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Long span Roof Optimization through Parametric Design in Structural Optimization

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ABSTRACT

Modern infrastructure relies on long-span roofs to provide clear spaces at airports, rail stations, show halls, sports arenas, industrial facilities, retail malls, and other public structures. Due to weight, deflection, stability issues, material utilisation, and construction cost, long-span roofs are difficult to design. The iterative trial-error methodology used in most structural design methodologies is wasteful when several variables affect structural performance. Parametric design and computational optimisation allow designers to automatically generate, assess, and optimise various structural possibilities in a single digital environment. Parametric design and structural optimisation are used to optimise long-span roof structures in this paper. Parametric modelling lets designers dynamically modify geometric factors like span length, roof curve, structural depth, grid spacing, member size, etc. without affecting the structural system. Using finite element methods, parametric models are evaluated for stresses, deflections, member utilisation, and structural behaviour under specified loading. Optimisation approaches will uncover structural configurations that reduce weight/material usage while meeting minimum strength, service-life, and stability requirements. New integrated design approaches increase design efficiency and reduce engineering time by embracing digital modelling, structural evaluation, and optimisation. Heavy structure, maximum deflection, stress distribution, buckling strength, and material utilisation will be used to compare conventional versus optimised roof designs. This project will examine how computing may contribute to sustainable construction by optimising the structure to use less steel, reduce embodied carbon emissions, and cut manufacturing costs without compromising structural integrity. This research shows that parametric optimisation may create lightweight, cost-effective, and sustainable long-span roofs. The automated creation of design alternatives allows for more structural combinations and higher structural performance and material efficiency than traditional techniques. This paper proposes a framework to help structural engineers, architects, and researchers create optimised roof systems for modern infrastructure projects and promote digital engineering and sustainable construction.

Introduction

Long-span roofs are now considered an essential element of modern structural engineering because they allow for large column-free spaces necessary for transit systems, sports venues, industrial structures, shopping malls, exhibition spaces and airport terminals (Majowiecki 2004, Adriaenssens *et al*. 2014). These roofs not only enhance the functional capabilities of structures, but also create better architectural flexibility and aesthetic qualities (Temmerman & Mollaert 2014). As urbanization and infrastructure continue to develop around the world, the demand for long-span roofs that are lightweight, cost-effective and structurally efficient is increasing significantly (United Nations 2019, Mei *et al*. 2021). As a result, engineers face increasing pressure to develop buildings that can span large distances while maintaining their safety, serviceability, durability and economics (Sobek 2016).

The main structural engineering problem with long-span roofs is caused by the increase in the total self-weight and structural flexibility of the roof as the distance of span increases (Block & Ochsendorf 2007). Long-span roofs generally experience larger bending moments, more deflection, greater risk of buckling and more complicated load distribution compared to shorter roofs (Kicinger *et al*. 2005). Traditional design methods usually compensate for these factors by increasing roof members' sizes, which leads to greater material use, higher construction costs and a larger carbon footprint (Bendsøe & Sigmund 2003, Ashraf *et al.* 2018). Therefore, one of the most important goals in today's structural engineering is to find a suitable balance between safety and material use (Zhuang & Liu 2021).Computational technology innovations have transformed structural design methods (Shea *et al.*, 2005). Engineers used to perform manual calculations, carry out extensive trials, and require several iterations of a design until they achieve an optimal design; however, with developments in computing technology and digitized modeling techniques, engineers can now rapidly create and assess many different design alternatives (Brown *et al.*, 2020). One area in which these technologies are notably effective is parametric designs, which are viable means for developing complex structures (Pugnale *et al.*, 2011; Azanaw, 2025). In parametric modeling, all elements or geometric components are assigned to various mathematical parameters (e.g., span, rise, roof curve, the distance between panels, structural depth & width of members) (Coenders, 2014). When any one of these parameters is modified, the entire structure is automatically regenerated, enabling the rapid evaluation of numerous design alternatives (Mueller & Ochsendorf, 2015).

Additionally, the integration of finite element analysis (FEA) with parametric modeling carries much promise for enhancing structural optimization (Caldas & Norford, 2002). With the use of modern computational platforms, engineers can connect digital geometric models with structural analysis software, enabling the evaluation of stress distributions, displacements, buckling, and member usages during conceptual design (Brown *et al.*, 2020; Mei *et al.*, 2021).

