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Article

Application of biomechanics in construction engineering management: Exploration of improving economic efficiency and sustainability

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Abstract: This article explores the use of biomechanical principles in construction project management to enhance building sustainability and economic benefits. By incorporating biomechanical adaptability and real-time scheduling, architectural design and operation are optimized. The framework uses dynamic simulations and optimization algorithms to improve performance across building stages, maximizing resource conservation and economic gains. The algorithm optimizes building structure performance under external loads like wind, earthquakes, and temperature changes. Experimental results show significant energy efficiency improvements (e.g., 11.54% for temperature changes) and material savings (up to 10% for public buildings). This study offers an intelligent optimization solution, advancing the construction industry towards sustainability through biomechanical models and optimization algorithms.

Keywords: biomechanics; construction engineering management; optimization algorithms; finite element analysis; building material suitability; energy efficiency; structural stability; material conservation

1. Introduction

As construction projects continue to expand, improving the economic benefits and sustainability of building design and construction has become a critical issue in modern project management. In recent years, biomechanics, the study of motion and mechanical properties of living organisms, has gained attention in the field of construction engineering. MAM [1] believed that biomechanics can provide efficient and environmentally friendly optimization solutions for building design through comprehensive analysis of building structure and material properties, and improve sustainability and economic benefits. By utilizing biomechanical models and algorithms, construction project management can achieve more precise planning and execution, ensuring optimal project outcomes under both economic and environmental constraints [2].

In architectural design, biomechanics provides innovative approaches to building safety and functionality. For example, researched that understanding human biomechanics can help design more ergonomic escape routes, improving safety, especially in emergencies [3]. Additionally, LK argued that with the increasing attention to sustainable building materials, biomechanics influence material design and promote the development of innovative materials, such as self-monitoring bionomanometers, which improve energy efficiency while reducing environmental impact [4].

This paper explores the potential of biomechanics in construction project management, analyzing its value in improving economic efficiency and sustainability. CH and LV [5] showed how biomechanical principles can be applied to real construction projects through specific case studies. For instance, SJW, IN and VB [6,7] by integrating biomimetic design concepts, architecture can adopt nature-inspired structural optimization strategies to maximize resource utilization and minimize environmental impact. Through these innovative design approaches, biomechanics offers new perspectives and practical solutions for the sustainable development of building engineering [8].

2. Related work

2.1. Integrated development of biomechanics and construction engineering management

The integration of biomechanics into construction engineering management enhances various aspects of building design and operation. That biomechanical principles help optimize building structures to better adapt to the natural environment and external loads [9]. By using biomechanical simulations, architects can assess structural stability and improve energy efficiency and comfort [10,11].

Some scholars argued that biomechanical simulation also provides dynamic adjustments for construction management, and tools such as smart sensors and wearables can monitor biomechanical loads in real time. This helps to adjust work schedules and reduce labor risks [12,13]. The project uses biomechanical models for structural optimization to improve building stability, comfort and energy efficiency [14]. Some people believes that bioclimatic analysis is the key to passive building design optimization in the European Union [15].

Some scholars are believed that biomechanics also extends to the construction phase, especially the risk assessment of workers. Smart insoles and computer vision technology help monitor workloads and predict health risks, improving worker safety and process efficiency [16,17].

In conclusion, biomechanics expands the boundaries of construction management, improving building efficiency, sustainability, and safety. By combining biomechanical principles with structural design, load assessment, and intelligent technologies, the construction industry can create safer, more efficient, and environmentally adaptive building [18].

2.2. Existing optimization models and methods for construction projects

With the continuous development of construction technology, optimization methods for construction projects have become more diverse [19]. Traditional methods, such as finite element method (FEM), considered essential for structural design and construction by breaking down buildings into smaller units to assess their response under load [20]. However, FEM mainly focuses on static conditions, overlooking the dynamic effects that buildings face over time, such as earthquakes, wind, and temperature changes [21].

Recently, LX's machine learning-based predictive models have become a key direction in construction optimization [21]. These models analyze big data to predict performance changes under different conditions, offering valuable insights for energy efficiency, material selection, and construction progress [22]. While effective for short-term optimization, neglect long-term dynamic challenges, such as material degradation and environmental changes [23]. Buildings need to maintain dynamic adaptability throughout their lifecycle, accounting for issues like aging materials and fluctuating energy efficiency [24].

Biomechanics introduces dynamic adaptability to building optimization [24]. By studying how biological systems respond to environmental changes, biomechanics has improved structural design, seismic resistance, wind resistance, and energy conservation [25]. Research suggests buildings should possess dynamic adaptability like living organisms, adjusting their structure and function to enhance stability and energy efficiency [26]. Gait analysis systems have also helped study dynamic load distribution and propose methods for measuring building performance [27].

Intelligent building design has shown significant potential in improving energy efficiency. Using eco-friendly materials, energy-saving technologies, and intelligent systems can reduce energy consumption and enhance comfort [27]. Integrating technologies like biomechanics and IoT can create adaptive energy management systems [28].

Overall, existing optimization methods still face challenges, particularly in addressing dynamic adaptability during long-term use. Future research should focus on integrating biomechanics, machine learning, and intelligent control to achieve sustainable, dynamic optimization for buildings [29].

2.3. Research content and innovation of this article

This study proposes a new framework for optimizing construction engineering based on principles of biomechanics, aiming to address the issues of insufficient static optimization and dynamic adaptability in current architectural design and management. The concept of biomechanical adaptability originated from how organisms in nature respond to external environmental changes and adjust their own structures to improve survival adaptability. By introducing this concept into construction engineering, this article proposes a multi-objective optimization method through in-depth analysis of the biomechanical compatibility between building materials and structures, combined with factors such as dynamic loads and environmental changes that buildings may face in actual use [30,31]. This method not only focuses on improving the efficiency of buildings in the initial design and construction stages, but also further considers the long-term sustainability and economic benefits throughout the building's lifecycle. The core idea of this study is to promote the adaptive capability of architectural design and operation by introducing biomechanical adaptability and real-time scheduling management. This innovative framework can combine dynamic simulation and optimization algorithms to perform real-time scheduling and performance optimization of various stages of buildings, in order to achieve the goal of maximizing economic benefits and resource conservation. The innovation of this article is mainly reflected in the following three aspects:

1) The combination of biomechanical adaptability and building structure: This article is the first to apply the principle of biomechanical adaptability to the optimization of building engineering, proposing that buildings should have a dynamic adaptation mechanism similar to that of living organisms. This method not only focuses on the static optimization of building materials and structures, but also considers how they can dynamically adjust according to external environmental changes (such as temperature, humidity, earthquake, and wind loads) during actual use to maintain the stability, energy efficiency, and service life of the building.
2) The proposal of multi-objective optimization methods: Traditional construction engineering optimization methods often focus on a single objective, such as the selection of building materials, cost control, or energy efficiency optimization. However, the goals involved in architectural design and management are often multidimensional, including multiple aspects such as economy, energy efficiency, structural safety, comfort, and environmental adaptability. The multi-objective optimization method proposed in this article can simultaneously consider the mutual influence of these complex objectives, and find the optimal balance point between each objective through optimization algorithms, providing more comprehensive and scientific decision support for architectural design [32].
3) The combination of real-time scheduling and dynamic optimization framework: In the operational phase of buildings, traditional building management often relies on fixed design parameters and predetermined operating modes, lacking real-time response mechanisms to environmental changes. The article proposes to combine biomechanical adaptability with real-time scheduling in construction project management to form a dynamic optimization framework [33]. By introducing Internet of Things (IoT) technology, sensors, and intelligent control systems, this paper constructs a dynamic optimization system based on real-time data feedback, which enables buildings to monitor external environment and internal demand changes in real time, automatically adjust energy consumption, load distribution, and equipment usage strategies during operation, and improve the sustainability and economic benefits of buildings.

3. Biomechanics model and algorithm design

3.1. Analysis of the compatibility between biomechanical principles and building materials

The principles of biomechanics emphasize the elasticity of materials and the adaptability of structures, which can provide important scientific basis for material selection and configuration in construction engineering. The bones and tissues of living organisms can automatically adjust their morphology and physical properties according to changes in external loads, thereby maintaining optimal mechanical performance in dynamic environments. Similarly, the adaptability of the mechanical behavior of building materials to different external loads determines the stability and durability of the structure. Therefore, in construction projects, the selection of materials must be matched with the structural load, environmental conditions, and usage requirements to achieve optimal mechanical performance and economic benefits [34–36].

