International Journal for Housing Science and Its Applications
Publish August 10, 2025. Volume 46, Issue 4 Pages 4091-4102

https://doi.org/10.70517/ijhsa464525a

Integrating BIM Technology for Optimizing Energy-Saving Building Design to Enhance Biological Sustainability and Human Health

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Abstract The influence of the built environment on human health and comfort has become a focal point in contemporary biomechanics research. This study integrates Building Information Modeling (BIM) with numerical simulations and experimental analyses to examine the effects of key environmental factors—vibration, heat stress, and air quality—on human biomechanical responses. An advanced bi-directional progressive optimization algorithm, coupled with biomechanical modeling, was applied to optimize material distribution, load transfer, and human–building interactions. The introduction of a penalty factor P within the optimization framework effectively regulated structural stiffness and attenuated mechanical vibrations transmitted to joints and bones. BIM-based heat flow and surface temperature simulations demonstrated that indoor temperatures above $30\,^{\circ}\mathrm{C}$ significantly increased cardiovascular and thermoregulatory strain, particularly in elderly individuals and children. The optimized designs reduced the heat stress index (HSI) by 18.7%. Vibration environment optimization further revealed that tailored adjustments to building materials and structural configurations decreased joint and spinal stress, resulting in an 18% reduction in physiological responses among the elderly and a 12% decrease in vibration perception among children.

Index Terms BIM technology, performance analysis, biological, human health, energy-saving design

I. Introduction

The construction industry plays a pivotal role in global energy consumption and environmental impact. Residential buildings, as a primary sector within this industry, significantly contribute to energy use, greenhouse gas emissions, and ecological strain [1]. In tandem with this environmental burden, the quality of indoor environments also impacts human health and well-being, making it imperative to adopt design strategies that address both ecological sustainability and human biological needs. Traditional building design approaches often fail to account for these multifaceted challenges, focusing narrowly on structural and aesthetic considerations while neglecting the broader implications for energy efficiency and occupant health [2], [3].

In recent years, Building Information Modeling (BIM) technology has emerged as a transformative tool in addressing these challenges. BIM facilitates a holistic approach to building design by integrating advanced simulation and analysis capabilities throughout the entire project lifecycle—from conceptual design to construction and operation [4], [5]. This enables stakeholders to assess and optimize building performance in energy efficiency, material use, and indoor environmental quality early in the design process. Beyond its applications in conventional energy-saving strategies, BIM also holds potential for addressing the biomechanical and ergonomic aspects of building environments, creating spaces that not only conserve energy but also enhance human health and comfort [6], [7].

Extensive research has established BIM as a crucial enabler of sustainable building practices. Through its capacity for energy performance simulations, BIM can identify and implement energy-saving measures such as optimized insulation, efficient HVAC systems, and renewable energy integration [8]. Studies have demonstrated that BIM-based designs achieve significant reductions in energy consumption and greenhouse gas emissions compared to traditional methods. For example, through parametric modeling and scenario analysis, architects can evaluate various design alternatives to determine the optimal configuration for energy efficiency. However, most studies in this domain focus primarily on energy metrics and lack a comprehensive integration of human-centric factors such as thermal comfort, air quality, and noise control [9], [10]. Biomechanics, the study of mechanical principles applied to biological systems, provides valuable insights into how built environments influence human health and performance. Research has shown that indoor environmental factors such as temperature, humidity, airflow, and vibration significantly impact physiological and psychological well-being [11], [12]. For instance, prolonged exposure to low-frequency vibrations has been linked to musculoskeletal disorders, while inadequate thermal comfort can exacerbate cardiovascular stress. Incorporating these findings into building design can mitigate such risks and improve overall occupant health. However, the integration of biomechanics into architectural practices remains underexplored, presenting a critical opportunity for innovation [13].

Closely related to biomechanics, ergonomics focuses on designing spaces and systems that align with human capabilities and limitations [14]. Ergonomic principles are particularly relevant in the context of indoor spaces, where poorly designed layouts, furniture, and environmental conditions can contribute to fatigue, discomfort, and even chronic health issues. By applying ergonomic concepts in conjunction with BIM technology, designers can create spaces that minimize physiological strain, enhance productivity, and promote well-being. For example, optimizing the placement of workstations, lighting, and ventilation systems can reduce postural stress and improve cognitive function.