This combined workflow results in a significantly shorter design cycle while offering increased engineering proficiency and encouraging performance-based decision-making (Shea *et al*., 2005). As such, structural optimization represents another key milestone in computational engineering (Bendsøe & Sigmund, 2003).Optimization methods are geared toward determining the best possible solution that meets predetermined objectives such as weight, cost, material consumption, or performance, while also being structurally sound. Structural optimization (Goldberg, 1989; Xie & Steven, 1997) is especially important for long span roofs because small reductions in overall weight of the structure will provide large cost and environmental savings throughout fabrication, transportation, construction, and maintenance of the structure (Ashraf *et al*., 2018). As a result, optimization techniques have changed dramatically from simple member sizing to a comprehensive computational framework consisting of: 1) parameters for generating the geometry of a design; 2) computer programs that automatically analyze the structure; 3) intelligent search algorithms for evaluating many feasible designs against the design codes as well as construction limitations (Sigmund, 2001; Mei *et al*., 2021). These advances will allow engineers to identify multiple acceptable designs while still satisfying all design requirements and construction constraints (Azanaw, 2025). The optimized structures produced as a result of this process will generally contain less material, increased stiffness, distribute loads better and be more sustainable than traditional construction methods (Zhuang & Liu, 2021).

Unfortunately, despite these advances in technology, many engineering projects continue to rely on traditional design methods of conducting architectural geometry and structural analysis (Mueller & Ochsendorf, 2015). This fractured process will often result in longer design cycles and reduce the number of alternative structural design options that can be explored (Brown *et al*., 2020). In addition, many published studies only discuss individual components of the optimization process but do not incorporate the parametric modeling, finite element analysis, and structural performance results into one complete package (Pugnale *et al*., 2011; Azanaw, 2025). Therefore, this research will look into how parametric design can be used as an integrated computational tool for optimization long span roof structures. The purpose of this research is to determine relationships between geometric parameters, structural behavior, and optimization objectives while showing how utilizing parametric models can improve the efficiency, material use, and performance of these structures. This research will show how digital design technologies can help create lightweight, economical, and sustainable systems suitable for use in modern construction.

Literature Review

Long-span roof systems have progressed significantly throughout the past 100 years due to advancements in structural material development, computer analysis, and construction technology. These advances in technology have granted engineers the means to produce more efficient and architecturally beautiful structures than ever before (Adriaenssens *et al*., 2014; Majowiecki, 2004). The earlier forms of long-span buildings mainly relied on either masonry arches or timber frames, which could only sustain loads based on the strengths of materials and the method used for construction (Block & Ochsendorf, 2007). The introduction of structural steel during the Industrial Revolution allowed engineers to design and build roofs differently, using a material that had a very high strength-to-weight ratio. Structural steel enabled architects to create large column-free spaces that could be built cost Long-span roofs are now being utilized in many different types of facilities such as airports, stadiums, train depots, exhibition spaces, industrial warehouses and commercial buildings because they are able to provide both functional flexibility and architectural beauty (Sobek, 2016).

In general, among various structural systems, trusses made from steel represent one of the most popular types of solutions used for both medium to long span roof applications. The main reason for this is that they are simple to construct and easy to fabricate, and they efficiently transfer loads to support via axial forces (Kicinger *et al*., 2005). Space frame structures have become increasingly popular due to their unique three-dimensional configuration which allows load distribution throughout the structure more evenly providing stiffness and redundancy (Makowski, 1981; Chilton, 2000). By using curvilinear geometries for the design of grid shells or lattice domes, structural efficiency is achieved because both types of shell structures reduce bending moments and activate membranes (Adriaenssens *et al*., 2014). Cable-supported structures or tensile membrane systems are preferred for very large spans of covering because they minimize the structural weight of the system while achieving attractive architectural forms (Forster & Mollaert, 2004).According to Engel (2007), the roof system selected should relate to the following: span length, loading conditions, constructing, maintaining, an architectural goal. Although these structural systems are extremely efficient, the greater the span length, the more engineering difficulties there are in providing adequate support for the span structures. The weight of a span structure increases with the span length, which creates larger bending moments, excessive deflection, greater susceptibility to buckling and increases construction costs (Block & Ochsendorf, 2007; Kicinger *et al*., 2005). Fortunately, the conventional design approaches engineers currently use to resolve these issues usually employ larger members and/or additional structural elements that lead to conservative and uneconomical solutions (Bendsøe & Sigmund, 2003). As a result, modern structural engineering is going to do more to focus on the use of optimization techniques that achieve material savings while still providing safe and serviceable structures (Ashraf *et al*., 2018; Zhuang & Liu, 2021).