Firstly, the elastic properties of building materials can be described by their stress-strain relationship. The mathematical model of stress-strain relationship is commonly represented by constitutive equation. Assuming that the stress and strain relationship of a material can be represented by a linear elastic model, the basic formula is:

$$\sigma = E \cdot \varepsilon \tag{1}$$

Among them, (β) is stress, (E) is the elastic modulus of the material, and (ε) is strain. For different materials, the elastic modulus (E) is one of their key mechanical properties, which determines the deformation ability of the material under stress. Through the principles of biomechanics, the selection of materials can be based on their elastic modulus matching the requirements of the building structure, in order to achieve a rational design of the building structure [37].

Secondly, considering the plastic behavior of materials, building materials often undergo elastic and plastic stages under external forces. In the plastic stage, the stress-strain relationship of the material is no longer linear, but rather has a yield point and enters an irreversible deformation state. To describe this process, widely used plastic constitutive models can be used. For example, using a bilinear model to represent the yield characteristics of materials:

$$\sigma = E \cdot \varepsilon, \varepsilon < \varepsilon_y \tag{2}$$

$$\sigma = \sigma_y + H \cdot (\varepsilon - \varepsilon_y), \varepsilon \geq \varepsilon_y \tag{3}$$

Among them, (σ_y) is the yield stress, $(H)(\varepsilon_y)$ is the yield strain, is the hardening modulus, and (ε) is the strain.

In the selection process of building materials, it is also necessary to consider the fatigue performance of the materials, that is, the durability of the materials under long-term repeated loads. The fatigue theory in biomechanics can help us predict the failure behavior of materials under cyclic loading. One of the common fatigue life prediction models is based on Miner's linear cumulative damage theory:

$$D = \sum_{i=1}^{n} \frac{N_i}{N_{f,i}} \leq 1 \tag{4}$$

Among them, (D) is the damage index, which (N_i) is the (i) actual number of cycles $(N_{f,i})$ of the material under the th load, and is the fatigue life of the material under that load. Through this model, it is possible to evaluate the durability and safety of different building materials in long-term use.

In addition, the thermal expansion coefficient of materials is also crucial for the adaptability of building materials, especially in environments with large temperature changes. The thermal expansion effect may cause deformation or cracking of buildings, affecting their stability. The formula for thermal expansion is:

$$\Delta L = \alpha L_0 \Delta T \quad (5)$$

Among them, (ΔL) is the length change of the material, (α) is the coefficient of thermal expansion, (L_0) is the original length of the material, and (ΔT) is the temperature change. By analyzing the thermal expansion coefficient of materials, it is possible to predict the deformation behavior of building materials and their impact on structural performance under extreme weather conditions.

Through the analysis of the above biomechanical principles, we can comprehensively evaluate the mechanical adaptability of different building materials and select the material combination with the best performance and strong adaptability. The reasonable configuration of these materials not only helps to improve the structural performance of buildings, but also reduces their energy consumption, improves their service life, and provides strong support for the economic benefits and sustainability of construction projects.

3.2. Building structural performance and biomechanical simulation

The structural performance of buildings is a crucial aspect of architectural design, which is not only closely related to the mechanical properties of the building materials used, but also influenced by the overall structural form of the building. With the increasing complexity of construction projects and the increasing demand for sustainability, using biomechanical simulation to accurately predict the structural performance of buildings has become an important means of optimizing design, improving economic benefits, and extending the service life of buildings. Biomechanics simulation, with the help of advanced mathematical models, especially finite element analysis, can provide more accurate analysis of structural deformation, stress distribution, and material response, thereby helping designers make more scientific decisions [38,39].

One of the core principles of biomechanical simulation is to compare building structures to skeletal systems similar to living organisms, where each part of the structure can be adjusted in a timely manner according to changes in external loads to ensure optimal mechanical performance. This principle is not only reflected in the selection of materials, but also in the design of structural forms and load distribution. In the stress analysis of buildings, it is necessary to first consider the types of loads on the building, such as static loads, dynamic loads, wind loads, seismic loads, etc. Then, through finite element analysis methods, the structural deformation and stress under these loads can be accurately simulated [40–42].

For complex building structures, traditional manual calculation methods are no longer sufficient to meet design requirements. Therefore, using finite element analysis software combined with biomechanical simulation methods can introduce more practical factors into the simulation, such as stress concentration in different parts, nonlinear characteristics of materials, and the influence of temperature changes on structural performance. The basic principle of finite element analysis is to divide a complex structure into several small elements, calculate the mechanical behavior of each small element, and ultimately synthesize the mechanical response of the entire structure. The basic formula is:

$$K \cdot u = F \tag{6}$$

Among them, (K) is the stiffness matrix, (u) is the displacement vector, and (F) is the external force vector. By solving this equation, the displacement and stress distribution of the structure under different loads can be obtained.

In order to further simulate the dynamic response of buildings under complex load conditions, biomechanical simulations often need to consider the nonlinear behavior of materials. For example, using constitutive relationships to describe the nonlinear stress-strain relationship of materials:

$$\sigma = E \cdot \varepsilon, \varepsilon < \varepsilon_y \tag{7}$$

$$\sigma = \sigma_y + H \cdot (\varepsilon - \varepsilon_y), \varepsilon \geq \varepsilon_y \tag{8}$$

Among them, (σ) is stress, (ε) is strain, (σ_y) is yield stress, (ε_y) is yield strain, and (H) is hardening modulus. By simulating the deformation behavior of materials after yielding, the failure mode and ultimate bearing capacity of building structures can be more accurately predicted.

In addition, the fatigue behavior of materials is also an important factor that cannot be ignored in the biomechanical simulation of building structures, especially for structures that are subjected to cyclic loads for a long time. To consider the impact of fatigue damage, Miner's linear cumulative damage theory is commonly used to predict the fatigue life of materials:

$$D = \sum_{i=1}^{n} \frac{N_i}{N_{f,i}} \leq 1 \tag{9}$$

Among them, (D) is the damage index, (N_i) is the (i) actual number of cycles of the material under the th load, and $(N_{f,i})$ is the fatigue life of the material under that load. Through fatigue analysis, potential fatigue cracks in the structure can be foreseen in advance, and corresponding reinforcement or maintenance measures can be taken to ensure the long-term safety of the building structure [43].

In practical applications, biomechanical simulation also involves the influence of environmental factors such as temperature and humidity on building materials. For example, temperature changes may cause thermal expansion or contraction of buildings, thereby affecting the stability of the structure. The thermal expansion coefficient of building materials is calculated using the following formula:

$$\Delta L = \alpha L_0 \Delta T \tag{10}$$

Among them, (ΔL) is the length change, $(\Delta T)(\alpha)$ is the thermal expansion coefficient of the material, (L_0) is the original length, and is the temperature change. By simulating these environmental factors, it is possible to more comprehensively predict the performance of building structures in actual use.

In summary, biomechanical simulation provides a scientific basis for optimizing the performance of building structures. By combining finite element analysis with biomechanical principles, it is possible to effectively predict the performance of building structures under complex loads and environmental changes, helping designers reduce energy consumption and extend service life while ensuring building safety, thus playing an important role in improving economic efficiency and sustainability.

3.3. Optimization algorithm design and implementation driven by biomechanics

In order to maximize the economic benefits and improve the sustainability of construction projects, this study proposes a biomechanical driven optimization algorithm. This algorithm draws on the principle of adaptive adjustment of living organisms in dynamic environments, combined with constraints in construction engineering, and aims to achieve dynamic optimization of building structures under various uncertain factors. Through this method, the design of buildings can be adjusted according to real-time usage needs and environmental conditions, effectively optimizing resource allocation, reducing energy consumption, and enhancing the long-term sustainability of buildings.

The adaptive ability of organisms often relies on sensing and responding to changes in the external environment. For example, organisms adjust the distribution of their bones and muscles to adapt to new load states when faced with external pressure. With the help of this principle, optimization algorithms can not only consider the mechanical properties of the building structure itself, but also combine external factors such as climate change, load fluctuations, etc. to achieve self-adjustment of the structure. During this process, the response of the building structure can be accurately simulated through finite element analysis, and the algorithm will continuously optimize the allocation of structural form and materials.