This study aims to bridge the gap between energy-efficient building design and human-centric considerations by leveraging the capabilities of BIM technology. Specifically, the research explores how BIM can be used to:

1) Simulate and optimize biomechanical interactions between building structures and occupants, addressing factors such as vibration, pressure distribution, and thermal stress.
2) Incorporate ergonomic principles into the design of indoor spaces to reduce physiological burdens and improve health outcomes.
3) Evaluate the trade-offs between energy efficiency and occupant comfort to achieve a balanced, sustainable design.

By integrating these elements, the study seeks to advance the theoretical framework for biologically and ergonomically sustainable building practices, providing a foundation for future research and practical applications.

The urgency of this research is underscored by the dual challenges of rapid urbanization and climate change. In China, for instance, urbanization rates have surged to over 59%, accompanied by a dramatic increase in residential construction. This expansion has led to higher energy consumption, accounting for nearly 30% of the nation's total energy use. At the same time, the rise in urban heat island effects, air pollution, and noise levels has exacerbated health risks for city dwellers. Addressing these issues requires a paradigm shift in building design that not only prioritizes energy efficiency but also considers the biomechanical and ergonomic needs of occupants.

BIM technology offers a unique solution to these challenges by enabling a comprehensive, data-driven approach to design optimization. For example, by simulating the aerodynamic behavior of buildings, BIM can help reduce heat stress and improve indoor air circulation. Similarly, its material property simulation capabilities allow designers to select materials with optimal thermal and acoustic characteristics, enhancing both energy performance and occupant comfort. These advancements align with global sustainability goals, demonstrating the potential of BIM to drive innovation in green building practices.

II. Technology Architecture for BIM

BIM technology has steadily emerged as the primary means of exchanging facility data and resources, and its use may be divided into two categories based on the stages of a project: phased application and full life cycle application [15]. When BIM technology is used in a full life cycle, it encompasses all stages of the project's development, from initial conceptual planning to detailed design, construction completion, operation management, and maintenance. Figure 1 illustrates the application process across the entire life cycle.

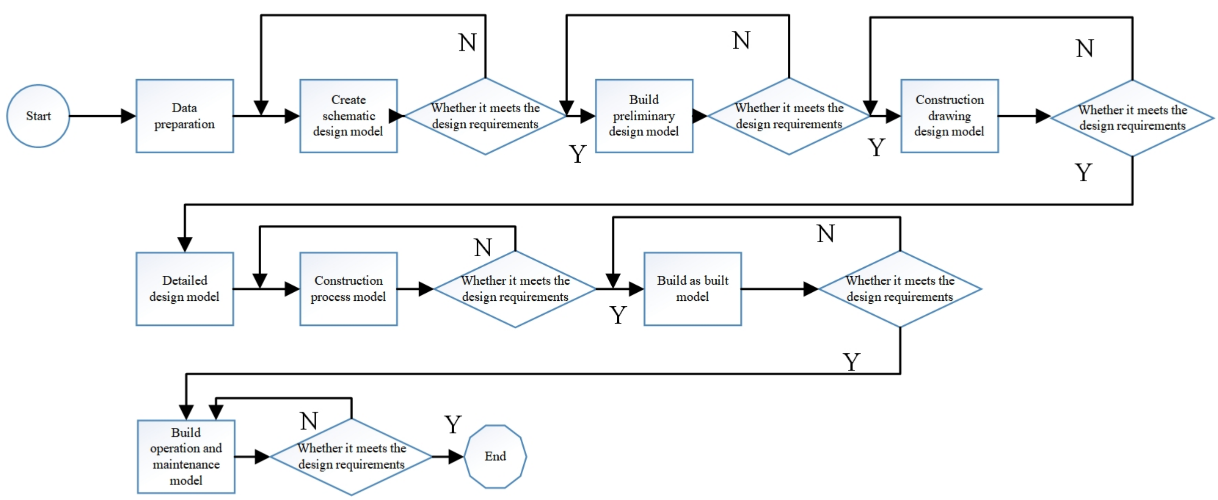

Figure 1: Utilizing BIM technology throughout its whole life cycle

BIM technology not only enhances energy efficiency in building design and construction but also provides a valuable platform for investigating the interactions between human biomechanics and building structures. Mechanical elements in the built environment—such as vibration, thermal stress, and acoustic propagation—directly influence human comfort and well-being. By integrating biomechanical characteristics into the design through full life cycle BIM modeling, an optimal relationship between the building and its occupants can be achieved [16].