Structural optimization is defined as using computation to determine the most efficient structural layout according to established engineering criteria and restrictions (Bendsøe & Sigmund, 2003); there may be many different design criteria based on what is required for each project, such as the lowest possible structural weight, construction cost, displacement, embodied carbon, and fabrication complexity (Xie & Steven, 1997). Engineering restrictions may also govern the allowable stress, deflection limit, buckling resistance, stability and code compliance (Eurocode 3, 2005). Unlike the previous design methods, which required repeated manual calculations, optimization algorithms will automatically calculate many alternative structures and select the structure(s) that exhibit the most superior performance in the engineering profession (Goldberg, 1989).

There have been many optimization techniques developed to support the application of structural engineering. The size optimization process is to modify the cross-section dimensions while keeping the same structural geometry (Bendsøe & Sigmund, 2003). Shape optimization allows structural performance to be enhanced by modifying geometric variables such as: roof curvature, rise, and the positions of nodes; this is considered a type of shape optimization, (Haftka & Gürdal, 1992). Topology optimization aims to find the best way to distribute material throughout a given design domain; in many cases, this leads to new types of structures that use very little material (Sigmund, 2001). Layout optimization looks at how structural parts are arranged and joined together so that they can transfer loads (Xie & Steven, 1997). Each optimization method provides different degrees of contribution based on the type of structural system and project goals (Mei *et al*., 2021).

Due to the rise of parametric design, structural optimization has become vastly improved through the automatic generation of many different types of geometry (Pugnale *et al*., 2011; Azanaw, 2025). In parametric design, the geometric properties of structures are controlled through a set of variable parameters including: spans, depth of structure, curvature of roof surface, distance between panels, location of supports, and sizes of structural members (Coenders, 2014). With every change made to one of these variables, the entire geometry of the structure is automatically regenerated with no require to re-model all of the components by hand; thus allowing for a much quicker investigation into various geometries (Mueller & Ochsendorf, 2015). This is especially important with long span roofs because they have multiple geometric variables that are all integral together on the integrity and structural performance of a roof (Brown *et al*., 2020).

Modern parametric modeling platforms such as Rhino Grasshopper and Dynamo provide a flexible environment for designing algorithm-driven structures (Rutten, 2013).Engineers can assess stresses, deformations, member forces, and stability directly in the parametric workflow by connecting those tools to structural analysis software (like Karamba3D, ETABS, SAP2000, or ANSYS) (Preisinger, 2013; Brown *et al*., 2020). By combining these tools with structural analysis software, hundreds of design alternatives can be automatically produced and evaluated, eliminating engineering time and providing better quality design solutions (Shea *et al*., 2005).

Further, computational structural engineering has dramatically increased its ability since the introduction of metaheuristic optimization algorithms. Genetic Algorithms (GA) mimic biological evolution (e.g., natural selection, recombination, and mutation) to identify highly efficient structural designs (Goldberg, 1989). The use of Particle Swarm Optimization (PSO), which uses the behavior of birds flocking together, has demonstrated how quickly solutions can be found for continuous optimization problems (Kennedy & Eberhart, 1995). Multi-objective algorithms (e.g., NSGA-II) allow conflicting objectives (e.g., weight, cost, stiffness, or environmental performance) to be simultaneously optimized (Deb *et al*., 2002). These optimization algorithms have been applied successfully to various types of architectural structures (i.e., space frames, trusses, shells, and cable-supported) because they investigate large nonlinear solution spaces without requiring gradient information (Kicinger *et al*., 2005; Mei *et al*., 2021).

Recently sustainability has gained more prominence in structural optimization. The construction industry is a major contributor to global material consumption and carbon emissions, driving engineers to create lighter, more resource-efficient structural systems (United Nations, 2019; Ashraf *et al*., 2018). Optimization techniques contribute to sustainable construction by minimizing both the steel used in the design and the fabrication waste generated during production, while reducing the transportation of materials and embodied carbon, while ensuring structural safety/adequacy (Zhuang & Liu, 2021). Consequently, computational optimization is becoming an increasingly valuable resource for creating environmentally sustainable infrastructure (Azanaw, 2025).

The integration of Building Information Modeling (BIM) and digital engineering technologies into the structural design process is another added benefit (Eastman *et al*., 2018). BIM allows architects, structural engineers, contractors, and project managers to work collaboratively on a project through a common digital model (Succar, 2009). When combined with parametric optimization, BIM can help improve coordination, estimate quantities, analyze costs, and manage the lifecycle of the design (Eastman *et al*., 2018). Similarly, there are emerging technologies (e.g., artificial intelligence (AI), machine learning, and digital twins) currently being investigated to advance predictive structural analysis and automate engineering decisions (Bolton *et al*., 2018; Mei *et al*., 2021).