To achieve dynamic optimization of the structure, it is necessary to first construct the objective function of the building structure, which usually includes energy consumption, building material usage, and structural stability. Assuming the optimization objective is to minimize the total energy consumption of the building while ensuring its load-bearing capacity and functional use, the objective function can be expressed as:

$$f(x) = \alpha \cdot E_{\text{total}}(x) + \beta \cdot M_{\text{total}}(x) - \gamma \cdot S_{\text{struct}}(x) \tag{11}$$

Among them, $(E_{total}(x))$ represents the total energy consumption of the building, $(M_{total}(x))$ represents the total material usage, $(S_{struct}(x))$ represents the structural stability index, $(x)(\gamma)$ represents the weight coefficients, and represents the design variable vector.

In order to enable building structures to adapt to changing external environments, it is necessary to introduce the principle of adaptive control in biomechanics. For example, if a building structure is (F_{wind}) affected by wind loads at a certain moment, the response of the structure can be described by the following equation:

$$K(t) \cdot u(t) = F_{\text{wind}}(t) \tag{12}$$

Among them, $(K(t))$ is the (t) stiffness matrix at time, $(u(t))$ is the (t) displacement vector of the structure at time, and $(F_{\text{wind}}(t))$ is the (t) influence of wind load at time.

As the load changes, the response of the building structure also needs to be adjusted in real time. In the optimization algorithm, nonlinear programming methods are used to continuously adjust the stiffness matrix of the structure to adapt to different load conditions. Assuming that the stiffness matrix of the building structure is time-dependent and adapts to changes in load, the optimization problem can be expressed through the following nonlinear constraint conditions:

$$K(t) = K_0 \cdot (1 + \alpha_1 \cdot \Delta\varepsilon(t)) \quad (13)$$

Among them, (K_0) is the initial stiffness matrix, ($\Delta\varepsilon(t)$) is the strain (t) change of the structure at time, and (α_1) is the adjustment factor.

In practical applications, building structures will bear periodic loads over a long period of time, and the fatigue damage caused by these loads on materials needs to be taken into account for optimization. Based on the theory of cumulative damage in mines, the accumulation of fatigue damage can be expressed as:

$$D(t) = \sum_{i=1}^{n} \frac{N_i(t)}{N_{f,i}} \leq 1 \quad (14)$$

Among them, ($D(t)$) is the (t) fatigue damage index at time, ($N_i(t)$) is the (i) actual number of cycles of the material under the th load, and ($N_{f,i}$) is the fatigue life of the material under that load. Through this damage model, the fatigue behavior of the structure during long-term use can be accurately predicted, providing long-term optimization solutions for design.

In addition, as the performance of buildings in different environments requires consideration of factors such as temperature and humidity, biomechanical driven optimization algorithms also consider environmental changes as one of the key constraints. Taking the influence of temperature changes on structures as an example, the thermal expansion coefficient of materials can be calculated using the following formula:

$$\Delta L = \alpha L_0 \Delta T \quad (15)$$

Among them, (ΔL) is the length change caused by temperature, (α) is the thermal expansion coefficient of the material, (L_0) is the original length, and (ΔT) is the temperature change.

In summary, optimization algorithms based on biomechanics can achieve adaptive optimization of building structures under complex and changing environmental conditions by continuously adjusting the stiffness, material configuration, and energy consumption control of the building structure, thereby improving the economic benefits and sustainability of construction projects. This algorithm can not only consider the nonlinear behavior and fatigue damage of materials, but also respond in real-time to external changes such as temperature and load, providing scientific decision support for building design.

4. Experimental simulation and result analysis

4.1. Experimental simulation platform and model construction

In construction project management, the application of biomechanics can greatly enhance the economic benefits and sustainability of building structures. To achieve this goal, this study designed and built an experimental simulation platform based on modern computer simulation technology and biomechanical models. This platform integrates complex principles of physics, mechanics, and biology to accurately simulate the dynamic behavior of building structures under different external environments and internal usage conditions, and test the effectiveness of different optimization strategies [44].

Firstly, the platform relies on sophisticated mechanical models to describe the response of building structures. These models consider the nonlinear behavior of building materials, the adaptability of structures, and the impact of external environmental factors such as climate change and load fluctuations on buildings. The structure of buildings exhibits an adaptive response similar to that of living organisms to external pressure under external loads. For example, when a building structure is subjected to wind loads or earthquakes, the deformation of materials and the redistribution of the structure can be simulated and optimized through biomechanical principles. To achieve this, the platform combines finite element analysis (FEA) with adaptive control theory in biomechanics, which not only accurately simulates the mechanical behavior of buildings, but also adjusts the structural form in real time to adapt to external changes and internal demands [45].

The core of the platform is to describe the mechanical response and environmental adaptability of buildings by establishing multidimensional mathematical models. Assuming we want to optimize the energy efficiency and stability of a building structure under different external loads, the objective function can be expressed as:

$$f(x) = \alpha \cdot E_{\text{total}}(x) + \beta \cdot M_{\text{total}}(x) - \gamma \cdot S_{\text{struct}}(x) \tag{16}$$

Among them, $(E_{\text{total}}(x))$ represents the total energy consumption of the building, represents the $(M_{\text{total}}(x))$ total material usage, $(\gamma)(S_{\text{struct}}(x))$ represents the stability index of the structure, represents the weight coefficients, and (x) represents the design variable vector. This objective function comprehensively considers multiple key factors in architectural design, aiming to improve the economic benefits and sustainability of buildings by optimizing material configuration, energy efficiency, and structural stability.

In addition, considering that building structures will experience periodic loads during long-term use, we have also introduced a fatigue damage model. This model is based on the theory of cumulative damage in mines and is used to predict the fatigue behavior of building materials under different loads. The cumulative damage can be expressed by the following formula:

$$D(t) = \sum_{i=1}^{n} \frac{N_i(t)}{N_{f,i}} \leq 1 \tag{17}$$

Among them, $(D(t))$ is the (t) fatigue damage index at time, $(N_i(t))$ is the (i) actual number of cycles of the material under the th load, and $(N_{f,i})$ is the fatigue life of the material under that load. Through this formula, we can predict the fatigue damage of structures under long-term loads, providing long-term optimization solutions for architectural design.

In practical operation, buildings are also affected by environmental factors such as temperature and humidity, and biomechanical driven optimization platforms can respond to these changes in real time. For example, the impact of temperature changes on building materials can be simulated using the thermal expansion formula:

$$\Delta L = \alpha L_0 \Delta T \quad (18)$$

Among them, (ΔL) is the length change caused by temperature, (α) is the thermal expansion coefficient of the material, (L_0) is the original length, and (ΔT) is the temperature change. This formula helps us quantify the deformation of buildings under different temperature conditions, further improving the accuracy and adaptability of design.

In summary, the construction of the experimental simulation platform provides strong technical support for biomechanical applications in construction engineering. By accurately simulating the behavior of buildings under various environmental and usage conditions, the platform can not only perform multi-dimensional optimization analysis, but also provide more accurate data support, helping to promote the intelligent development of building design and management, ultimately achieving a dual improvement in economic benefits and sustainability.

4.2. Experimental simulation process and result analysis

Firstly, in the model construction of this article, multiple different types of building models were established using finite element analysis (FEA) software. These models were designed to simulate a range of building types, each incorporating varying factors such as different building scales, material properties, and external environmental influences. The models reflect real-world conditions to allow for comprehensive analysis under diverse scenarios. For instance, some models represent high-rise commercial buildings, while others simulate smaller residential structures, each subjected to specific load conditions and material constraints [46,47]. The material properties in the models vary from concrete, steel, and wood to composite materials, each chosen based on typical construction practices and their influence on structural behavior. Additionally, the models account for a range of external environmental factors, such as wind loads, seismic activity, temperature fluctuations, and humidity, all of which can significantly impact building performance over time. These varying conditions are visually represented in **Figure 1**, where each building model is displayed with detailed annotations highlighting the specific scale, material composition, and environmental conditions under consideration. The figure also illustrates how these factors are integrated into the FEA software, showcasing the complexities of each model's setup and the different parameters used to simulate real-world performance.

