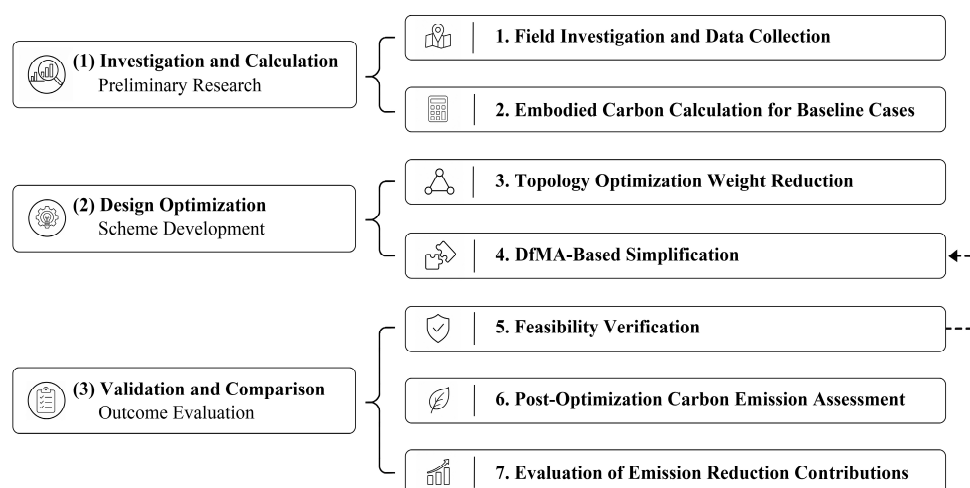


Figure 1. Research framework.

First, through on-site surveys, this study systematically collected fundamental data on the typical structures to calculate the baseline embodied carbon emissions. Second, Autodesk Fusion software (version 2704.1.23, 64-bit, Educational License) was utilized to identify the primary load-bearing paths of the structures, based on which topology optimization was conducted to achieve preliminary weight reduction. Subsequently, DfMA principles were introduced to translate the highly complex generated topological forms

into structural systems that are easy to manufacture, transport, and assemble. Finally, after verifying structural feasibility, the embodied carbon emissions of each design were calculated, allowing for a systematic comparison of their efficacy in structural weight reduction and embodied carbon reduction.

3.1. Study Case Selection

To systematically understand the current material and structural status of landscape structures in the Beijing Olympic Forest Park, this study conducted field surveys to investigate the basic conditions of landscape benches, pavilions, and bridges, including key indicators such as materials, structural forms, dimensions, and weight grades (Table 1). The survey results indicate that some current landscape facilities suffer from component weight redundancy, insufficient material utilization, and low structural efficiency, highlighting a potential for lightweight optimization.

Table 1. Investigation of structures in the Beijing Olympic Forest Park.

Type	No.	Material	Footprint Area (m ²)	Structural Type	Weight Grade
Landscape Bench	1	Stone, iron, wood–plastic	0.64	Frame	Heavy
	2	Steel frame, wood	1.14	Frame	Medium
	3	Steel frame, wood	0.36	Frame	Medium
	4	Steel frame, wood	0.56	Frame	Medium
	5	Steel frame, wood	1.76	Ring-frame	Light
	6	Wood	3.60	Box-type	Light
	7 (a)	Concrete, wood	0.95	Solid	Heavy
Landscape Pavilion	1 (b)	Steel frame	29.0	Frame	Heavy
	2	Wood	64.0	Frame	Light
	3	Steel frame, alloy, glass	53.2	Frame	Medium
Landscape Bridge	1	Reinforced concrete, metal railings	322.4	Beam bridge	Light
	2	Reinforced concrete, metal railings	416.0	Beam bridge	Light
	3 (c)	Reinforced concrete, wooden railings	192.0	Arch bridge	Heavy
	4	Wood	11.2	Arch bridge	Light
	5	Reinforced concrete, wooden railings	235.2	Arch bridge	Heavy

Based on the survey results, this study selected three typical landscape structures as analysis cases: a landscape bench (No. 7), a landscape pavilion (No. 1), and a landscape bridge (No. 3). The selection criteria prioritized objects with high usage frequency, relatively large weight grades, and representative structural characteristics (Table 2). The selected cases provide comprehensive coverage of a small-scale concrete structure, a medium-scale steel system, and a large-scale concrete structure. This selection aims to compare and verify the applicability and carbon reduction efficacy of the topology optimization-DfMA synergistic method across multiple scales, material types, and structural systems.

3.2. Carbon Emission Calculation Method

This study employs the Life-Cycle Assessment (LCA) method to calculate the embodied carbon emissions. Based on the construction characteristics of the landscape structures, the life-cycle embodied carbon is divided into the materialization phase and the demolition phase [42]. The materialization phase includes material production, material transportation, and construction; the demolition phase encompasses building demolition, waste transportation, waste disposal, and recycling (Table 3).

Table 2. Selected research cases.

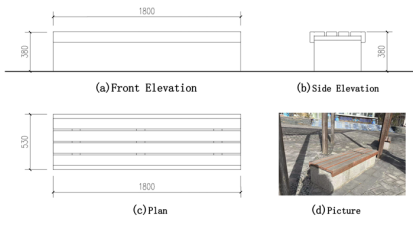
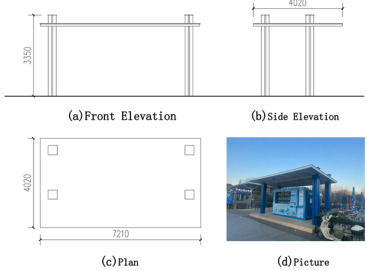
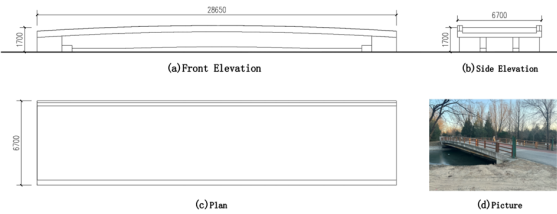
Project	No.	Material	Dimensions (mm)	View
Landscape Bench	a	Concrete structure, wooden surface	1800 × 530 × 380	
Landscape Pavilion	b	Steel frame	7210 × 4020 × 3350	
Landscape Bridge	c	Reinforced concrete structure, wooden railings	28,650 × 6700 × 1700	

Table 3. Life-cycle embodied carbon emissions of structures.

Phase	Life Cycle Stage
Materialization Phase	Material Production C _{sc}
	Material Transportation C _{ys}
	Construction C _{jz}
Demolition Phase	Demolition C _{cc}
	Waste Transportation C _{ly}
	Waste Disposal C _{cl}
	Recycling C _{hs}

The total embodied carbon emissions of a structure equal the sum of emissions from material production to waste disposal, minus the carbon reduction generated by recycling:

$$C = C_{sc} + C_{ys} + C_{jz} + C_{cc} + C_{ly} + C_{cl} - C_{hs} \quad (1)$$

The impact of topology optimization and DfMA simplification on carbon emissions is primarily reflected in material consumption, construction methods, labor hours, and recycling proportions. This study prioritizes the default values from the “Standard for Building Carbon Emission Calculation” of China (GB/T 51366-2019) [43] and incorporates the existing literature to adjust values for additive manufacturing (3D printing) and recycling scenarios.