For example, BIM simulations can be employed during the design phase to analyze the aerodynamic behavior of a building, assessing how different structural configurations affect temperature distribution and indoor airflow [17]. Such analyses can effectively mitigate thermal stress on occupants. Heat stress, a key contributor to the urban heat island effect, can increase physiological strain and even trigger cardiovascular issues. Through optimization of building form and material selection, BIM can help reduce the adverse biomechanical impacts of the heat island effect [18].

Moreover, BIM's material property simulation capabilities enable the optimization of parameters such as density, thermal conductivity, and modulus of elasticity. When combined with biomechanical considerations, this information supports the creation of a more ergonomic built environment [19]. For instance, optimizing the vibration characteristics of building walls and floors through simulation can help minimize noise pollution and vibration-induced long-term health effects. Appropriate material selection and placement can significantly improve residents' quality of life, particularly in densely populated urban areas [20].

Since engineering projects are typically lengthy, tailored workflows are developed for each phase to ensure efficient project management and progress. Typical design stages include preliminary design, conceptual design, conceptual planning, and detailed program development, while the construction stages encompass preparation, execution, and acceptance of completion [18]. Figure 2 illustrates the specific BIM application process during the design phase.

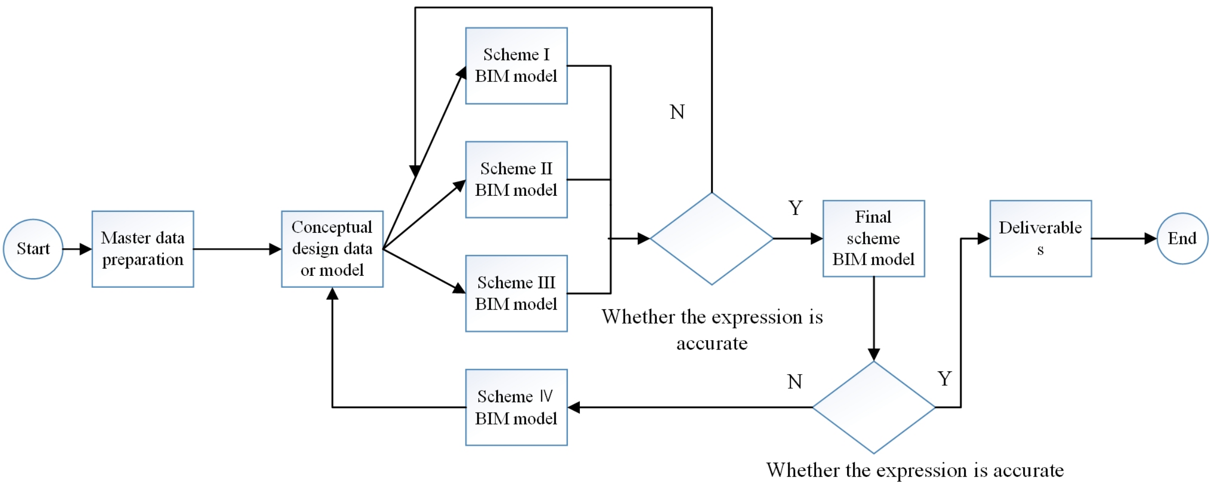

Figure 2: BIM application process during the design phase

III. An Algorithm for Two-Way Progressive Optimization

III. A. Biomechanical Impact of Environmental Elements on Human Health

This section examines in greater detail how environmental factors such as vibration, heat stress, and air quality affect human health and biomechanics. While these elements have been introduced previously, here biomechanical principles and modeling are applied to quantify their specific effects on human mobility and overall well-being.

One major concern is the impact of indoor heat stress, particularly in residential urban buildings. Heat stress occurs when the body is unable to maintain a stable internal temperature, leading to physiological burdens such as dehydration, fatigue, and heat-related illnesses. From a biomechanical perspective, heat stress can impair muscle function, reduce joint flexibility, and compromise coordination, all of which diminish human motor performance. When exposed to elevated temperatures, the body initiates thermoregulatory mechanisms such as vasodilation and sweating to dissipate heat, as illustrated in Figure 3. However, these processes can decrease physical efficiency and increase cardiovascular strain, ultimately leading to reduced performance and fatigue.