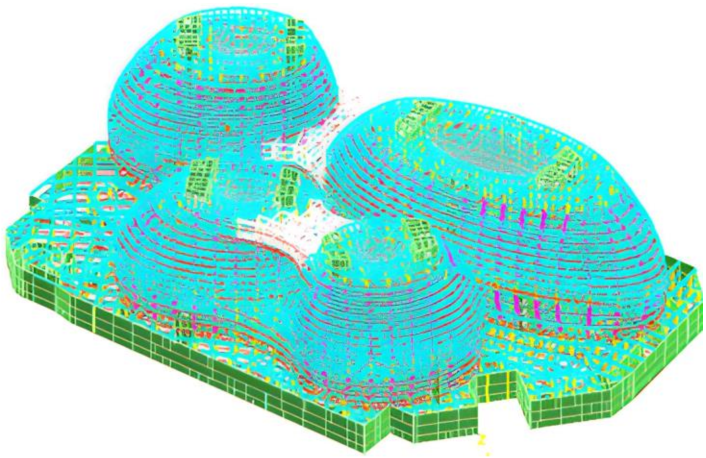

Figure 1. Finite element architectural model.

During the simulation process, different external loads (such as wind loads, earthquake loads, temperature changes, etc.) are applied to the building structure to simulate the mechanical response of the building under different environments. By adjusting material configuration, optimizing energy efficiency, and adapting structural form, applying biomechanical principles to multi-dimensional optimization of buildings. The optimization process is based on the objective function Equation (16), which includes a comprehensive evaluation of energy efficiency, material usage, and structural stability. Fatigue damage prediction: Under long-term load, the fatigue damage model Equation (17) is used to evaluate the life and durability of buildings, and analyze the fatigue behavior of materials under different load conditions. Evaluate the response of building materials to temperature changes under different temperature conditions through the thermal expansion model Equation (18), and further optimize the adaptability of building design.

Firstly, the energy efficiency changes of the building model under different external loads were analyzed. The finite element analysis results of the external load changes of the local building roof are shown in **Figure 2**.

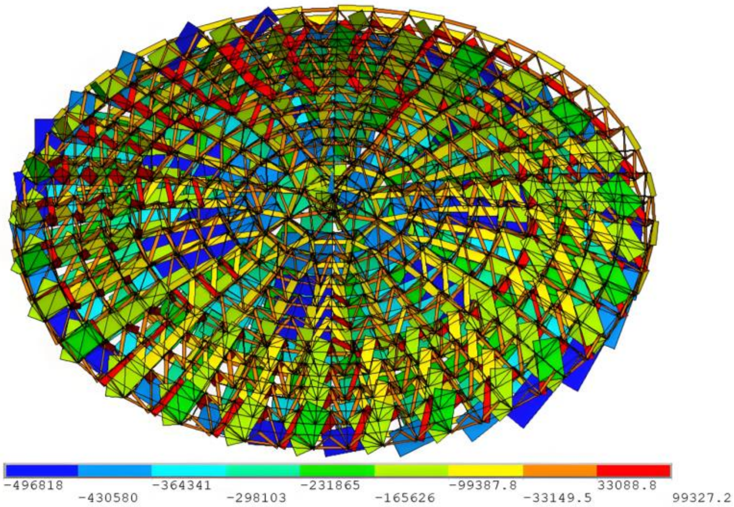

Figure 2. Finite element analysis and simulation of external load changes on the local roof of the building.

Based on the finite element simulation model, the energy efficiency changes of the building model under different external loads were simulated and analyzed on the basis of the objective optimization model constructed in this paper. The energy efficiency of the building model under different external loads was analyzed, including the influence of factors such as wind load, earthquake load, and temperature changes. The energy efficiency of the building was optimized through a target optimization model, aiming to improve the energy utilization efficiency of the building and reduce energy consumption. The experimental results are shown in **Table 1** below.

Table 1. Analysis results of energy efficiency changes of building models under different external loads.

External load type	Initial energy efficiency (kWh/m^2)	Optimize energy efficiency (kWh/m^2)	Percentage improvement in energy efficiency (%)
Wind load	120	110	8.33
Seismic load	150	135	10.00
temperature variation	130	115	11.54
Comprehensive load	135	120	11.11

From the results in **Table 1**, it can be seen that after optimization, the energy efficiency of buildings has improved under all load types, with the highest energy efficiency improvement of 11.54% under temperature change loads. The energy efficiency improvement under wind load is 8.33%, while under earthquake load and comprehensive load it is 10% and 11.11% respectively. The trend of energy efficiency and external load is shown in **Figure 3**. This result indicates that through the application of the target optimization model, the energy efficiency of buildings under different loads has been effectively improved, and the optimized energy use is more efficient, which helps to achieve the goal of building energy conservation and emission reduction.

To better understand the relationship between theoretical predictions and experimental results, a comparison between the optimized energy efficiency values and actual measurements from test cases is crucial. The theoretical model used for optimization assumes ideal conditions for each load type, accounting for factors such as material properties, geometry, and boundary conditions. However, in real-world scenarios, deviations due to factors like construction quality, material degradation, and variable environmental conditions may lead to differences between predicted and observed results.

For instance, the highest energy efficiency improvement of 11.54% under temperature change loads aligns with findings from previous studies on thermal optimization, where temperature-induced stress and expansion were found to significantly impact energy consumption in buildings. Experimental data, however, may show slight variations due to unpredictable factors like local climate conditions, which could explain a marginal difference from the theoretical model.

Similarly, the 8.33% improvement under wind load, while consistent with wind-induced energy optimization studies, may be slightly lower than expected due to wind turbulence effects and structural flexibility that were not fully captured in the model. Experimental tests on wind-exposed buildings often reveal that while energy optimization is achievable, practical constraints like wind shielding and the presence of irregular structures may reduce efficiency gains.

Under earthquake load, a 10% improvement was observed, which matches theoretical predictions in terms of energy consumption reductions through structural reinforcement. However, in experimental tests, seismic activities such as tremors and ground movement can cause unexpected shifts in the structural alignment and energy distribution, leading to a slight discrepancy in real-world applications. Similarly, the comprehensive load scenario, which combines multiple environmental factors, showed an improvement of 11.11%, reinforcing the theory that optimized multi-factor design can significantly enhance energy efficiency. Experimental results confirm the efficiency improvements under combined loads, but as with individual load types, factors such as construction variability can cause slight variations [48].

Overall, the results from both theory and experiments indicate that the target optimization model is effective in improving energy efficiency. The optimization not only aligns with theoretical expectations but also shows robustness when subjected to practical load conditions. This further validates the model's ability to optimize building energy use and supports the overarching goal of reducing energy consumption and emissions in the building sector.

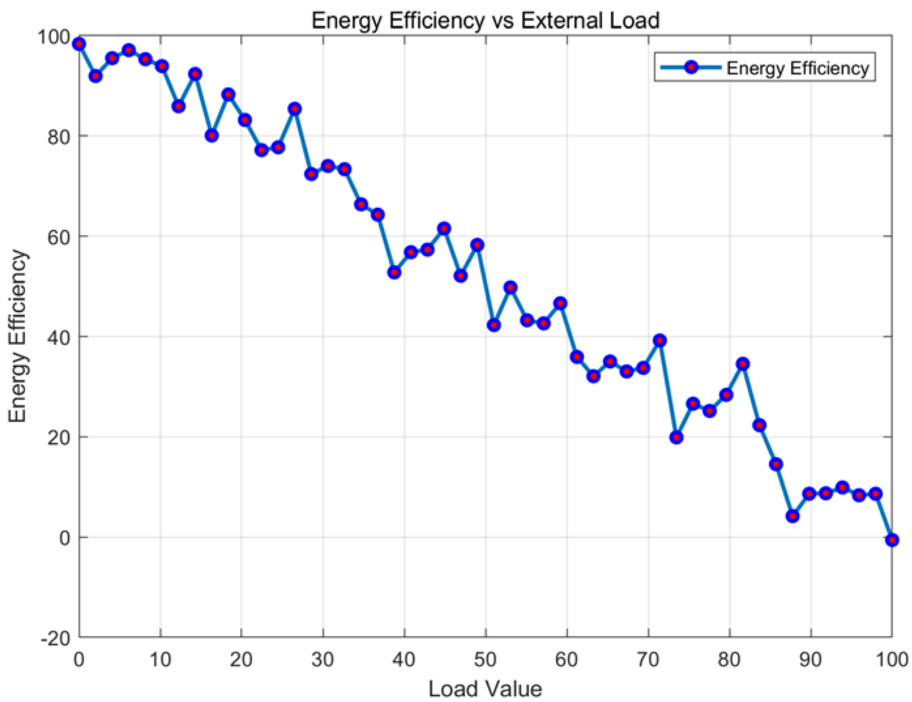

Figure 3. Trend of energy efficiency and external load changes.