1. Material Production Stage:

$$C_{sc} = \sum (M_i \times F_i) \quad (2)$$

where C_{sc} is the carbon emission during the material production stage (kgCO_2e), M_i is the consumption of the i -th main material (m^3), and F_i is the carbon emission factor of the i -th main material ($\text{kgCO}_2\text{e}/\text{m}^3$).

This study categorized and quantified the structural materials obtained through on-site survey. The carbon emission factors are sourced from GB/T 51366-2019.

2. Material Transportation Stage:

$$C_{ys} = \sum (M_i \times D_i \times T_i) \quad (3)$$

where C_{ys} is the carbon emission during the material transportation stage (kgCO_2e), M_i is the consumption of the i -th main material (t), D_i is the average transportation distance of the i -th main material (km), and T_i is the carbon emission factor for transporting a unit weight of the i -th material over a unit distance [$\text{kgCO}_2\text{e}/(\text{t}\cdot\text{km})$].

Transportation distances were determined based on default values in GB/T 51366-2019: 40 km for concrete and 500 km for other materials. The factor for light gasoline vehicles is $0.334 \text{ kgCO}_2\text{e}/(\text{t}\cdot\text{km})$. For transporting concrete for the bridge, heavy diesel trucks (46 t payload) were assumed, with a factor of $0.057 \text{ kgCO}_2\text{e}/(\text{t}\cdot\text{km})$. Trip counts were calculated based on actual volumes.

3. Construction Stage:

$$C_{jz} = \sum (E_{jz,i} \times EFi) + \sum (P_i \times Fp) \quad (4)$$

where C_{jz} is the construction stage carbon emission (kgCO_2e), $E_{jz,i}$ is the total consumption of the i -th energy source (kWh or kg), EF_i is its emission factor ($\text{kgCO}_2\text{e}/\text{kWh}$ or $\text{kgCO}_2\text{e}/\text{kg}$), P_i is the total labor input (man-days), and Fp is the labor emission factor ($\text{kgCO}_2\text{e}/\text{man-day}$).

The construction primarily utilized woodworking saws, profile steel shears, spiral drills, and welding machines. Power and labor parameters were adopted from GB/T 51366-2019 defaults. The electricity emission factor used was $0.8 \text{ kgCO}_2\text{e}/\text{kWh}$ (North China) [44], and labor was set at $10.1 \text{ kgCO}_2\text{e}/\text{man-day}$ [45]. For irregular components that are difficult to build, additive manufacturing energy consumption was adjusted: 2.72 kWh/kg for steel [46] and 35.2 kWh/m^3 for concrete 3D printing [47].

4. Building Demolition Stage:

This stage is calculated using an estimation method, assumed to be 10% of the carbon emissions generated during the construction stage [48].

5. Waste Transportation Stage:

This stage is referenced to Equation (3). The default average distance from the demolition site to secondary markets, waste treatment facilities, and landfills is set at 50 km [49].

6. Waste Disposal Stage:

$$C_{cl} = \sum [M_i \times (R_{tm,i} \times Li + R_{fs,i} \times Bi)] \quad (5)$$

where C_{cl} is the disposal stage carbon emission (kgCO_2e), M_i is the consumption of the i -th material (t), $R_{tm,i}$ and $R_{fs,i}$ are the landfill and incineration proportions (%), and Li and Bi are their respective emission factors ($\text{kgCO}_2\text{e}/\text{t}$).

Based on the relevant literature [45,50,51], this study determined the proportions in Table 4 to calculate the corresponding emissions.

Table 4. Landfill, incineration, and recycling proportions.

Material	Initial/Topology Optimization Project			DfMA Project		
	Landfill	Incineration	Recycling	Landfill	Incineration	Recycling
Wood	55%	15%	30%	55%	15%	30%
Steel	15%	—	85%	3%	—	97%
Concrete	45%	—	55%	30%	—	70%

7. Recycling Stage

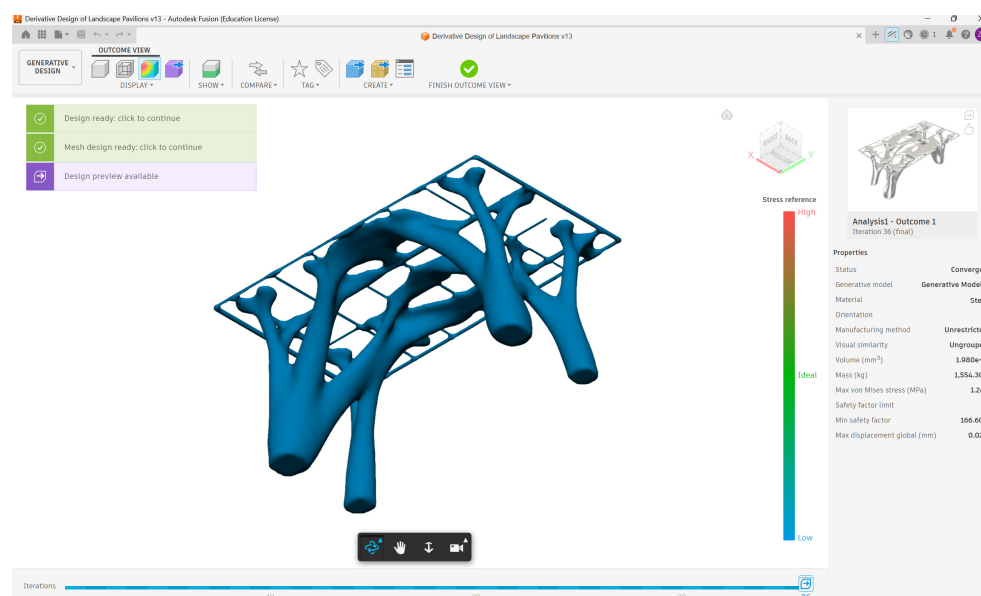
$$\text{Chs} = \Sigma(\text{Csc},i \times \text{Rhs},i \times 50\%) \quad (6)$$

where Chs is the carbon emission reduction from recycling (kgCO_2e), Csc,i is the material production emission of the i-th material (kgCO_2e), and Rhs,i is its recycling proportion (%).

Recycling substitutes part of the primary raw material production and is counted as a carbon offset (deducted by 50% according to GB/T 51366-2019). For the DfMA designs, due to higher component standardization, clear assembly, and superior conditions for material separation, the recycling proportions for steel and concrete were adjusted upward [52–55].

3.3. Topology Optimization Method

This study utilized Autodesk Fusion to perform topology optimization on the three structures (Figure 2). The goal of this step is not to generate the final buildable form, but to identify the primary material distribution and core load-bearing paths within specific boundary conditions. This strips away redundant, non-load-bearing material to provide a prototype for subsequent DfMA translation.

**Figure 2.** Topology optimization of structures in Autodesk Fusion.

The process followed a workflow of “defining design domains—setting preserved regions—applying loads and constraints—calculating optimal material paths.” In the model, the primary load-bearing or supporting sections subject to material reduction are defined as design domains. The parts directly related to functional usage, component connections, and load transmission at supports are set as preserved regions. And the spaces

where structural intrusion is prohibited—such as areas for passage, activities, legroom, and under-bridge clearance—are designated as obstacle regions. The optimization objective is to reduce non-essential material consumption by more than 50% while satisfying the basic structural load-bearing and overall stiffness requirements (Table 5).