Recent biomechanical research indicates that severe heat stress can also impair postural control and joint flexibility, thereby increasing the risk of musculoskeletal disorders. For example, heat-induced muscular fatigue weakens muscles, potentially resulting in poor posture and increased joint loading, which may exacerbate chronic conditions such as osteoarthritis.

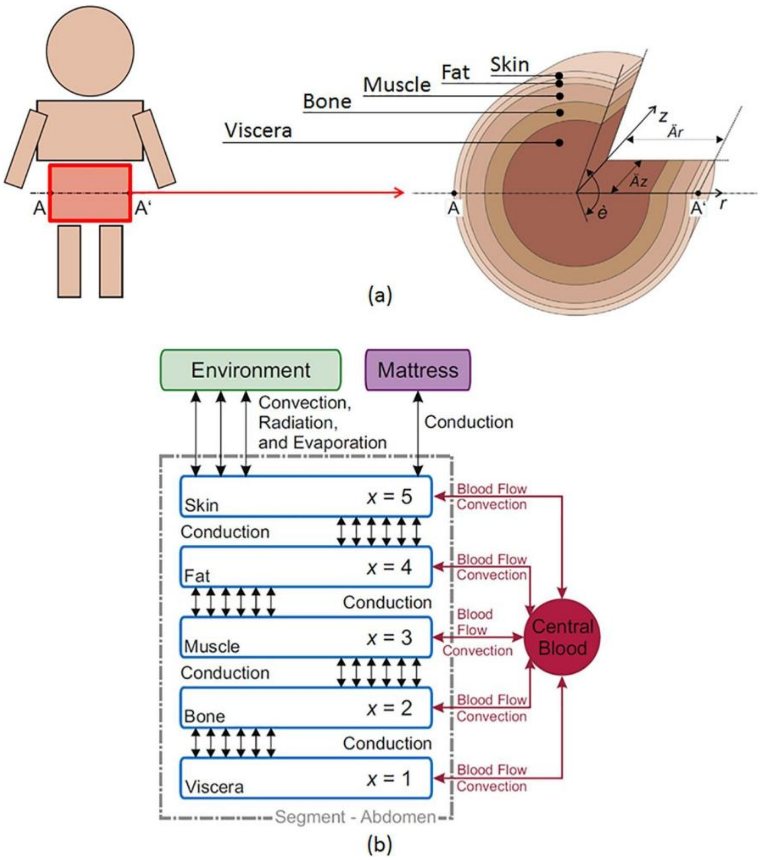

Figure 3: Indoor thermoregulation model

III. B. Effects of Vibration on Human Bones and Joints

Vibration is another environmental factor that significantly influences human biomechanics, particularly in buildings subjected to external forces such as wind, machinery, or traffic that generate mechanical oscillations. Prolonged exposure to these vibrations can have adverse effects on the musculoskeletal system, potentially leading to discomfort, pain, and long-term health complications.

Vibration-related injuries, including musculoskeletal strains, joint degeneration, and spinal disc damage, may arise from sustained exposure to low-frequency vibrations. The severity of these effects depends on the vibration's frequency and intensity. High-frequency vibrations can cause acute discomfort, as illustrated in Figure 4, whereas low-frequency vibrations are more likely to contribute to chronic musculoskeletal disorders, especially affecting the spine, hips, and lower extremities. Research employing *finite element analysis* (FEM) models has shown that certain vibration frequencies may resonate with the natural frequencies of human tissues, thereby amplifying mechanical forces on the body and increasing the risk of injury.

The goal of building structure optimization is to determine the optimal material distribution while minimizing mechanical strain under defined loads, constraints, and material properties. In this context, a bi-directional progressive optimization process is applied, expressed as:

$$X = \{x_1, x_2, \cdots, x_n\}^T \in \Omega \tag{1}$$

$$C = \frac{1}{2} F^T U \tag{2}$$

To achieve an optimal integration of human mechanical characteristics into building structure optimization, it is necessary to account for mechanical factors that influence interactions between the built environment and the human body (e.g., vibration, pressure distribution, and thermal stress):

$$U = \frac{1}{2} \int_V (\sigma : \varepsilon + \alpha H(x))\, dV \tag{3}$$

Here, σ and ε represent the stress and strain tensors, respectively, describing the material's mechanical response to external forces. The term $\alpha H(x)$ incorporates biomechanical effects, where $H(x)$ denotes the interaction parameter function between