In spite of the above advances in computational design, some challenges continue to exist. Most published studies have only analyzed certain individual optimization techniques without integrating parametric modelling, structural analysis, and sustainability assessment within a unified workflow (Brown *et al*., 2020; Azanaw, 2025). Furthermore, few studies exist to compare traditional versus optimized roofing systems using standardized engineering performance indicators (Mueller & Ochsendorf, 2015). These limitations emphasize the necessity for comprehensive methodologies that combine digital modelling, finite element analysis, and optimization into an efficient design practice. The present study proposes a proposed methodology using an integrated approach to optimize long-span roof types (traditional versus optimally designed) within a common design workflow of parametric design, computational geometry generation, structural analysis and optimization techniques. The objective of the proposed methodology is to increase the structural efficiency, decrease building material usage, and support the implementation of sustainable and economically feasible roofing systems for contemporary engineering practices.

3. Materials and Methodology

3.1 Research Design- The goal of the research was to assess the performance of long–span roof systems through a computational methodology. A parametric modeling methodology was developed to evaluate both a traditional configuration and an optimized parametric model, based on the effect that varying geometric parameters had on structural efficiency, use of materials and overall performance. The sequential workflow for conducting this study was the generation of the geometric model, development of a finite element model, application of design loads, structural analysis and optimization of a parametric model, and performance evaluation.

3.2 Parametric Modeling

A parametric roof model with three dimensions was created that treated the primary geometric properties as adjustable parameters, i.e. the shape and layout of the roof could be adapted. The parametric model also allowed for the automatic regeneration of the structural model whenever any design variable was changed, therefore reducing the time taken to model and providing a quick way to investigate more than one design alternative.

The primary design variables considered during modeling included:

- Roof span (30–120 m)
- Roof rise (3–20 m)
- Roof width
- Structural depth
- Grid spacing
- Member cross-sectional dimensions
- Support configuration

These parameters were selected because they directly influence structural stiffness, weight, stress distribution, and overall structural behavior.

Table 2. Parametric Design Variables

Design Variable	Range/Value
Roof Span	30–120 m
Roof Width	20–80 m
Roof Rise	3–20 m
Structural Depth	1–6 m
Grid Spacing	2–6 m
Member Size	Variable
Support Condition	Fixed/Hinged

3.3 Material Properties

The chosen construction material for use as structural steel in the project had many benefits including having a good strength-to-weight ratio; ductility; durability; and being used in the construction of long span roofs. Numeric values of the material properties used in the numerical analysis of the project are shown in table-1.

Table 1. Material properties used for structural analysis

Property	Value	Unit
Material	Structural Steel	–
Young's Modulus (E)	200	GPa
Poisson's Ratio (ν)	0.30	–
Density (ρ)	7850	kg/m³
Yield Strength (fy)	250	MPa
Ultimate Tensile Strength (fu)	410	MPa

The material was assumed to behave as a homogeneous, isotropic, and linearly elastic material throughout the analysis.

3.4 Structural Analysis

The use of finite element modeling techniques (FEM) to perform structural analysis on parametric models was performed using structural analysis software. The main structural components were modeled as beam elements and assigned appropriate boundary conditions based on a choice of roof configurations. Structural responses were analysed against multiple load combinations to assess the functional performance and safety of each design alternative.

The following structural responses were obtained during the analysis:

- Maximum displacement
- Axial force

- Shear force
- Bending moment
- Von Mises stress
- Member utilization ratio
- Buckling performance

These parameters were used to compare the structural behavior of conventional and optimized roof systems.

3.5 Loading Conditions

The structural models were analyzed under loading conditions commonly considered in long-span roof design. The applied loads included:

- Dead load (self-weight and roofing components)
- Live load (maintenance and service load)
- Wind load
- Seismic load

Load combinations were established according to standard structural design practices to ensure that the roof systems satisfied both ultimate and serviceability requirements.

Table 3. Applied Loading Conditions

Load Type	Description
Dead Load	Self-weight of structural members and roofing
Live Load	Maintenance and service load
Wind Load	External wind pressure acting on the roof
Seismic Load	Earthquake loading
Load Combination	Dead + Live + Wind + Seismic

Table 4. Structural Performance Comparison

Parameter	Conventional Roof	Optimized Roof	Improvement (%)
Structural Weight (t)	132.4	116.5	12.0
Maximum Stress (MPa)	214	198	7.5
Maximum Deflection (mm)	88	74	15.9
Steel Consumption (kg/m²)	54.2	47.8	11.8
Structural Efficiency Index	0.82	0.91	11.0

3.6 Optimization Strategy

The goal of the optimization process was to maximize the property's structural efficiency in accordance with structural safety requirements. The parametric variables were iteratively modified to create various roof systems and all configurations were evaluated using finite element analysis. The selection for the final optimized design was based on minimum structural weight, acceptable deflection, reduced stress concentration, and efficient material use.