Table 5. Topology optimization settings for the three case structures.

Object	No.	Design Domain	Preserved Regions	Obstacle Regions	Primary Loads	Boundary Conditions
Landscape Bench	a	Support area below the seat	Seat outline, end connection faces, ground contact faces	Leg activity space, clear space below the seat	Structural dead load, live load	Fixed at 4–12 bottom support areas
Landscape Pavilion	b	Support and connection area below the roof	Column bases, roof connection interfaces, necessary support areas	Passage space between columns, activity clearance height	Structural dead load, live load	Fixed at 16 bottom support areas
Landscape Bridge	c	Load-bearing system below the deck	Deck, end bearings, railing connection interfaces	Clearance below bridge, deck passage space	Structural dead load, live load	Fixed at 8 both end support areas

3.4. DfMA Simplification Method

The DfMA simplification adheres to the core principles of “retaining load-bearing paths, standardizing components, and enabling joint assembly,” transforming complex free-form surfaces, intricate nodes, and continuous irregular entities into standardized component systems that are easy to manufacture, transport, and assemble on-site (Figure 3). This morphological simplification relies on explicit, fundamental design rules rather than solely engineering judgment.

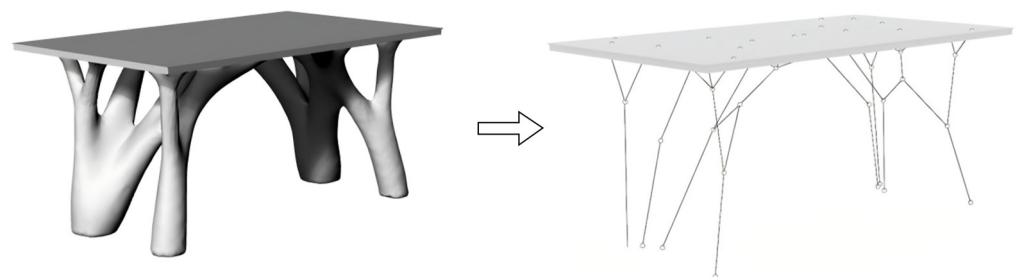


Figure 3. DfMA simplification of the tree-like support structure of the landscape pavilion.

1. The high-density material regions identified by topology optimization are abstracted into a logically continuous geometric skeleton.
2. Complex, continuous free-form entities are discretized into physical units that comply with standard manufacturing and logistics constraints.
3. To minimize non-standard fabrication, component and connection types are reduced through modular repeatability.
4. Complex continuous intersections are converted into modular, reversible joints to facilitate rapid on-site assembly and end-of-life deconstruction.

To ensure reproducibility during this translation process, the numbers and sizes of the standardized modules were determined by mapping the required load paths directly to commercially available standard profiles, thereby avoiding custom mold manufactur-

ing. These principles facilitate structural rationalization by merging complex, free-form geometries into regularized forms while strictly preserving primary load-bearing paths. To enhance manufacturing efficiency, morphologically similar components are consolidated into repeatable, standardized units. Furthermore, irregular junctions are transformed into standardized joint systems that support modular prefabrication, bolting, or sleeving, thereby ensuring structural feasibility and ease of assembly [56].

3.4.1. DfMA Simplification of the Landscape Bench

Simplification for the bench focuses on the load transfer relationship between the seat and the supports. The core paths transmitting loads downwards are retained, and free-form supports are converted into plates, rods, diagonal braces, or arched ribs that can be conventionally manufactured. This transforms the bench into an easily manufacturable system.

3.4.2. DfMA Simplification of the Landscape Pavilion

For the pavilion, simplification centers on its tree-like spatial support system. Primary load-bearing paths were first extracted in Rhino 8.0, abstracting continuous irregular entities into rod centerlines, categorized into main trunks, primary branches, secondary branches, and local supports based on load transfer hierarchy. The uneven supports were uniformly translated into standard hollow circular steel tubes. Multi-directional spherical sleeve joints were introduced at branch intersections (Figure 3).

3.4.3. DfMA Simplification of the Landscape Bridge

The bridge simplification extracted the main endpoints of the topology-optimized structure, combining them with the midpoints of the bridge deck's underside to generate precise arched control lines. These were organized into an assembled "complete central arch and two end half-arches" configuration. The central arch was divided into six standardized blocks, and each side's half-arch was split into two independent components. Structural interfaces were standardized into base joints, transforming non-standard solid entities into a modular arched block system ready for manufacturing, transport, and assembly.

3.5. Result Verification Method

To verify the structural feasibility of the topology optimization and DfMA designs, static analysis models were established for all three structures. This verification serves the conceptual design stage to macroscopically assess whether load-bearing paths, overall stiffness, and strength are within reasonable ranges.

For the concrete structures (bench and bridge), static stress analyses were conducted using Autodesk Fusion to extract key indicators like von Mises equivalent stress, maximum total displacement, and safety factors. Because the landscape pavilion is a complex spatial tree-like steel tube structure, Dlubal RSTAB 9.14 software was utilized for verification. In RSTAB, steel parameters, cross-sectional properties, support constraints, and equivalent vertical top loads were assigned to compute nodal displacements, member deformations, internal forces, and strains.

4. Results and Analysis of Topology Optimization and DfMA

4.1. Topology Optimization Results

The analysis indicates that topology optimization demonstrates significant potential for material reduction across landscape structures of varying scales, material types, and

structural systems. However, notable variations exist in weight reduction efficiency and morphological evolution characteristics among the cases (Tables 6–8).

Table 6. Material usage before and after topology optimization for the landscape bench.

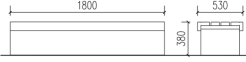
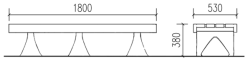
Design	No.	Wood Volume (m ³)	Concrete Volume (m ³)	Weight (kg)	Weight Reduction Rate	Projection View	Axonometric View
Initial Case	a	0.0474	0.2430	606.900	—		
Long-side-supported TO	a1-T	0.0474	0.0274	89.484	85.26%		
Three-short-side-supported TO	a2-T	0.0474	0.0367	111.804	81.58%		
Two-short-side-supported TO	a3-T	0.0474	0.0322	100.980	83.36%		

Table 7. Material usage before and after topology optimization for the landscape pavilion.

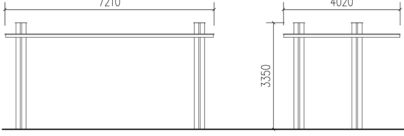
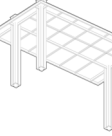
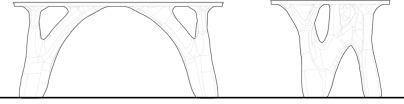
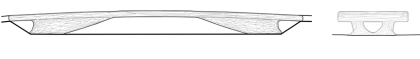
Design	No.	Steel Volume (m ³)	Weight (kg)	Weight Reduction Rate	Projection View	Axonometric View
Initial case	b	0.245	1923.25	—		
Topology optimization	b-T	0.198	1554.30	19.18%		

Table 8. Material usage before and after topology optimization for the landscape bridge.