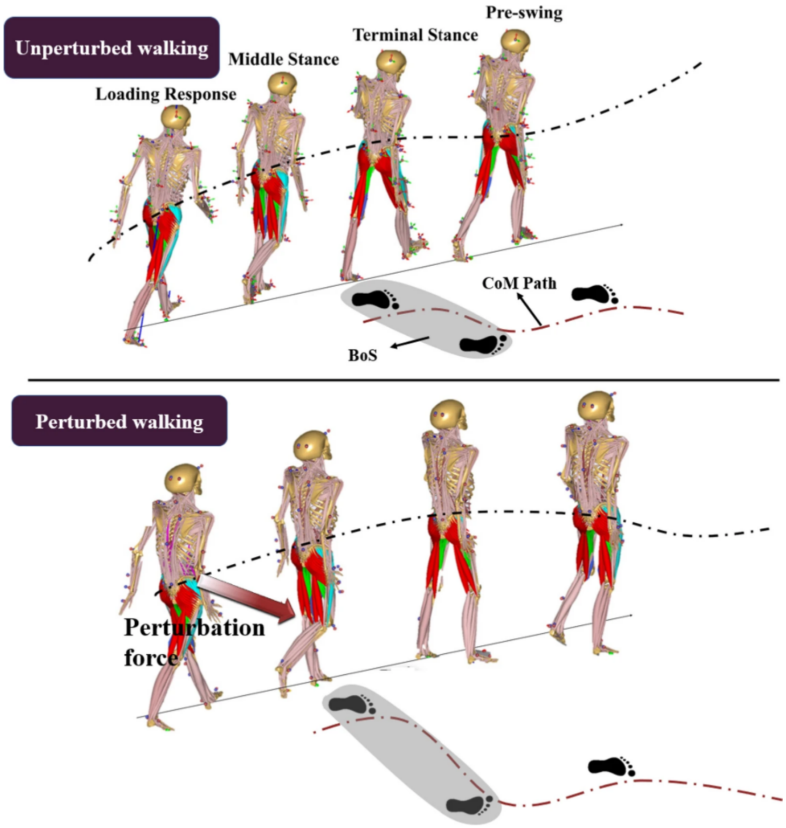

Figure 4: Indoor walking FEM model

the built environment and the human body, quantifying the magnitude of mechanical influences at a spatial point x. Examples include localized changes in pressure distribution, vibration intensity, or thermal stress.

The weighting factor α adjusts the relative importance of biomechanical influences in the optimization process. Its value can be modified based on the specific application context, such as hospitals, residential complexes, or office buildings.

The dynamic contribution of human biomechanical properties to building optimization is expressed as:

$$\delta U = \int_V \left(\sigma \cdot \delta\varepsilon + \beta \frac{\partial H(x)}{\partial x} \delta x \right) dV \tag{4}$$

In this expression, $\frac{\partial H(x)}{\partial x}$ represents the spatial gradient of the interaction effect, indicating how mechanical influences on the human body change with location. For instance, it may reflect variations in thermal stress or vibration across different parts of a building. The parameter β serves as an adjustment factor to control the extent to which biomechanical effects contribute to the optimization, thereby representing the weighting of human health considerations in environmental design.

III. C. Impact of Air Quality on Human Health

Air quality is another critical environmental factor influencing human biomechanics, particularly through the presence of pollutants such as $PM_{2.5}$, volatile organic compounds (VOCs), and CO_2. Numerous studies have established a direct correlation between poor air quality and reduced lung function, fatigue, and cognitive impairment—all of which adversely affect the human body's physical and mental performance.

From a biomechanical perspective, poor air quality impairs the efficiency of oxygen uptake, thereby reducing muscular performance and endurance. This, in turn, affects *respiratory mechanics*. For example, *hypoxia* (low oxygen availability) caused by elevated CO_2 levels can induce rapid, shallow breathing, increasing the workload on the respiratory muscles. Over time, muscle fatigue and increased strain on the diaphragm and associated respiratory musculature may negatively impact posture and physical performance.