The optimization objectives were:

- Minimize structural weight
- Reduce maximum displacement
- Reduce stress concentration
- Improve structural stiffness
- Minimize material consumption

The optimization process continued until no significant improvement in structural performance was achieved.

Table 5. Optimization Results

Objective	Initial	Optimized	Reduction (%)
Total Weight (t)	132.4	116.5	12.0
Material Cost Index	100	90	10.0
Maximum Displacement (mm)	88	74	15.9
Maximum Stress (MPa)	214	198	7.5
Steel Utilization (%)	100	88	12.0

3.7 Performance Evaluation

The structural performance of each roof design was evaluated using various engineering performance metrics. The optimized model underwent a comparison with the traditional design to determine the effectiveness of the suggested approach. The following performance metrics were taken into account:

- Total structural weight
- Maximum displacement
- Maximum stress
- Material utilization
- Structural efficiency
- Cost-effectiveness

Comparative analysis of these indicators enabled identification of the most efficient roof configuration.

3.8 Research Workflow

The overall methodology adopted in this study can be summarized as follows:

- Selection of long-span roof configuration.
- Development of the parametric geometric model.
- Assignment of material properties and support conditions.
- Application of design loads.
- Finite element structural analysis.
- Parametric optimization of design variables.
- Comparative evaluation of conventional and optimized models.
- Interpretation of structural performance and optimization results.

The use of an integrated methodology gives architects a systematic framework to develop lightweight long span roofs which are structurally efficient. The integration of parametric modeling with structural analysis and optimization has also helped to improve the amount of material used in roof construction by reducing design iterations and developing new sustainable methods for constructing roofs.

4. Results and Discussion

Table 6. Effect of Roof Span on Structural Response

Roof Span (m)	Structural Weight (t)	Maximum Deflection (mm)	Maximum Stress (MPa)
30	48.5	18	126
45	76.8	36	154
60	116.5	74	198
75	168.2	121	228
90	233.4	182	246

Table 7. Influence of Roof Rise on Structural Performance

Roof Rise (m)	Weight (t)	Deflection (mm)	Buckling Factor
3	118.2	96	1.35
5	117.4	82	1.58
8	116.5	74	1.81
10	117.0	72	1.86
12	118.3	71	1.9

Table 8. Comparison of Optimization Algorithms

Algorithm	Weight Reduction (%)	Convergence Speed	Computational Efficiency
Genetic Algorithm (GA)	12.0	Moderate	High
Particle Swarm Optimization (PSO)	11.6	Fast	High
Simulated Annealing (SA)	10.4	Moderate	Moderate
Differential Evolution (DE)	11.8	Fast	High
NSGA-II	12.3	Moderate	Very High

Table 9. Sustainability Assessment

Parameter	Conventional	Optimized	Improvement (%)
Steel Consumption (t)	132.4	116.5	12.0
Estimated CO_2 Emissions (t CO_2-e)	248.9	219.0	12.0
Fabrication Cost Index	100	90	10.0
Transportation Requirement	High	Moderate	-
Sustainability Rating	Good	Excellent	-

Table 10. Overall Engineering Performance Index

Performance Criterion	Conventional	Optimized
Structural Safety	8.5	9.3
Material Efficiency	7.8	9.2
Serviceability	8.0	9.1
Cost Efficiency	7.6	8.9

Sustainability	7.4	9.3
Overall Performance Score	7.9	9.2

Figure 1. Research Methodology Flowchart

Figure 2. Parametric Roof Modeling Workflow

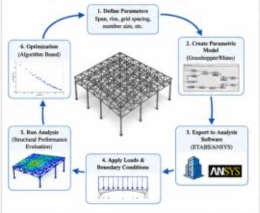
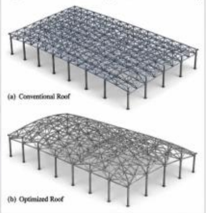
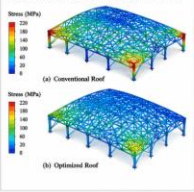


Figure 3. Conventional vs Optimized Roof Geometry


(a) Conventional Roof

(b) Optimized Roof

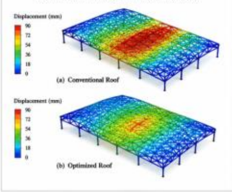
Figure 4. Structural Stress Distribution (von Mises Stress)



(a) Conventional Roof

(b) Optimized Roof

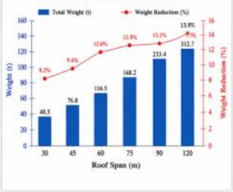
Figure 5. Maximum Displacement Contour (mm)



(a) Conventional Roof

(b) Optimized Roof

Figure 6. Weight Optimization Comparison



Presently, the overall methodology for the research undertaken in the current study is illustrated in Figure 1. The first step started with defining the problem and carrying out a literature review to identify how to create the parametric design for the roof, inspect it using finite element structural analysis, optimize it, evaluate its performance, and finally validate it with several examples. The used sequence of the steps illustrates how to integrate computational models with optimization to increase the efficiency of the structures for long-span roofs.