Design	No.	Concrete Volume (m ³)	Weight (kg)	Weight Reduction Rate	Projection View	Axonometric View
Initial case	c	130.90	314,160	—		
Topology optimization	c-T	97.72	234,528	25.35%		

Among the three objects, the landscape bench achieved the highest weight reduction ratio. This is primarily because its initial design consisted of a heavy, solid concrete block with material usage far exceeding actual load-bearing requirements. For the concrete support, topology optimization was conducted under three different support conditions (arranged along the long side and short sides). The results show that the weight reduction

rates for all three optimized designs exceeded 80% (Table 6). Notably, the long-side support configuration achieved a material reduction of up to 85.26% through an approximate triangular load-bearing structure. This demonstrates that optimizing the spatial distribution of support materials can drastically cut concrete consumption.

The initial design of the landscape pavilion utilized a conventional frame system, and its optimization focused on simplifying spatial load-bearing paths. Following topology optimization, the structure evolved into a biomimetic tree-like branching morphology, restructuring the original uniform frame supports into a distinct “trunk–branch” load transfer topology. This achieved a 19.18% reduction in total material volume (Table 7). However, the continuous solid morphology generated by this optimization is highly complex, suffering from localized excessive mass and highly irregular joints. This indicates that for complex spatial structures, topology optimization results can rarely be directly translated into practical, lightweight construction schemes.

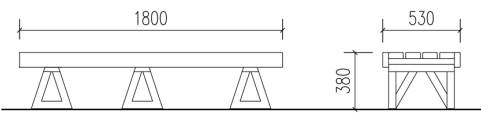
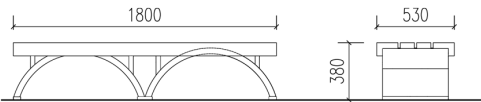
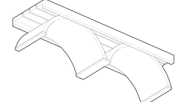
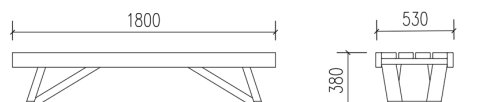
As the largest structure among the three cases, topology optimization of the landscape bridge effectively trimmed the redundant volume of the concrete support beneath the bridge deck, achieving a weight reduction rate of 25.35% (Table 8). Although the relative weight reduction percentage for the landscape bridge is lower than that of the landscape bench, its absolute material reduction (a total saving of 79,632 kg of concrete) is exceptionally prominent. This outcome validates the lightweight design value of topology optimization in the large-scale landscape structures.

4.2. DfMA Simplification Results

4.2.1. DfMA of Landscape Bench

DfMA simplification of the landscape bench focuses on the support system beneath the seat. Based on the preceding topology optimization results, three candidate DfMA options were constructed (Table 9).

Table 9. DfMA options for the landscape bench.

Design	No.	Component	Weight (kg)	Projection View	Axonometric View
Long-side-supported	a1-D	Triangular module	82.98		
Three-short-side-supported	a2-D	Arched plate	112.02		
Two-short-side-supported	a3-D	Diagonal brace	169.38		

Evaluating material consumption alongside component standardization reveals that the long-side support configuration performs best. This scheme reconstructs the lower support into repeatable, assemblable triangular modules with clear load transfer logic, reducing the total mass by an additional 7.27% compared to the pure topology optimization design. These selected DfMA schemes were considered preferable because they achieved the optimal balance among minimal material consumption, highest part repeatability, and overall ease of assembly compared to other potential geometric translations. Composed

of identical repeating support units, this design achieves high standardization, providing an excellent foundation for modular factory fabrication and rapid on-site assembly.

The three-short-side support design translates continuous load paths into arched plate components, offering good structural integrity. However, it increases processing requirements for curved plates and joint connections. The two-short-side support design relies on end supports and longitudinal diagonal braces for load transfer. While it provides high overall stiffness, it leads to a relative increase in material consumption. Although both short-side support options offer certain conveniences for conventional fabrication and construction, they fail to achieve further material savings.

4.2.2. DfMA of Landscape Pavilion

During the DfMA of the landscape pavilion, the branching tree-like characteristics from topology optimization were adopted as the structural prototype, which was subsequently transformed into a tree support system composed of standard hollow circular steel tubes (Figure 4). This DfMA scheme not only drastically simplifies the manufacturing and fabrication difficulties, but also decreases the total weight to 1233.39 kg, representing an additional weight reduction of 20.65% compared to the topology optimization results.

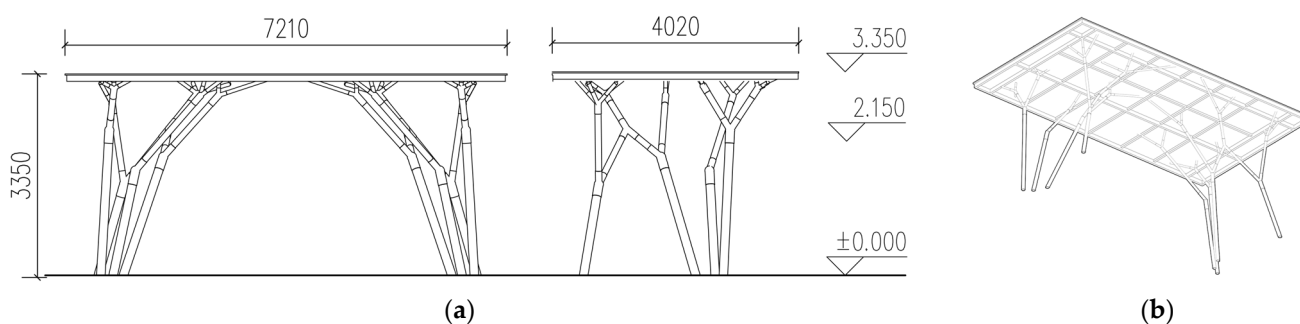


Figure 4. DfMA scheme for landscape pavilion: (a) projection view; (b) axonometric view.

Following DfMA, the support system of the pavilion is disassembled into 6 main trunks, 14 primary branches, 26 secondary branches, and 6 localized tertiary branches. Members across all layers employ hollow circular steel tubes, configured with matching cross-sectional specifications based on their load transfer hierarchy. This strategy effectively avoids the manufacturing obstacles associated with continuous, variable-section components. As illustrated in Figure 5, standardized spherical sleeve joints were introduced to replace complex on-site welding, facilitating rapid bolt assembly and end-of-life deconstruction.

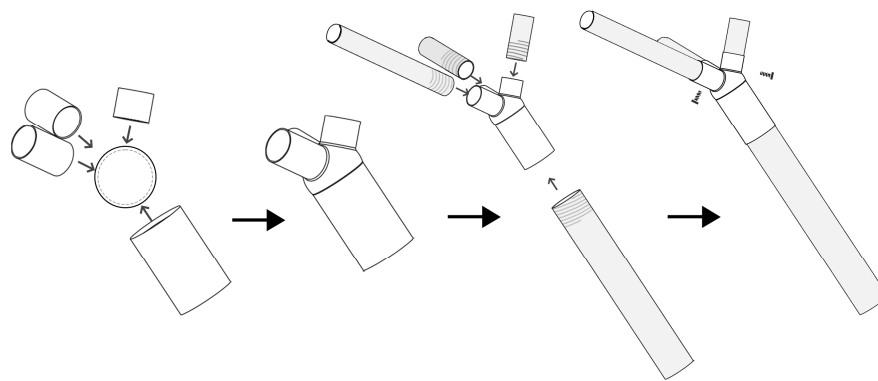


Figure 5. Joint assembly for landscape pavilion DfMA scheme.