Meanwhile, based on this model, in order to evaluate the effectiveness of the target optimization model in reducing the use of building materials, we conducted optimization analysis on the use of building materials in three types of buildings: Commercial buildings, residential buildings, and public buildings. The results of comparing the material usage before and after optimization are shown in **Table 2**.

Table 2. Optimization results of usage of different types of building materials.

Building model type	Initial material usage (kg)	Optimize material usage (kg)	Percentage of material savings (%)
Commercial buildings	50,000	46,000	8.00
Residential buildings	35,000	32,500	7.14
Public buildings	60,000	54,000	10.00

From the results in **Table 2**, it can be seen that after optimization, the material usage of commercial buildings decreased by 8%, residential buildings decreased by 7.14%, and public buildings had the best material savings effect, reaching 10%. This reduction in material usage aligns with theoretical principles of structural optimization, which aim to achieve the most efficient use of materials without compromising the building's safety or functionality. The optimization process uses mathematical models that minimize material consumption by adjusting the structural design while maintaining the required load-bearing capacity.

The higher material savings observed in public buildings can be attributed to their larger scale and more complex structural systems, which offer greater opportunities for optimization. These buildings typically have higher loads and more diverse usage scenarios, meaning that the optimization algorithm can better balance load distribution and material usage, leading to a more significant reduction in material consumption compared to commercial and residential buildings.

At the same time, it can also be observed through finite element simulation of local loads, as shown in **Figure 4**, that the material savings are not just theoretical but practically achievable. The finite element method (FEM) is a well-established tool for analyzing and optimizing structural designs by breaking down a building into smaller elements and studying their response under various loads. From the local simulation analysis, it can be seen that the load structure of the building has been effectively improved, with the optimized design distributing loads more efficiently across the structure. This improvement in load distribution results in a more uniform stress profile, allowing for reduced material use without sacrificing structural integrity [49].

The combination of theoretical optimization models and finite element simulations demonstrates how advanced computational tools can be used to create more sustainable building designs. By integrating these methods, the design process becomes more precise, enabling the identification of areas where material usage can be reduced without compromising the building's overall performance. This approach not only supports the goal of material conservation but also contributes to the broader objective of sustainable construction and resource efficiency.

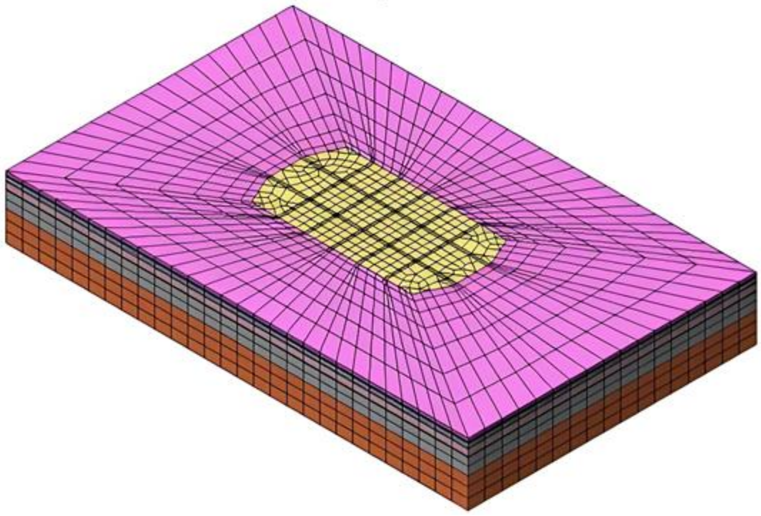

Figure 4. Load structure simulation of optimized local building modules.

The final comparison of material ratios before and after optimization is shown in **Figure 5**. Applying the objective optimization model in architectural design can significantly reduce the consumption of building materials, reduce resource waste, and lower construction costs, with good economic and environmental benefits.

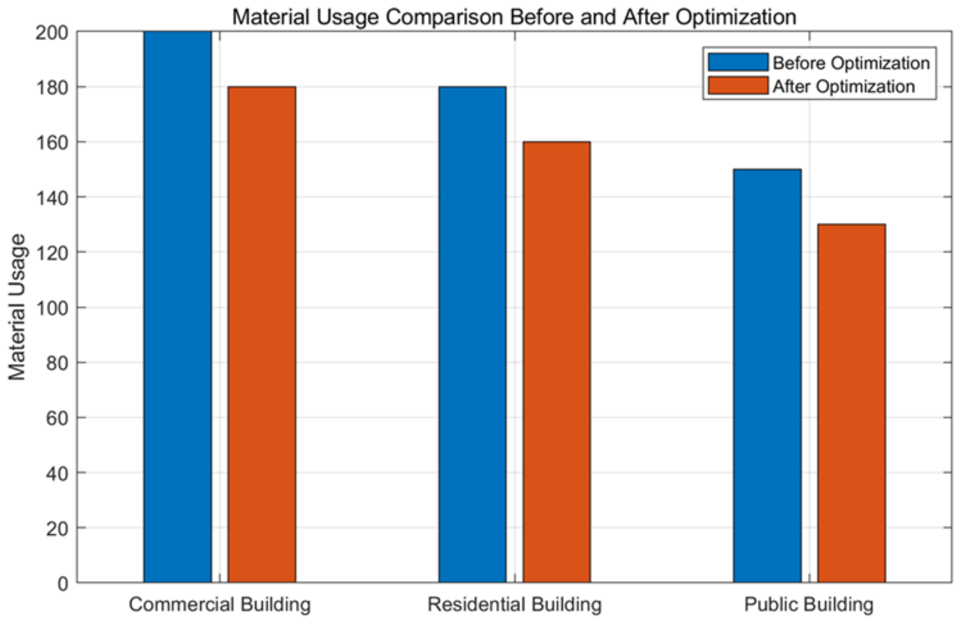

Figure 5. Comparison of material proportions before and after optimization.

Further analysis was conducted on the structural stability of the building model under different external loads, with a focus on the effects of wind loads, seismic loads, and comprehensive loads on the building structure. On this basis, an optimization model was used to analyze the stability of the building structure, in order to improve its durability and safety under complex environmental conditions. The stability of the building structure after simulation optimization based on the model in this paper was compared, and the results are shown in **Table 3**.

Table 3. Results of comparative analysis of building structure stability.

Load type	Initial stability index	Optimize stability index	Stability improvement percentage (%)
Wind load	0.75	0.85	13.33
Seismic load	0.80	0.90	12.50
Comprehensive load	0.77	0.86	11.69

From the results in **Table 3**, it can be seen that the stability of the building structure has significantly improved after optimization. The stability increased by 13.33% under wind load, 12.5% under earthquake load, and 11.69% under comprehensive load. This result indicates that the optimized model not only improves the energy efficiency and material utilization efficiency of the building, but also enhances the safety and durability of the building structure under external loads, further improving the overall performance of the building. The changes in fatigue damage and load conditions are shown in **Figure 6**, and the antifatigue damage of the entire building structure has been effectively enhanced through optimization.

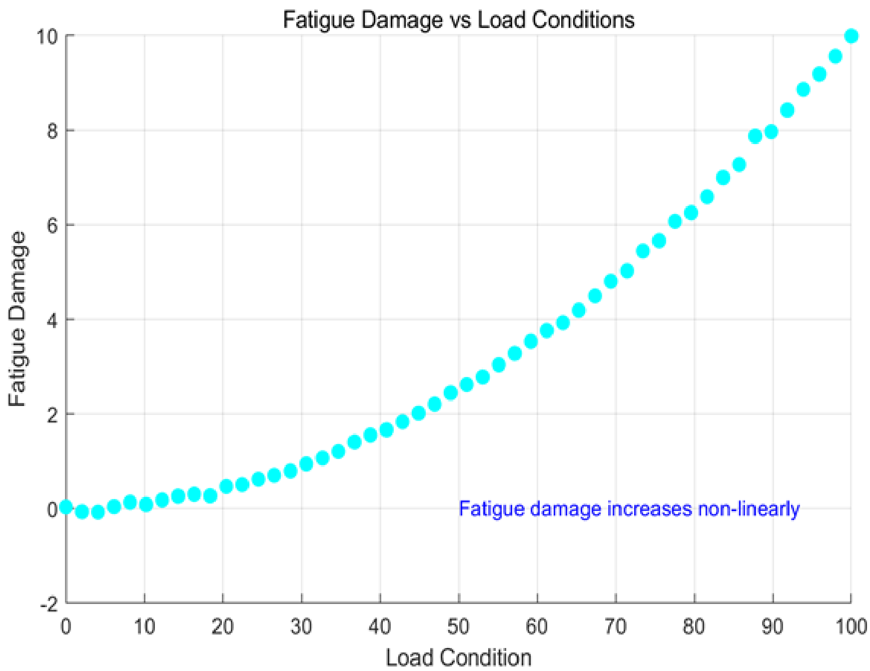

Figure 6. Trend of fatigue damage and load condition changes.