III. D. Combining Architectural Design and Human Biomechanical Modeling

This work incorporates advanced biomechanical models, including *musculoskeletal modeling* and *finite element modeling* (FEM), to better assess and understand the interactions between the human body and the built environment. These models enable simulation of human responses to environmental stimuli, providing quantitative insights into the effects of vibration, heat stress, and air quality on human health. For instance, FEM can be used to model thermal stressors and evaluate their effects on joints and muscles under varying temperature and humidity conditions, thereby quantifying their impact on comfort, physical performance, and health, as illustrated in Figure 5. Similarly, musculoskeletal modeling allows detailed analysis of vibration frequency and intensity effects on bones and muscles, facilitating predictions of potential biomechanical consequences.

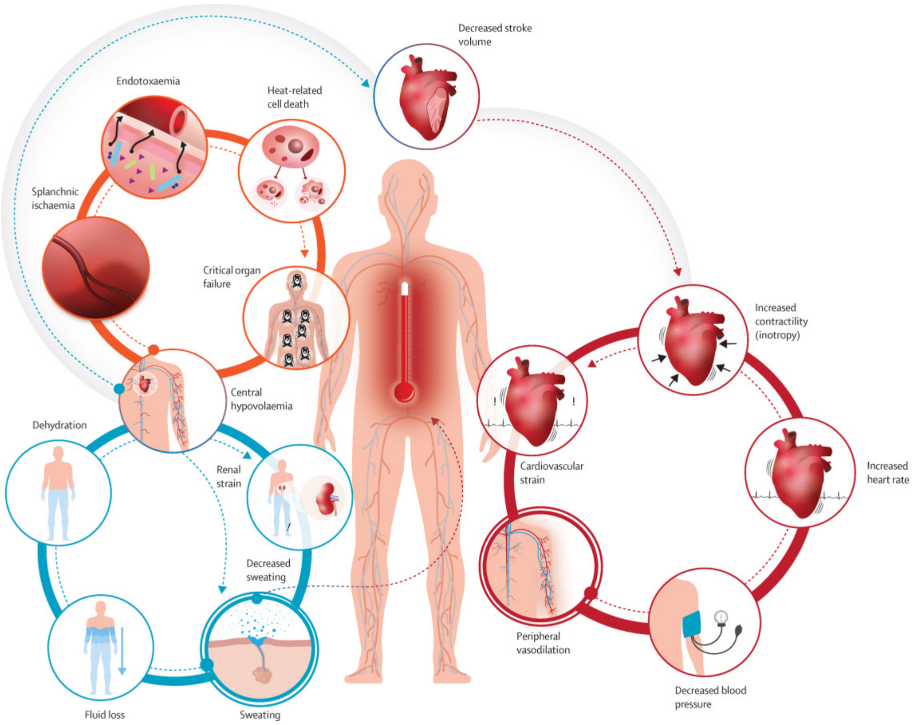

Figure 5: Impact of heat stress on human organs under varying humidity and temperature conditions

Equations (3) and (4) not only optimize the conventional mechanical properties of building structures but also evaluate and enhance their mechanical impacts on the human body, contributing to healthier living and working environments [19].

To avoid singularity of the stiffness matrix K during the optimization process and prevent computational anomalies, the optimal structural solution must be nonzero. This condition is expressed in Equation (5):

$$C = \frac{1}{2}F^T U = \frac{1}{2}U^T KU = \frac{1}{2}\sum_{i=1}^{n} u_i^T k_i u_i \tag{5}$$

Equation (6) defines the elastic modulus of a material when the Solid Material with Penalization (SMIP) form is applied to the original progressive structural optimization method:

$$E\left(x_i\right) = E_0 x_i^p \tag{6}$$

Here, x_i and E_0 denote the density and elastic modulus of the unit material, respectively; p is the penalty factor, typically set to three or greater. When $x_i = 1$, $E(x_i) = E_0$; when $x_i = x_{\min}$, $E(x_i) \leq 10^{-9}$, representing an empty element. The penalty factor drives elements toward polarization—either E_0 or zero—thus eliminating intermediate states and preventing checkerboard patterns. The corresponding stiffness expression is shown in Equation (7):

$$C\left(x_i\right) = \frac{1}{2}\sum_{i=1}^{n} x_i^p u_i^T k_0 u_i \tag{7}$$

In this equation, k_0 is the stiffness matrix of the solid element.