4.2.3. DfMA of Landscape Bridge

Through DfMA simplification, this bridge was restructured into an assemblable system consisting of an “upper bridge deck slab–central arch–two end half-arches–base joints” (Figures 6 and 7). The lower substructure was converted from a heavy, non-standard solid entity into a modular, segmented arch combination structure.

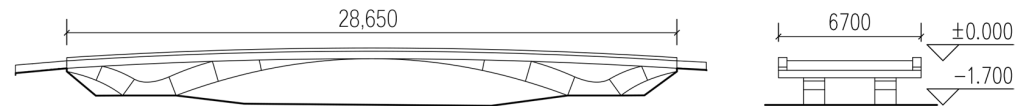


Figure 6. Projection view of landscape bridge DfMA scheme.

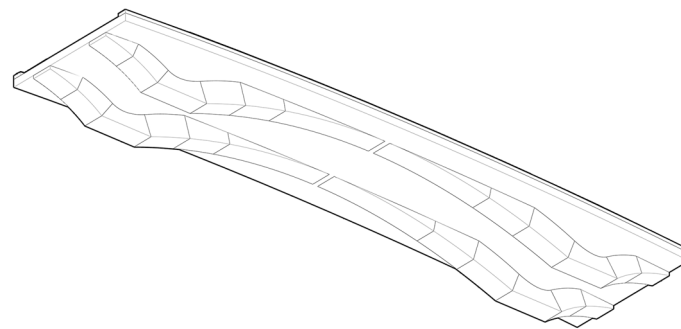


Figure 7. Axonometric view of landscape bridge DfMA scheme.

The structural system can be systematically categorized into modules such as bridge deck slabs, central arch blocks, side half-arch blocks, and base joints (Figure 8). Furthermore, the central arch is divided into six standardized arch blocks, and the side half-arches are split into two independent components each. Due to the bilateral symmetry of the overall structure, components can be fabricated using mirror imaging, thereby minimizing component variety and mold requirements.

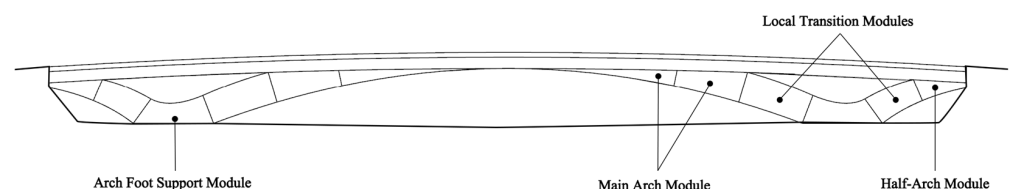


Figure 8. Module schematic of landscape bridge DfMA scheme.

Although the total weight of the landscape bridge DfMA design (244,560 kg) was not reduced further compared to the topology optimization design, the scheme successfully enables high-precision factory prefabrication and rapid on-site assembly of the arch blocks. This modular characteristic significantly reduces construction difficulty while granting excellent deconstructability, which ultimately boosts material recycling rates at the end of its life cycle.

4.3. Structural Feasibility Verification Results

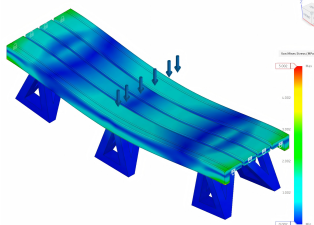
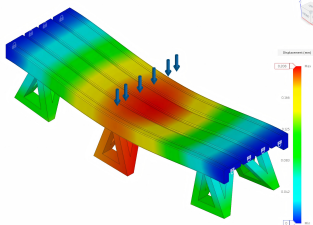
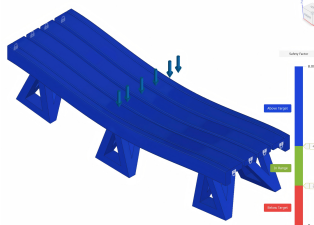
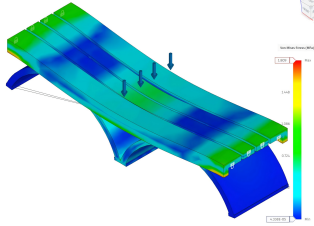
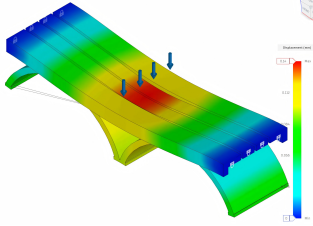
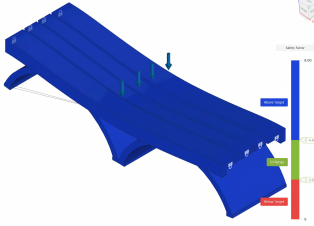
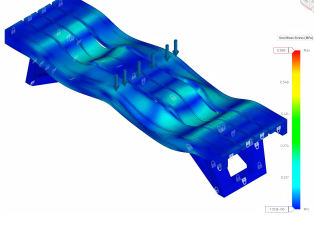
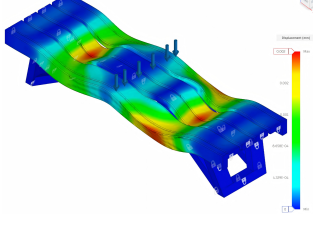
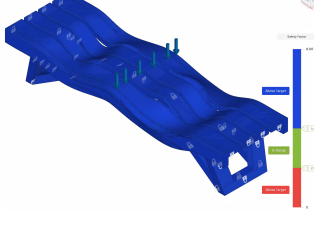
To evaluate whether the structures of DfMA serve as a sound mechanical foundation for further development, this study conducted structural feasibility verifications (Table 10). These verifications focus on macro-level load-bearing feasibility and do not extend to local connection capacities, bolt stresses, weld fatigue, foundation anchoring, or complex construction-stage load cases.

Table 10. Structural verification results for the three landscape structures.

Object	Analysis Tool	Verification Indicators	Verification Results
Landscape bench	Autodesk Fusion	Stress, displacement, safety factor	All three options meet conceptual safety limits
Landscape Pavilion	RSTAB	Support reactions, displacement, member stress	Minimal displacement and stress
Landscape bridge	Autodesk Fusion	Stress, displacement, safety factor	Safety factor is 3.71, minimal overall deformation

For the three DfMA options of the landscape bench, static stress analyses were conducted under a vertical load of 3.0 kN. The calculations show that the minimum safety factors for all three options are significantly higher than 1.5, confirming that they are absolutely safe under the established load case (Table 11). Although the long-side support design generates higher internal stress and displacement responses, it fully satisfies conceptual safety while exhibiting the highest potential for standardized modular assembly. The three-short-side support configuration balances load continuity with material efficiency, while the two-short-side support setup exhibits the smallest characteristic displacement, indicating the highest overall structural stiffness.

Table 11. Structure analysis results for the landscape bench DfMA design options.

Design	Max von Mises Stress (MPa)	Max Displacement (mm)	Min Safety Factor
Long-side-supported	5.002 	0.208 	5.997 
Three-short-side-supported	1.809 	0.140 	16.581 
Two-short-side-supported	0.685 	0.002 	43.811 

For the landscape pavilion, 3D static analysis of the spatial rod system was executed via RSTAB software. The results show a maximum displacement of only 0.15 mm and a

maximum combined stress of approximately 1.90 MPa. These data confirm the macro-level structural feasibility of the pavilion's DfMA scheme.