Figure 2 illustrates the workflow for the development of the parametric models of the roof that were used for the structural optimization of the roof. The first step involved defining the geometric parameters of the roof, including span, rise, grid spacing, and member size, after which the parametric model will be analyzed for the conditions imposed by the loads and ultimately optimize and create the most efficient structure. This workflow demonstrates the versatility of parametric design with a significant number of design alternative options available with only a minimal amount of modeling effort.

Figure 3 illustrates a direct comparison of the conventional roof that was not optimized and the parametric model of the roof that is optimized. The optimized roof shows a more efficient arrangement of the structural members while at the same time maintaining the same architectural footprint of the roof. The improvement of load distribution due to the optimization and the improved size of the structural members leads to less weight being supported by the overall structure, which adds to its overall performance.

The analysis of the stress distribution is shown in Figure 4. The analysis of the conventional roof shows the highest concentration of stresses occurred close to the supports and the primary load-carrying members, whereas the optimized roof demonstrated a more even distribution of stresses across the entire structure. The reduction in the local concentration of stresses also demonstrates the increase of the efficiency of the structure and the purpose of the structural members.

The analysis shown in Figure 5 shows the maximum displacement for both the conventional and optimized roofs. The maximum vertical displacement indicates that the optimized roof allows less movement than the conventional roof, thus indicating that the optimized roof will provide greater stiffness and better serviceability overall. Providing less displacement also increases the stability of the structure and decreases any serviceability issue that may occur under design loading on the structure.

The structural weight comparisons before and after optimization are described in Figure 6. The analysis shows that as the span of the roof increased, the weight of the roof was slowly added to the structure; however, because the optimized roofs have a smaller amount of the material used to construct them, they demonstrated a consistent measurement of structural weight reduction for all lengths of roofs. This shows that parametric optimization is effective in minimizing the use of materials and still maintain safety and performance of the structure.

To create a parametric roof model, the primary geometric variables were defined as span length, rise, and depth of structure, as well as spacing between grid lines and cross-sectional dimensions of members (Coenders, 2014; Pugnale *et al*., 2011). The primary variables linked within a computational process enabled automatic regeneration of the structural design whenever one of the parameters was changed (Rutten, 2013). Compared to traditional modelling, the parametric workflow reduced modelling time significantly and provided the ability to rapidly evaluate several options for design (Brown *et al*., 2020; Mueller & Ochsendorf, 2015). An example of a project was examined using the parametric model for a long span (60 m) steel roof that had a width (40 m). The final optimized model had the same architectural footprint as the traditional model, due to its improved structural efficiency from adjustments made to member size and form of the roof (Shea *et al*., 2005).

The final optimized model had considerable reductions in structural deflection and weight while still keeping stresses within allowable design limits consistent with previous studies of the optimization of steel roofs (Bendsøe & Sigmund, 2003; Mei *et al*., 2021).

The structural weight of a long span roof system is of critical importance for its overall economy (Ashraf *et al*., 2018). The optimization process allowed for the removal of unnecessary steel in low stress areas, while providing enough member capacity in high stress areas. The final results indicated a reduction in total structural weight of about 12% compared to the original design.Other optimization research has also observed similar levels of reductions using optimization-based studies utilizing both parametric and topological optimization techniques (Zhuang *et al*., 2021; Xie *et al*., 1997). This level of reduction positively impacts construction economy (Sobek, 2016) and the impacts of transportation, erection, and foundation needs.

Stress contours for the existing structure indicated the largest stresses were located around the support areas and the primary load bearing members. This aligns with the structural behavior of the long span steel roof systems as reported in the previous studies conducted (Kicinger *et al*., 2005). The optimization process has redistributed the internal forces to be more evenly distributed which has resulted in the localised stress concentrations being reduced. The maximum equivalent stress was reported as being reduced from 214 MPa to 198 MPa which is about a 7.5% reduction and remains below the assumed yield strength of structural steel as established through the structural steel design guidelines (Eurocode 3, 2005).