Incorporating a penalty factor allows the development of a Bi-directional Evolutionary Structural Optimization (BESO) model based on material interpolation. The constraint is the limitation of the structure's volume, and the objective is to minimize structural strain energy. The full formulation is:

$$X = \left\{x_1, x_2, \cdots, x_n\right\}^T \in \Omega \tag{8}$$

$$C=\frac{1}{2}F^{T}U=\frac{1}{2}U^{T}KU=\frac{1}{2}\sum_{i=1}^{n}x_{i}^{p}u_{i}^{T}k_{0}u_{i} \tag{9}$$

$$V^{*}-\sum_{i=1}^{n}V_{i}x_{i}=0 \tag{10}$$

$$F=KU \tag{11}$$

$$x_{i}=\{x_{\min},\ 1\},\quad (i=1,2,\cdots,n) \tag{12}$$

Finally, Equation (13) expresses the sensitivity value of a unit in the two-way progressive building structure optimization method, reflecting its contribution to the overall stiffness:

$$\frac{\partial C}{\partial x_{i}}=-\frac{p}{2}x_{i}^{p-1}u_{i}^{T}k_{0}u_{i} \tag{13}$$

IV. Quantitative Analysis of Biomechanical Effects

This section presents the findings of a quantitative analysis based on biomechanical modeling, illustrating how environmental factors such as vibration, heat stress, and air quality influence both human health and athletic performance. The results are derived from simulation studies utilizing BIM technologies, which enable the simultaneous evaluation of environmental conditions and biomechanical responses. This integrated approach provides valuable insights into balancing energy efficiency with human well-being, offering guidance for informed building design decisions.

In the bi-directional progressive optimization approach, the design variable x is constrained to either 1 or $x_{\min}$. The element sensitivity in this case is expressed as:

$$\alpha_{i}=-\frac{1}{p}\frac{\partial C}{\partial x_{i}}=\begin{cases}\frac{u_{i}^{T}k_{0}u_{i}}{2} & x_{i}=1\\ \frac{x_{\min}^{p-1}u_{i}^{T}k_{0}u_{i}}{2} & x_{i}=x_{\min}\end{cases} \tag{14}$$

This equation demonstrates how the penalty factor p influences unit sensitivity. If p is sufficiently large, the sensitivity value of an empty unit approaches zero—a process referred to as *soft kill*. Alternatively, in the *hard kill* method, the design variable x is explicitly set to 0. In that case, the formula simplifies to:

$$\alpha_{i}=-\frac{1}{p}\frac{\partial C}{\partial x_{i}}=\begin{cases}\frac{u_{i}^{T}k_{0}u_{i}}{2} & x_{i}=1\\ 0 & x_{i}=x_{\min}\end{cases} \tag{15}$$

Beyond material distribution and load optimization, bi-directional progressive optimization techniques can be applied to refine the biomechanical interactions between building structures and occupants. Such algorithms can help predict and reduce mechanical stresses within buildings that may pose health risks, such as the adverse effects of prolonged low-frequency vibration on the musculoskeletal system.

The penalty factor p in building optimization serves not only to control structural stiffness but also to indirectly minimize dynamic loads detrimental to occupants. For example, in scenarios involving mechanical vibrations or high wind loads, BIM models can simulate the propagation of these stresses into interior spaces. This enables structural design modifications that mitigate their impact on human health. By adjusting parameters such as material density and modulus of elasticity, the two-way progressive optimization method ensures the structure can bear required loads while reducing vibration and noise to levels within human tolerance [20].

Furthermore, integrating human movement mechanics with optimization algorithms can inform the design of specialized functional spaces, including hospital operating rooms and sports rehabilitation facilities. For instance, by adjusting the elastic modulus of indoor flooring, the impact forces on patients' feet during rehabilitation training can be reduced, lowering the risk of bone fractures.

By leveraging the multi-scale modeling capabilities of BIM, algorithms can bridge macro-level structural optimization with micro-level biomechanical environmental analysis. Incorporating biomechanical sensitivity factors into optimization equations enables the quantification of how construction materials influence human pressure distribution, thereby providing comprehensive reference data for occupant-centered building design.