For the landscape bridge, static stress analysis via Autodesk Fusion indicates that the DfMA scheme for the arch bridge achieves a minimum safety factor of 3.71, a maximum von Mises stress of 3.86 MPa, and a maximum displacement of only 2.90 mm. These findings verify that the overall structure exhibits no signs of localized strength deficiencies or overall stiffness issues.

5. Analysis of Carbon Emission Calculation Results

5.1. Changes in Embodied Carbon Emissions Before and After Optimization

To evaluate the impact of topology optimization and DfMA on life-cycle embodied carbon emissions, this study compared the initial schemes, topology-optimized schemes, and DfMA-translated schemes for the three types of landscape structures (Table 12, Figures 9 and 10). The results indicate that although topology optimization can reduce material usage, the total life-cycle carbon emissions are still influenced by construction methods, component complexity, and recycling rates. In contrast, the DfMA schemes successfully achieved emission reductions across all three landscape structures compared to the initial schemes by improving manufacturing feasibility, logistics and transportation efficiency, on-site assembly, and the recyclability of disassembled materials.

Table 12. Embodied carbon emissions before and after optimization.

Object		Initial Scheme (kgCO ₂ e)	Topology Optimization			DfMA		
			Carbon Emissions (kgCO ₂ e)	Carbon Reduction (kgCO ₂ e)	Reduction Rate	Carbon Emissions (kgCO ₂ e)	Carbon Reduction (kgCO ₂ e)	Reduction Rate
Landscape Bench	Long-side-supported	140.612	51.175	89.437	63.61%	50.182	90.430	64.31%
	Three-short-side-supported		54.430	86.182	61.29%	54.395	86.216	61.32%
	Two-short-side-supported		52.851	87.761	62.41%	62.718	77.894	55.40%
Landscape Pavilion		791.323	6406.641	−5615.318	−709.61%	437.550	353.773	44.71%
Landscape Bridge		44,630.731	34,370.609	10,260.122	22.99%	29,773.090	14,857.641	33.29%

Note: Carbon reduction = Initial scheme carbon emissions − Optimized scheme carbon emissions; negative values indicate an increase in carbon emissions after optimization.

Among all cases, the landscape pavilion best illustrates the limitations of topology optimization methods in practical applications. Although the topology optimization of the pavilion reduced its weight by 19.18%, its total life-cycle embodied carbon emissions surged by 709.61%. This result primarily stems from the high degree of geometric irregularity in the topology-optimized steel components, which necessitated the use of additive manufacturing processes during the construction phase, thereby leading to an increase in electricity consumption and labor inputs. Therefore, despite achieving certain emission reductions during the material production and transportation phases, the adverse effects generated during the construction and recycling phases outweighed the benefits of material savings. In contrast, the DfMA scheme reduced the pavilion's total embodied carbon emissions to 437.55 kgCO₂e, achieving a 44.71% carbon reduction rate compared to the initial scheme. This indicates within the selected cases the important role of constructability-oriented geometric regularization design in realizing low-carbon outcomes for complex spatial structures.

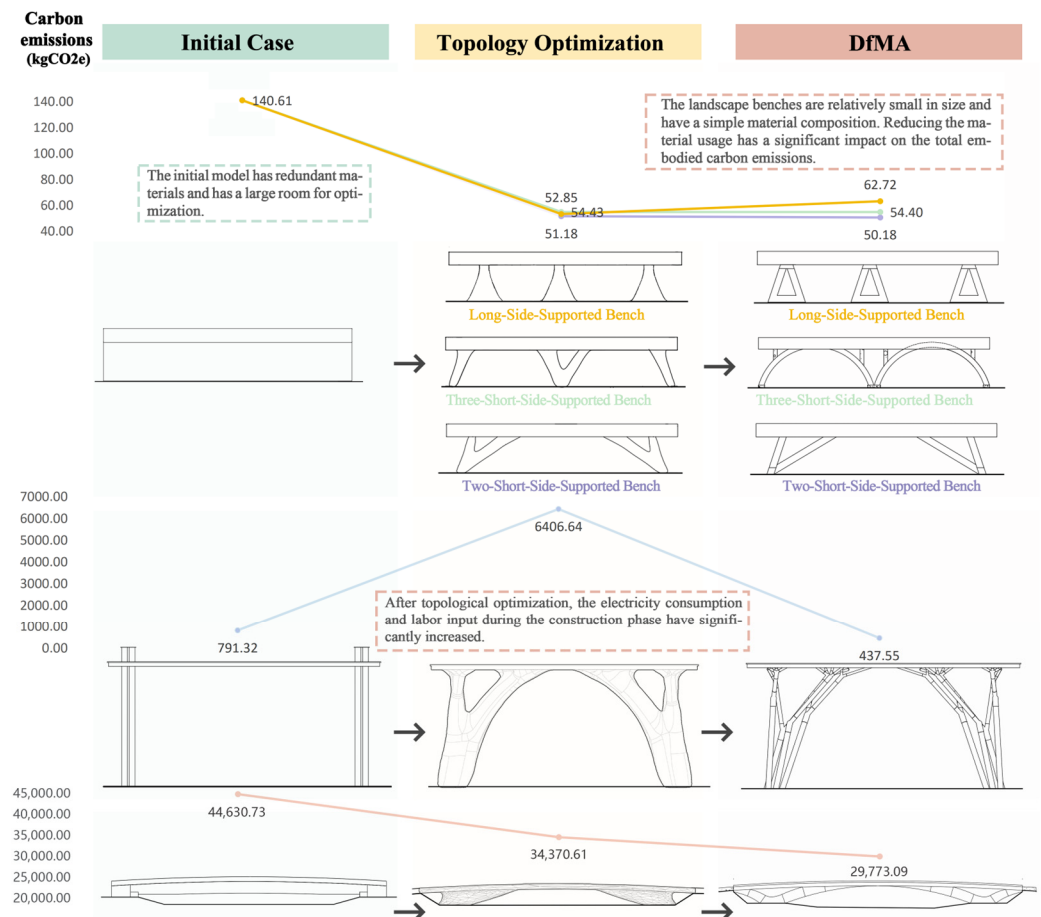
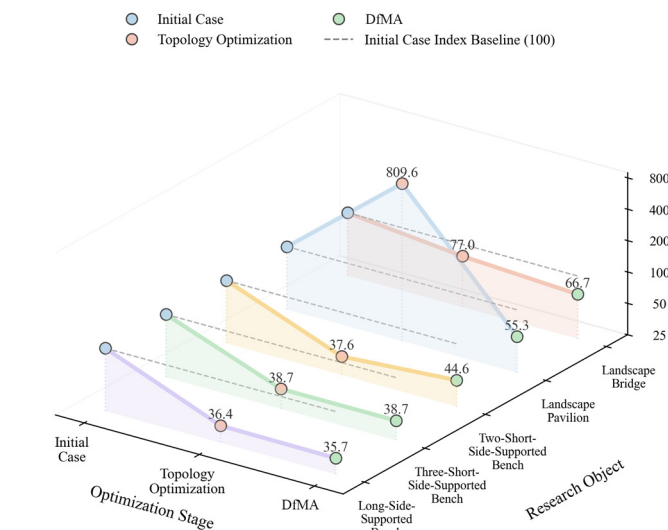


Figure 9. Comparison of embodied carbon emissions for each scheme before and after optimization.