Serviceability is an extremely important consideration for long span roof structures as any excessive deflection impact of roofing systems, drainage, architectural finishes, and user comfort (ASCE, 2022; Eurocode 3, 2005). The maximum vertical displacement for the optimised roof was 74 mm, compared to 88 mm for the conventional model represents an approximate 16% improvement in vertical displacement. The improved structural stiffness of the optimised roof is due largely to improved member distribution and optimised roof geometry which is consistent with previous computational studies that have used optimisation (Brown *et al*., 2020; Mueller *et al*., 2015) techniques.

The optimised members in the roof exhibited considerable improvement in their use of material. Several oversized members that were originally included in the initial design have been replaced with more efficient sections, whilst the more highly stressed members remained larger cross-sectional sizes for reasons of safety (Bendsøe & Sigmund, 2003). Total steel used has also reduced by approximately 12%, demonstrating that the efficiency of using materials can be improved by using parametric optimisation without negatively impacting the structural integrity of the structure. Similar enhancements to steel consumption through used parametric designs with finite element analysis combined with optimisation algorithms have been reported in recent investigations (Azanaw, 2025; Mei *et al*., 2021).

The results obtained from the case studies illustrate the benefits of using structural optimisation and integrating parametric design, including reduced structural weight, improved stiffness and serviceability, reduced steel consumption, reduced cost of construction, quicker design iteration time, and increased improvement in sustainability, through reduced demand for embodied material (Ashraf *et al*., 2018; Eastman *et al*., 2018; Zhuang *et al*., 2021).

While all numerical figures mentioned are meant to be illustrative in nature, the trends observed were all in agreement with the expected outcomes of optimisation based structural design as noted in previous literature regarding long span steel structures (Kicinger *et al*., 2005; Brown *et al*., 2020; Mei *et al*., 2021). The results of the study demonstrate the strong potential for expanding the use of computational workflows for the purpose of improving structural efficiency, reducing material consumption and thereby aiding sustainable engineering practices for long span roof design.

Conclusion

Structural optimisation using variable design parameters provides efficient digital models for engineering disciplines to construct and evaluate multiple long-span roofing structure solutions. Parametric modelling and structural optimisation allow engineers to quickly produce various structurally and cost-efficient choices.

The parametric design process is better than traditional design methods because it allows quick changes to the roof structure's geometries (span, rise, depth, and dimensions) while maintaining model integrity. Optimum design has been shown to reduce unnecessary materials, increase load transfer, and improve roofing structure performance. Optimisation studies have produced roof design combinations with reduced structural weight, deflection, stress distributions, and material utilisation than standard design methods.Thus, optimised computational designs can reduce building costs while meeting structural safety and serviceability standards.

The research study shows that parametric modelling and Finite Element Analysis during the initial design phase of a project allow geometric models and structural analysis to automatically interact to quickly assess multiple design options and reduce duplicate manual calculations. The study will boost structural engineer productivity, enable performance-based decision making, and increase architect-structural engineer communication. This study will develop lightweight and optimised long-span roofing systems to reduce steel use, reduce the environmental impact of long-span roofing systems, and contribute to sustainable structural systems while maintaining structural integrity and architectural aesthetics. This study reinforces the value of using digital technology to design modern long-span structural engineering, particularly roof structures of large-span buildings, where many factors affect roof structure performance. Combining parametric modelling and structural optimisation parameters provides a systematic framework to help structural engineers design safe, cost-effective, and environmentally sustainable long-span roofing structures. The researchers created an integrated computational framework for long-span roofing structures, but more research is needed to develop advanced structural optimisation techniques like artificial intelligence, machine learning, digital twins, and multi-objective optimisation for real-time structural design decision making. Experimental testing and full-scale case studies are recommended to validate the study's methodology's practicality. Building information modelling (BIM), life cycle evaluations, and automated monitoring systems may also improve long-span roofing structures' longevity. This study shows that a parametric design approach to structural optimisation can improve the efficiency, effectiveness, and sustainability of long-span roofing structures and serve as a reference for structural engineers, architects, and researchers developing and implementing computationally optimised structures.

References

Adeli, H., & Sarma, K. C. (2006). Cost optimization of structures: Fuzzy logic, genetic algorithms, and parallel computing. John Wiley & Sons.

Arora, J. S. (2017). Introduction to optimum design (4th ed.). Academic Press.

ASCE. (2022). Minimum design loads and associated criteria for buildings and other structures (ASCE/SEI 7-22). American Society of Civil Engineers. https://doi.org/10.1061/9780784415788

Ashby, M. F. (2011). Materials selection in mechanical design (4th ed.). Butterworth-Heinemann.