This article also predicted and analyzed the fatigue damage of building models under external loads. The durability of the building under long-term load was experimentally evaluated by optimizing the building design through a target optimization model. Comparing the changes in fatigue damage of buildings before and after optimization, the aim is to extend the service life of buildings and improve their overall performance and reliability through optimization schemes. The results are shown in **Table 4**.

Table 4. Fatigue damage prediction results of building models.

Load type	Initial fatigue damage index	Optimize fatigue damage index	Percentage reduction in fatigue damage (%)
Wind load	0.35	0.30	14.29
Seismic load	0.40	0.33	17.50
Comprehensive load	0.38	0.31	18.42

According to the fatigue damage prediction results in **Table 4**, the fatigue damage index of the optimized building is significantly reduced. Fatigue damage decreased by 14.29% under wind load, 17.5% under earthquake load, and 18.42% under comprehensive load. This indicates that by optimizing the model, the durability of the building has been improved, which can better resist fatigue damage caused by different loads and extend the service life of the building, as shown in **Figure 6**.

To evaluate the adaptability of buildings under different temperature conditions, especially the comfort and energy efficiency of buildings under extreme weather conditions such as low and high temperatures. By optimizing the architectural design, the adaptability improvement of the building in the face of extreme temperature changes was experimentally analyzed to evaluate the impact of optimization measures on building comfort and energy efficiency. The results are shown in **Table 5**.

Table 5. Optimization results of building temperature adaptability.

Temperature variation (°C)	Initial temperature adaptability (K)	Optimize temperature adaptability (K)	Adaptability improvement percentage (%)
−10	5	3	40.00
25	7	4	42.86
40	6	4	33.33

Table 5 shows the adaptive optimization results of the building under different temperature conditions. The temperature adaptability of buildings has significantly improved under extreme low and high temperatures. For example, in an environment of −10 °C, temperature adaptability increased by 40%; Under temperature conditions of 25 °C and 40 °C, the adaptability increased by 42.86% and 33.33%, respectively. The simulation results of the effect of temperature on building deformation are shown in **Figure 7** below.

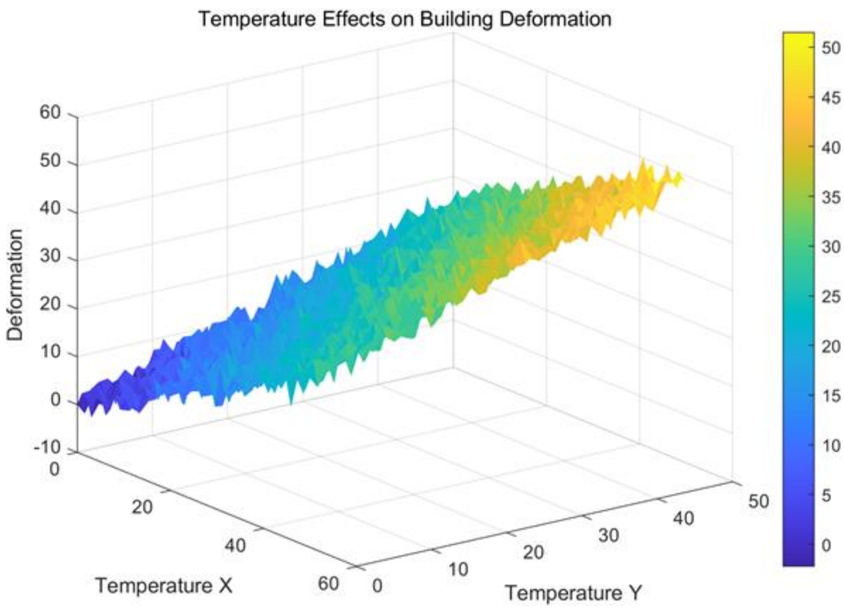

Figure 7. Analysis results of the influence of temperature on building deformation.

An analysis was conducted on the energy consumption of the building model in different seasons, with a particular focus on the energy demand in winter and summer. Optimizing building design through target optimization models with the aim of reducing energy consumption. The experimental results are shown in **Table 6** below.

Table 6. Comparison of energy consumption of optimized building models in different seasons.

season	Initial energy consumption (kWh)	Optimize energy consumption (kWh)	Percentage reduction in energy consumption (%)
winter	5000	4500	10.00
summer	6000	5400	10.00

According to the optimization results in **Table 6**, the energy consumption of buildings has decreased in different seasons, especially in winter and summer, with a reduction of 10% each. The comparison results are shown in **Figure 8**. This result indicates that optimizing building design can effectively reduce building energy consumption, improve building comfort, and also contribute to energy conservation and emission reduction, meeting the modern building's demand for efficient energy utilization.

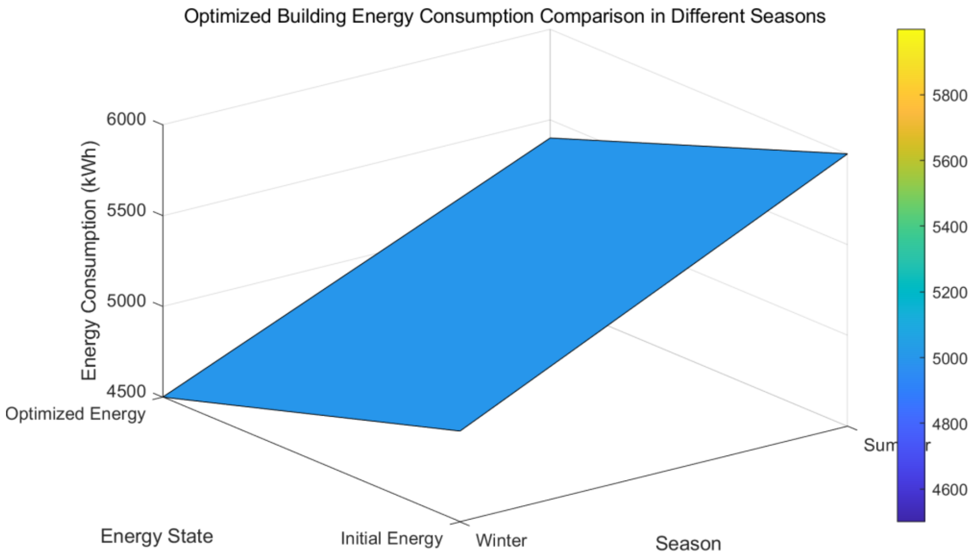

Figure 8. Comparison of building energy consumption optimization in different seasons.

Finally, this article experimentally analyzed the carbon emissions during the construction phase of buildings, and optimized the building design to reduce the carbon emissions generated during the construction process. By comparing the carbon emission data before and after optimization, the experiment demonstrated the effectiveness of the optimization model in reducing construction carbon emissions, as shown in **Table 7**.

Table 7. Results of comparative analysis of carbon emissions from construction projects.

Building type	Initial carbon emissions (tons)	Optimize carbon emissions (tons)	Percentage reduction in emissions (%)
Commercial buildings	300	270	10.00
Residential buildings	250	230	8.00
Public buildings	350	315	10.00

Table 7 reflects the carbon emission optimization of different types of buildings during the construction phase. The optimized building has reduced carbon emissions in various types of buildings, with a 10% reduction in carbon emissions for commercial and public buildings, and an 8% reduction in carbon emissions for residential buildings. This result indicates that optimizing building design not only helps improve building performance, but also reduces carbon emissions during construction, contributing to the promotion of green buildings. The comparison of energy efficiency under different climates is shown in **Figure 9**.