Note: Carbon emission index = total embodied carbon emissions at each stage / total embodied carbon emissions of the initial case for the same research object $\times 100$. Relative indices and logarithmic scaling are used to avoid scale compression caused by the high index of the topology-optimized landscape pavilion.

Figure 10. Variation in embodied carbon emissions for each scheme.

All three optimized schemes for the landscape bench achieved emission reductions relative to the initial scheme. Because the bench has a relatively small volume but high concrete usage, the reduction in material volume exerted a strong impact on total embodied carbon. Although the total carbon emissions of the topology-optimized schemes were

slightly lower than those of the corresponding DfMA schemes, the DfMA schemes still maintained significant carbon reductions, with an average reduction rate of over 60%. Furthermore, they exhibit superior engineering feasibility in terms of industrialized manufacturing, on-site assembly, and recyclability.

The initial scheme of the landscape bridge had a total embodied carbon emission of 44,630.73 kgCO₂e, representing the highest carbon emission magnitude among the three research objects. While topology optimization reduced concrete material usage, the increased construction energy consumption and the loss in recycling benefits weakened the overall emission reduction effect. After introducing DfMA for modular simplification, the total embodied carbon emissions of the landscape bridge scheme dropped to 29,773.09 kgCO₂e, achieving a carbon reduction rate of 33.29%. This result indicates that for large-volume concrete landscape structures, low-carbon design must not solely rely on structural topology weight reduction. Instead, it requires a multi-dimensional synergistic consideration of material savings alongside component manufacturability, logistics efficiency, low-energy assembly, and recycling scenarios.

5.2. Changes in Embodied Carbon Emissions Across Various Stages

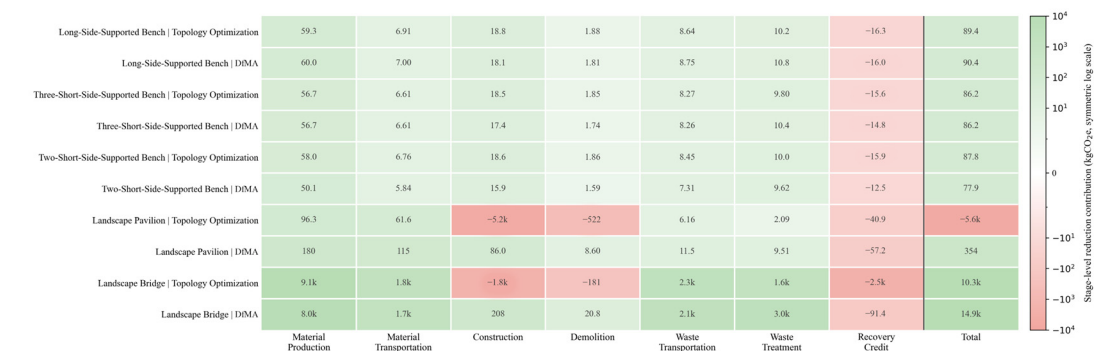
To identify the carbon reduction contributions of each stage throughout the life cycle, this study analyzed the emission reductions of each optimized scheme compared to the initial baseline scheme across various life-cycle stages (Figures 11 and 12). Since the recycling stage serves as a carbon offset item, it was calculated as “recycling offset amount of the optimized scheme—recycling offset amount of the initial scheme”. A positive emission reduction contribution indicates that the specific stage helps lower total embodied carbon emissions. Conversely, a negative value implies that the stage resulted in additional carbon emissions or a loss in recycling offsets.



Figure 11. Contributions of various stages to life-cycle carbon emissions for each object.

Analysis of the emission reduction results across different stages reveals that topology optimization primarily yields emission reduction contributions during the material production, material transportation, waste transportation, and waste disposal stages. Among these, the carbon reduction contribution of the material production stage is the most prominent, accounting for an average of over 60% of the total reductions. This is mainly attributed to the cutback in material consumption achieved through topology optimization.

Consequently, the reduction in material volume also drove a synchronous decline in carbon emissions during the subsequent logistics, transportation, and waste disposal stages.



Note: Positive values indicate reduction contributions relative to the Initial Case; negative values indicate emission increases or reduced recovery credits. For Recovery Credit, the contribution is calculated as optimized recovery credit minus Initial Case recovery credit.

Figure 12. Carbon reduction amounts at each stage compared to the initial design for each object.

However, topology-optimized schemes are highly likely to exert adverse impacts during the construction, building demolition, and recycling stages. This drawback is particularly evident in the landscape pavilion, where irregular steel components led to a massive surge in carbon emissions during the construction phase (a 41.5-fold increase compared to the initial scheme). The fundamental cause is that energy-intensive metal additive manufacturing significantly escalated electricity consumption. This demonstrates that pure material reduction via topology optimization does not equate to life-cycle carbon reduction.

In contrast, the comprehensive emission reduction rates of the DfMA schemes ranged between 33% and 64%, exhibiting stronger robustness in carbon reductions across all stages. With the exception of the recycling offset item—which experienced a reasonable absolute value decrease due to the reduction in the total material baseline—the carbon emissions in all other positive-emission stages decreased compared to the initial schemes. Notably, their carbon emission levels during the construction phase were significantly improved compared to the topology-optimized schemes. This suggests that component geometric simplification and assembly design executed through DfMA can effectively mitigate the additional carbon emissions triggered by complex construction.

In summary, topology optimization affects carbon emissions primarily in material-related stages through structural material optimization. Meanwhile, the DfMA method further ameliorates the construction, assembly, and recycling conditions of the structures, facilitating emission reduction contributions simultaneously across multiple stages. Therefore, the deep synergy of topology optimization and DfMA serves as a suitable and comprehensive optimization pathway for driving landscape structures toward high-performance and low-carbon practices.

5.3. Uncertainty and Sensitivity Analysis

To improve confidence in the reported carbon reductions and enhance the scientific robustness of the study, a sensitivity analysis was conducted on key life-cycle parameters. A $\pm 10\%$ variation was applied to material consumption, transportation distance, construction energy consumption, and recycling rate. The results indicate that material consumption had the greatest influence on total emissions, causing a $\pm 9.71\%$ change in the DfMA scheme, followed by recycling rate (about $\pm 5.75\%$), transportation distance ($\pm 2.56\%$), and construction energy consumption ($\pm 0.05\%$). Under all single-parameter scenarios, the DfMA schemes maintained a 32.38–34.86% carbon reduction compared with the initial designs. Even under a combined conservative scenario, the reduction rate remained 32.41%, confirming the robustness of the proposed framework.

6. Discussion

This study indicates that the carbon reduction benefits of topology optimization in landscape structure design are highly conditional. For heavy concrete structures, because the optimization direction mainly focuses on the reduction in solid materials, minimizing material consumption can directly lower carbon emissions stemming from material production, logistics, and waste disposal. However, for spatial branching steel structures such as the landscape pavilion, the continuous non-standard forms directly generated by topology optimization will exacerbate geometric complexity, subsequently driving up life-cycle carbon emissions. Therefore, topology optimization is not necessarily synonymous with low-carbon design. Its effectiveness is contingent upon a comprehensive integration of material types, structural forms, manufacturing methods, and recycling scenarios. It must be emphasized that the findings of this study are closely tied to the specific structural redundancy of the original designs. The proposed framework is demonstrated through these selected representative cases rather than statistically validated across a broad sample of landscape structures.