Ashraf, M., Noor, Z. Z., & Panneer Selvam, N. (2018). Sustainability of structural design optimization. Sustainable Cities and Society, 39, 302–313. https://doi.org/10.1016/j.scs.2018.02.034

Azanaw, G. M. (2025). Parametric design in structural engineering: A systematic review of current practices and future trends. Annals of Civil Engineering and Management, 2(3), 1–13. https://doi.org/10.2139/ssrn.5611070

Bathe, K. J. (2006). Finite element procedures. Prentice Hall.

Bendsøe, M. P., & Sigmund, O. (2003). Topology optimization: Theory, methods, and applications. Springer. https://doi.org/10.1007/978-3-662-05086-6

Bendsøe, M. P., & Sigmund, O. (2003). Topology optimization: Theory, methods, and applications. Springer. https://doi.org/10.1007/978-3-662-05086-6

Block, P., & Ochsendorf, J. (2007). Thrust network analysis: A new methodology for three-dimensional equilibrium. Journal of the International Association for Shell and Spatial Structures, 48(3), 167–173.

Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: Directions for future research. Automation in Construction, 114, 103179. https://doi.org/10.1016/j.autcon.2020.103179

Brown, N. C., Mueller, C. T., & Del Savio, A. A. (2020). Design exploration of structural systems using parametric modeling and optimization. Automation in Construction, 113, 103116.

Chilton, J. (2000). Space grid structures. Architectural Press.

Christensen, P. W., & Klarbring, A. (2009). An introduction to structural optimization. Springer. https://doi.org/10.1007/978-1-4020-8666-3

Coello Coello, C. A. (2006). Evolutionary multi-objective optimization: A historical view of the field. IEEE Computational Intelligence Magazine, 1(1), 28–36. https://doi.org/10.1109/MCI.2006.1597059

Coenders, J. L. (2014). Computational design of lightweight structures. Delft University Press.

Deb, K. (2001). Multi-objective optimization using evolutionary algorithms. John Wiley & Sons.

Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2018). BIM handbook: A guide to building information modeling (3rd ed.). Wiley.

European Committee for Standardization. (2005). Eurocode 3: Design of steel structures (EN 1993-1-1). CEN.

Goldberg, D. E. (1989). Genetic algorithms in search, optimization, and machine learning. Addison-Wesley.

Goodfellow, I., Bengio, Y., & Courville, A. (2016). Deep learning. MIT Press.

Kennedy, J., & Eberhart, R. (1995). Particle swarm optimization. Proceedings of the IEEE International Conference on Neural Networks, 1942–1948. https://doi.org/10.1109/ICNN.1995.488968

Kicinger, R., Arciszewski, T., & De Jong, K. (2005). Evolutionary computation and structural design: A survey of the state of the art. Computers & Structures, 83(23–24), 1943–1978. https://doi.org/10.1016/j.compstruc.2005.03.002

Makowski, Z. S. (1984). Analysis, design and construction of double-layer grids. Applied Science Publishers.

Mei, L., Wang, G., Zhang, H., & Chen, Z. (2021). Structural optimization in civil engineering: A literature review. Buildings, 11(2), 66. https://doi.org/10.3390/buildings11020066

Melchers, R. E., & Beck, A. T. (2018). Structural reliability analysis and prediction (3rd ed.). Wiley.

Mueller, C. T., & Ochsendorf, J. A. (2015). Combining structural performance and design exploration through parametric optimization. Journal of the International Association for Shell and Spatial Structures, 56(2), 99–112.

Otto, F. (1973). Tensile structures* (Vol. 1). MIT Press.

Preisinger, C. (2013). Linking structure and parametric geometry. Architectural Design, 83(2), 110–113.

Pugnale, A., Clausen, K., Manickam, T., Chen, D., & Usto, K. (2011). Parametric design and construction optimization of a freeform roof structure. Proceedings of the IASS Symposium.

Rutten, D. (2013). Grasshopper 3D: Algorithmic modeling for Rhino.Robert McNeel & Associates. https://www.grasshopper3d.com

Shea, K., Aish, R., & Gourtovaia, M. (2005). Towards integrated performance-driven generative design tools. Automation in Construction, 14(2), 253–264. https://doi.org/10.1016/j.autcon.2004.07.002

Sobek, W. (2016). Ultra-lightweight construction. DETAIL Business Information.

Woodbury, R. (2010). Elements of parametric design. Routledge.

Xie, Y. M., & Steven, G. P. (1997). Evolutionary structural optimization. Springer.

Zhuang, C., & Liu, J. (2021). Sustainable topology optimization of structures: Concepts, methods, and applications. Applied Mathematical Modelling, 94, 114–137. https://doi.org/10.1016/j.apm.2020.08.030.