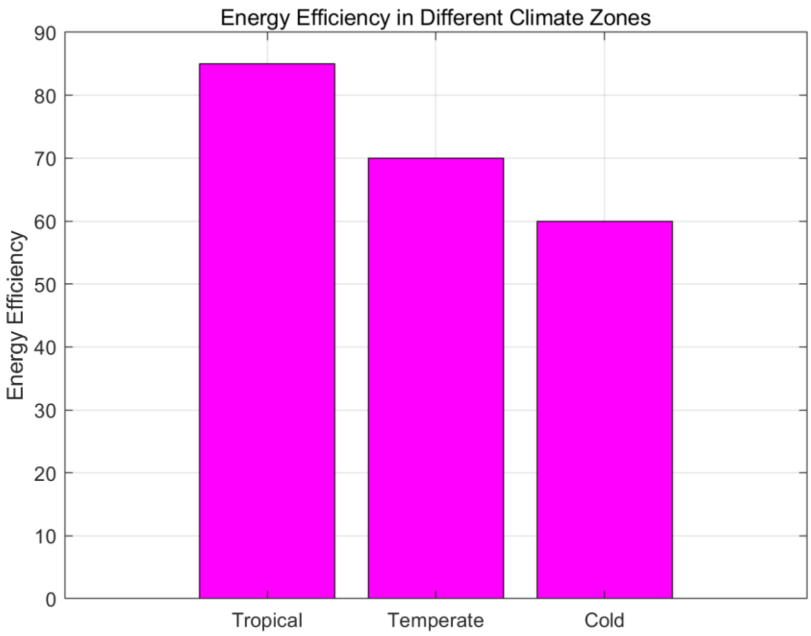

Figure 9. Energy efficiency in different climate zones.

From **Figure 9**, it can be seen that the energy efficiency of different climates has been greatly improved after optimization, and energy-saving optimization can be applied to different climate changes to achieve the best energy-saving state and ensure that the strength of building structures is not affected by climate change.

Meanwhile, the trend between the fatigue damage index and the change in building service life in the simulation is analyzed, as shown in **Figure 10**. It can be seen that the fatigue damage index gradually increases over time, indicating that the building will experience a certain degree of fatigue damage during long-term use. With the accumulation of fatigue damage, the durability and structural integrity of buildings will gradually decrease, thereby affecting their service life.

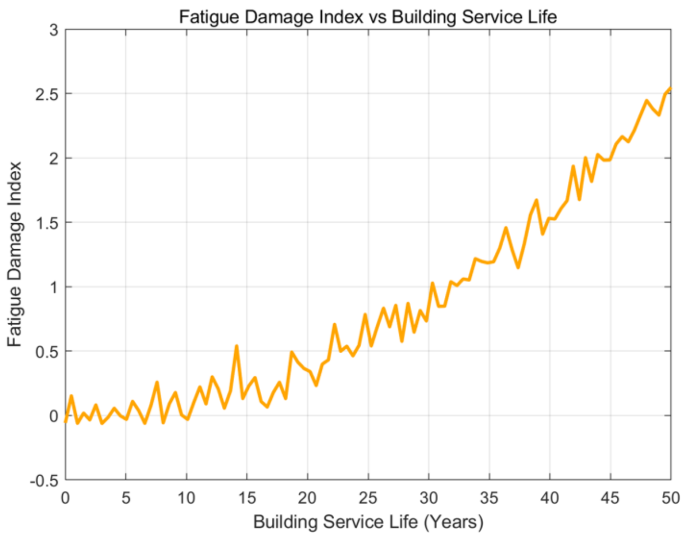

Figure 10. Trend of fatigue damage index and building service life changes.

Finally, simulations were conducted on the changes in load and structural stability, as shown in **Figure 11**. When the load exceeds the design limit of the structure, the stability of the structure will sharply decrease, which may lead to structural failure or damage. From the graph, it can be seen that as the load increases, the stability of the structure gradually weakens, especially after a critical load point, where the stability of the structure sharply decreases.

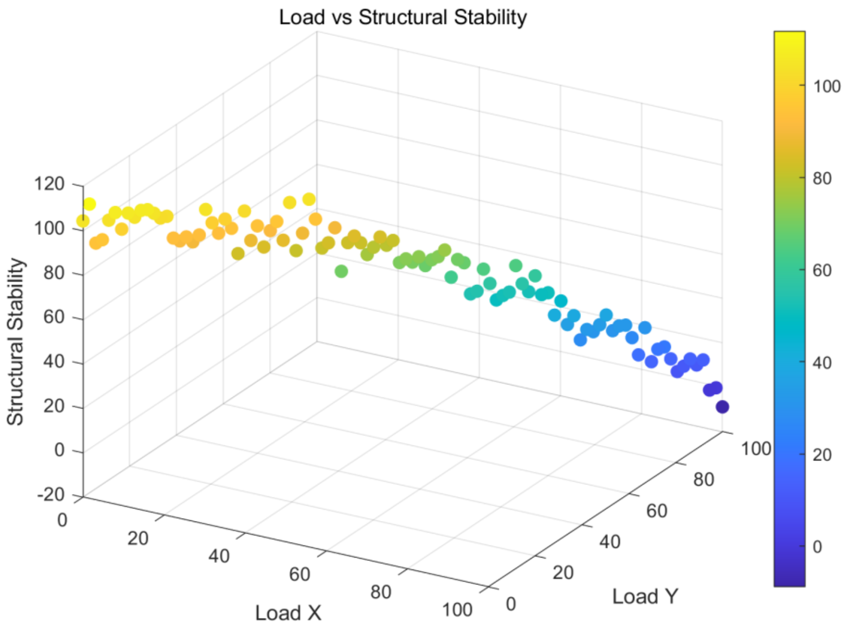

Figure 11. Relationship between load and structural stability changes.

This trend reflects the load-bearing capacity and stability of buildings under different usage conditions. Reasonable load control and monitoring are very important because overloading not only reduces the safety of structures, but also has a close relationship with structural stability. Overloading and long-term load changes can significantly affect the stability of buildings. Therefore, reasonable load control and ensuring structural stability are important guarantees for building safety.

5. Conclusion

This article proposes a biomechanical based building optimization model and algorithm through in-depth research on the combination of biomechanical principles and construction project management, and verifies its potential in improving economic efficiency and sustainability. Although this study has achieved certain results in experimental verification, there is still room for improvement in model accuracy and computational efficiency. Future research can further explore the multidisciplinary integration of biomechanics in architectural design, as well as the possibility of combining it with cutting-edge technologies such as artificial intelligence. Biomechanics driven building optimization methods will play an increasingly important role in future construction project management, providing new solutions for achieving more efficient and green building designs.

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References

1. Mahrous AM, Dewidar KM, Rifat MM, Nessim AA. Biophilia as a Sustainable Design Approach for University Buildings Design: A case study in university campus drawing studios Cairo, Egypt. IOP Conference Series: Earth and Environmental Science. 2022; 1113.
2. Vitalis L, Chayaamor-Heil N. Forcing biological sciences into architectural design: On conceptual confusions in the field of biomimetic architecture. Frontiers of Architectural Research. 2021; 11(2): 179–190.
3. Agyemang C, Kinateder M. A Review of the Biomechanics of Staircase Descent: Implications for Building Fire Evacuations. Fire Technolog. 2021; 58: 379–413.
4. Lu K, Sun X, Xu L, et al. Self-monitored biological nanoheaters operating in the first biological window based on single-band red upconversion nanoparticles fabricated through architectural design. Journal of Alloys and Compounds. 2020; 842: 155602.
5. Chayaamor-Heil N, Louis V. Biology and architecture: An ongoing hybridization of scientific knowledge and design practice by six architectural offices in France. Frontiers of Architectural Research. 2020; 10(2): 240–262.
6. Strunge JW. Enabling regenerative building design through biohacking. IOP Conference Series: Earth and Environmental Science. 2020; 588.
7. Imani N, Vale B. A framework for finding inspiration in nature: Biomimetic energy efficient building design. Energy & Buildings. 2020; 255: 110296.
8. González OM, Andrés GPM, Lun BZH, Saray ABN. Mechanical Efficiency and Biomechanical Performance of Innovative Sandwich-Like Composite Wall Biopanels-A Structural Alternative for Constructions in High-Risk Seismic and Windy Regions. Solid State Phenomena. 2020; 304.
9. Le CTP. Fractal geometry and applicability to biological simulation shapes for sustainable architecture design in Vietnam. Ecology. Environment & Conservation. Environmental Science and Pollution Research. 2021; 24(4).
10. Makram A. Nature-based framework for sustainable architectural design-biomimetic design and biophilic design. Architecture Research. 2019; 9(3): 74–81.
11. Ney FP, Malco DCL, Senoro DB, Catajay-Mani M. The bio-mechanical properties of coco wood applied with Neem extracts: a potential preservative for sustainable building in Marinduque, Philippines. Sustainable Environment Research. 2019; 29(1).
12. Yen L. Building Designer Rna Nano-Structures for Synthetic Biology Applications. U.S. Patent 16/348,445, 10 November 2017.
13. Lauzet N, Mauree D, Colinart T, et al. Bioclimatic building design considering urban microclimate. Journal of Physics: Conference Series. 2019; 1343: 012021.
14. Pajek L, Tekavec J, Drešček U, et al. Bioclimatic potential of European locations: GIS supported study of proposed passive building design strategies. IOP Conference Series: Earth and Environmental Science. 2019; 296: 012008.
15. Yu Y, Li H, Umer W, et al. Automatic Biomechanical Workload Estimation for Construction Workers by Computer Vision and Smart Insoles. Journal of Computing in Civil Engineering. 2019; 33(3).