The DfMA method acts as a critical bridge connecting computational optimization and constructable implementation in this study. Through component standardization, joint geometric regularization, and assembly method optimization, DfMA can reduce the processing difficulty of complex irregular components and enhance both the disassemblability and material recycling potential of parts. In terms of practical implementation, integrating DfMA into the topology optimization workflow introduces critical manufacturability constraints early in the design process. This integration can substantially lower the cost implications associated with bespoke molds, material waste, and specialized on-site labor. While this approach proves effective for the landscape amenities studied, its applicability naturally extends to other small-scale architectural structures, such as pedestrian bridges and modular urban furniture (Table 13). However, scaling this framework to high-rise buildings or complex long-span structures would require further considerations regarding dynamic loads, joint fatigue, and more stringent safety regulations.

DfMA circumvents the need for bespoke, energy-intensive manufacturing techniques (such as large-scale metal 3D printing) by enabling the use of conventional, low-energy fabrication methods. By synthesizing key performance indicators across the case studies, it is evident that the true value of the framework lies not just in material reduction, but in actively lowering manufacturing complexity and improving supply chain logistics.

Furthermore, the core pathways and focuses for low-carbon optimization vary among landscape facilities of different structural types. Concrete landscape benches rely primarily on reducing the solid volume of supports to achieve carbon reductions. Although the topology weight reduction ratio of the concrete landscape bridge was relatively low, its massive initial baseline allowed it to contribute the highest absolute material reduction and carbon emission reduction. On the other hand, because the landscape pavilion possesses both the 3D characteristics of a steel structure and complex nodes, its low-carbon benefits are highly dependent on the subsequent geometric simplification via DfMA. Thus, it is evident that when conducting low-carbon designs for landscape structures, appropriate optimization strategies and form simplification methods must be selected according to their material properties, structural forms, and spatial scales.

Although this study provides a methodological reference for low-carbon landscape construction, it still harbors certain limitations. First, the current DfMA simplification process has not yet fully realized automatic derivation via parametric algorithms. Second, in the accounting of embodied carbon emissions, default parameters were adopted for certain construction energy consumption, demolition losses, and waste disposal ratios. Third, this study has limitations regarding constructability assessment. While the framework is

DfMA-oriented and effectively evaluates structural performance and embodied carbon, it does not quantitatively evaluate several key objectives of DfMA. Specifically, performance indicators such as manufacturing complexity indices, assembly time efficiency, precise modularization constraints, and localized fabrication effort were not quantitatively measured. Future research could focus on quantitative DfMA metrics, BIM-LCA data linkages, multi-objective optimization algorithms for carbon reduction, and on-site measured construction data to further enhance the scientific rigor and engineering application accuracy of the “topology optimization–DfMA” low-carbon design framework.

Table 13. Embodied carbon emissions of all schemes (kgCO₂e).

Object		Initial Scheme	Topology Optimization	DfMA
Landscape bench	Long-side-supported		 51.175	 50.182
	Three-short-side-supported	 140.612	 54.430	 54.395
	Two-short-side-supported		 52.851	 62.718
Landscape pavilion		 791.323	 6406.641	 437.550
Landscape bridge		 44,630.731	 34,370.609	 29,773.090

7. Conclusions

Taking the landscape bench, pavilion, and bridge in the Beijing Olympic Forest Park as specific research objects, this study proposed a low-carbon design method for landscape structures driven by topology optimization and DfMA. By conducting structural verification and life-cycle embodied carbon emission accounting, the comprehensive effectiveness of this synergistic method was evaluated. The primary research conclusions are summarized as follows:

1. Topology optimization can identify the force transmission paths of landscape structures and guide the refined reduction in materials. In this study, the lightweighting effect of the concrete landscape bench was the most pronounced, with structural weight reduction rates exceeding 80% under three distinct boundary conditions. While the mass of the optimized concrete landscape bridge was reduced by 25.35%, its massive baseline contributed to the highest absolute volume of material reduction. The mass of the optimized steel structure landscape pavilion was reduced by 19.18%, yielding a tree-like branching topological structure with clearer force transmission paths.
2. DfMA is capable of simplifying topology optimization results into manufacturable, transportable, and assemblable component systems. In practical application, the landscape bench elevated its structural standardization level through highly repetitive support modules. The landscape pavilion mitigated the manufacturing difficulties of spatial irregular structures by introducing standard hollow steel tubular trusses. The landscape bridge achieved clear geometric boundaries for its components and well-organized on-site assembly through the modular partition. Compared to pure topology-optimized forms, the DfMA simplification did not lead to a massive rebound in structural weight during the geometric regularization process. Notably, the landscape pavilion achieved an additional 20.65% weight reduction relative to the initial topology results.
3. Compared to a single topology optimization pathway, the DfMA synergistic scheme exhibited more stable carbon reduction benefits across all stages, with its life-cycle embodied carbon emissions decreasing by an average of 51.80%. Among them, the carbon reduction intensity of the landscape bench DfMA scheme was the highest, attaining a reduction rate between 55.40% and 64.31%. The landscape pavilion scheme successfully reversed the detrimental flaws of the pure topology scheme, achieving a 44.71% emission reduction. The carbon reduction rate of the large-volume landscape bridge scheme also reached 33.29%. The DfMA method actualized a synergistic decline in carbon footprints across multiple stages through systemic improvements spanning construction, logistics, and recycling.
4. The accounting results for life-cycle embodied carbon emissions confirmed that without constructability-oriented DfMA simplification, pure topology optimization in practical engineering is highly susceptible to high process energy consumption and recycling losses. These factors severely restrict actual emission reduction effectiveness and can even trigger a net increase in carbon emissions. This is particularly evident in complex metal spatial structures, where the necessitated adoption of metal additive manufacturing (3D printing) has directly increased their total life-cycle carbon emissions. This demonstrates within the selected cases that topology optimization alone is not universally carbon-reducing, and it requires constructability-oriented translation to achieve reliable low-carbon outcomes.

While the results strongly suggest that the synergistic topology optimization–DfMA framework reduces life-cycle carbon emissions, broader claims regarding the general applicability of this framework to other, more complex structural typologies should be approached with caution.

In conclusion, the synergistic low-carbon reduction of topology optimization and DfMA embodies a continuous process: “force path identification–component system reconstruction–joint optimization–carbon emission calculation”. Future research must integrate quantitative DfMA performance indicators, evaluate broader structural typologies, and utilize real energy consumption data tracking via the Internet of Things (IoT) to further substantiate the engineering applicability of this low-carbon design framework.

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Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
BCA	Building and Construction Authority
BESO	Bi-directional Evolutionary Structural Optimization
BIM	Building Information Modeling
DfMA	Design for Manufacture and Assembly
ESO	Evolutionary Structural Optimization
GSIMP	Generalized Solid Isotropic Material with Penalization
LCA	Life Cycle Assessment
LSM	Level-set Method
MEP	Mechanical, Electrical, and Plumbing
MMC	Modern Methods of Construction
PPVC	Prefabricated Prefinished Volumetric Construction
RIBA	Royal Institute of British Architects
SIMP	Solid Isotropic Material with Penalization
TO	Topology Optimization

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