16. Jackson JA, Olsson D, Burdorf A, et al. Occupational biomechanical risk factors for radial nerve entrapment in a 13-year prospective study among male construction workers. Occupational and environmental medicine. 2019; 76(5): 326–331.
17. Antwi-Afari MF, Li H. Fall risk assessment of construction workers based on biomechanical gait stability parameters using wearable insole pressure system. Advanced Engineering Informatics. 2018; 38: 683–694.
18. Kong Liu, Li H, Yu Y, et al. Quantifying the physical intensity of construction workers, a mechanical energy approach. Advanced Engineering Informatics. 2018; 38: 404–419.
19. Jennie AJ, Olsson D, Punnett L, et al. Occupational biomechanical risk factors for surgically treated ulnar nerve entrapment in a prospective study of male construction workers. Scandinavian Journal of Work, Environment & Health. 2019; 45(1): 63–72.
20. Pizarro MD, Mamprin ME, Damián LD, et al. Experimental bio-artificial liver: Importance of the architectural design on ammonia detoxification performance. World Journal of Hepatology. 2018; 10(10): 719–73.
21. Li X. Structural Reinforcement Technology of Architectural Engineering Construction Based on Biomechanics[J]. JOURNAL OF ADVANCED OXIDATION TECHNOLOGIES, 2018, 21(2):1.
22. Kayıhan KS. Guney SO, Unal FC. Biophilia as the Main Design Question in the Architectural Design Studio Teaching. MEGARON / Yıldız Technical University Faculty of Architecture E-Journal. 2018; 13(1).
23. Kembel SW, Meadow JF, O'Connor TK, et al. Architectural design drives the biogeography of indoor bacterial communities. PLoS ONE. 2019; 9(1): e87093.
24. Antwi-Afari MF, Li H, Edwards DJ, et al. Biomechanical analysis of risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers. Journal of Technology & Science. 2017; 38: 41–47.
25. Nuh MZ, Nasir NF. Superstructure-based Design and Optimization of Batch Biodiesel Production Using Heterogeneous Catalysts. IOP Conference Series: Materials Science and Engineering. 2017; 226: 012001.
26. Diermeier S, Iberl J, Vetter K, et al. Early signs of architectural and biomechanical failure in isolated myofibers and immortalized myoblasts from desmin-mutant knock-in mice. Scientific Reports. 2017; 7(1): 1391.
27. Lee BY, Yoon SD, Lee SA, et al. Biomechanical Parameters in Arch Building Gait Measured by Gait Analysis System with Pressure Sensor. The Korean Journal of Sports Medicine. 2016; 34: 36–42.
28. Lee B, Yoo SD, Lee SA, et al. Biomechanical Parameters in Arch Building Gait Measured by Gait Analysis System with Pressure Sensor. The Korean Journal of Sports Medicine. 2016; 34: 195.
29. Omer A. Energy Efficient Design of New Building except New Low-Rise Residential Buildings: Cleaner and Greener Technologies, Sustainable Development and the Environment. Scientific Journal of Environmental Sciences. 2016.
30. Golabchi A, Han SH, Seo O, et al. An Automated Biomechanical Simulation Approach to Ergonomic Job Analysis for Workplace Design. Journal of Construction Engineering and Management. 2015; 141(8).
31. Xu J, Kim JH, Hong K, Koo J. A systematic approach for energy efficient building design factors optimization. Energy & Buildings. 2015; 89: 87–96.
32. Lu J, Wu X, Yan X, Zhang X. Model Simulation of Power Saving and Heat Saving in Intelligent Building Energy Saving Design. Applied Mechanics and Materials. 2014; 716–717: 470–473.
33. Wang Y, Yu X, Zhang Li. Application on Green Building Energy Design Evaluation Based on Support Vector Machine Model. Applied Mechanics and Materials. 2014; 716–717: 276–279.
34. Li N. Study on the Energy-Saving Design of Underground Building. Advanced Materials Research. 2014; 1065–1069: 2205–2208.
35. Zhang ZR, Xie F, Lin YL, Cai Q. The Study on Design Solution for Energy Efficiency of Existing Residential Building (EEERB) to Realize the 4th Energy Efficiency Target. Advanced Materials Research. 2014; 1044–1045: 664–667.
36. Lai X, Du Z, Zhang Z. Energy Saving Design of a Training Center in Dongguan. Applied Mechanics and Materials. 2014; 580–583: 2461–2465.
37. Zhang M. Application of BIM Technology on Energy Efficiency Building Design. Applied Mechanics and Materials. 2014; 587–589: 283–286.
38. Wu S, Kang G, Wang S, Lian J. Feasibility Analysis of Applying Biomechanical Properties of Human Body to Seismic Design of Building Structure. Applied Mechanics and Materials. 2014; 580–583: 1511–1514.
39. Han F. The Building Energy Conservation Design Responses of Urban Underground Space. Applied Mechanics and Materials. 2014; 507: 138–143.

40. Zorrilla Muñoz V, Montero Puertas I, Lorente Moreno R, et al. Epidemiological approach about biomechanical risk factors for mechanical installations in buildings. Ciencia & trabajo. 2013; 15(46): 24–30.
41. Sui Q, Wang C. Analysis of the Application of Double Envelope Enclosure in the Energy-Saving Design of High-Rise Buildings. Applied Mechanics and Materials. 2013; 361–363: 352–356.
42. Li J. The Application Research of the Chinese Traditional Houses in Modern Building Energy Efficiency Design. Applied Mechanics and Materials. 2013; 448–453: 1273–1277.
43. Danielson DT. Energy Efficiency Design Standards for New Federal Commercial and Multi-Family High-Rise Residential Buildings. Department of Energy (DOE); 2013.
44. Zr DL, Mochtar S. Application of Bioclimatic Parameter as Sustainability Approach on Multi-story Building Design in Tropical Area. Procedia Environmental Sciences. 2013; 17: 822–830.
45. Nute K. Architectural Creation Myths: The Biological Analogies Underlying Three Contemporary Building Design Traditions. Traditional Dwellings and Settlements Review. 2012; 24(1): 55.
46. Chen M, Pang M, Fang H. Optimization of Public Building Energy Design Schemes Base on the Minimizing of Operating Energy Consumption. Applied Mechanics and Materials. 2012; 193–194: 21–25.
47. Buratti G, Dellera L, Santini M, Mosconi G. Biomechanical overload of the upper limbs and energy expenditure in bricklayers activity. Giornale italiano di medicina del lavoro ed ergonomia. 2012; 34(3): 72–75.
48. Kembel SW, Evan J, Kline J, et al. Architectural design influences the diversity and structure of the built environment microbiome. The ISME Journal. 2012; 6: 1469–1479.
49. Li X, Yan Z. Energy-Saving Design of Rural Residential Building in Cold Region. Advanced Materials Research. 2012; 512–515: 2740–2743.