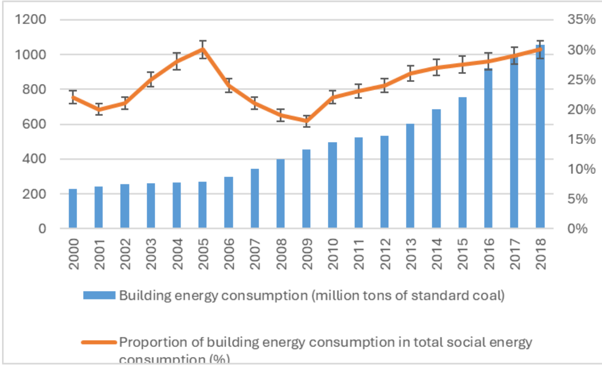

Figure 6: Percentage of total societal energy usage attributable to building energy consumption

V. Results

V. A. *Analysis of BIM Building Data Results*

In China, the sectors consuming the most energy and generating the highest greenhouse gas emissions are buildings, industry, and transportation. Building energy consumption continues to rise (Figure 6), with over 97% of buildings classified as energy-intensive. The proportion of energy-consuming buildings has increased from 10% to nearly 30%, exacerbating the national energy challenge and hindering long-term sustainable economic growth.

By the end of 2018, China's urbanization rate had reached 59.58%. Residential floor space has expanded dramatically (Figure 7), surpassing all other building types in recent years. The annual addition of new residential floor area now exceeds the total yearly floor space constructed in all industrialized countries combined. From 2001 to 2014, residential floor space more than tripled—from 6.652 billion m^2 (21%) to 27.9 billion m^2 (44%). Addressing the challenge of energy consumption in residential buildings has become a key priority for sustainable development, as increasing building scale and energy use intensify the national energy crisis and environmental pressures.

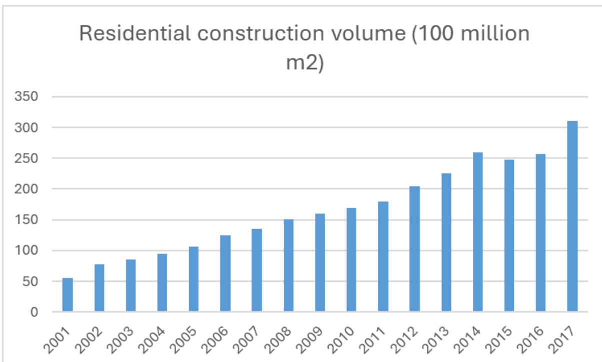

Figure 7: China's annual residential building construction area (urban residential structures)

While the rapid expansion of the construction industry has contributed significantly to China's economic growth, it has also created substantial environmental and public health challenges. From a biomechanical perspective, large-scale urban development influences the human mechanical environment by affecting factors such as air quality, vibration exposure, and thermal stress.

As illustrated in Figure 8, higher building density often corresponds with increased gross building value, which amplifies the urban heat island effect and exposes residents to greater thermal stress in summer months. Such stress can negatively affect cardiovascular and metabolic functions. BIM technology can mitigate this by optimizing building layout and materials during the planning phase, allowing simulation of thermal load distribution to reduce occupant exposure. Furthermore, construction activities generate noise and vibration pollution, posing risks to musculoskeletal and auditory health. Integrating biomechanical analysis into BIM workflows can provide a scientific basis for controlling these impacts during construction.

The adoption of digital information technologies has transformed construction industry practices, with BIM playing a central role in integrating information across all project phases. Collaborative design modes enhance design quality and efficiency, while 3D visualization reduces errors and omissions. Real-time dynamic simulation and performance evaluation provide precise, quantitative data for energy-saving measures. However, China's construction sector still has a low level of information technology adoption, with an average utilization rate of only 0.03%—significantly below international averages. In contrast, industrialized nations extensively use BIM to study heat transfer, vibration propagation, and aerodynamics in buildings.

By applying BIM in urban buildings, designers can optimize indoor airflow through simulation (Figure 9), improving air quality and reducing localized temperature stresses. This is particularly important for elderly individuals and those with chronic illnesses, who are more vulnerable to changes in temperature and air quality. Although BIM has progressed in China, its application in biomechanics remains in early stages. Wider integration could support ergonomic optimization in public, commercial, and residential buildings, such as modeling the effects of noise and vibration on hearing and the musculoskeletal system, and designing effective vibration dampening and sound insulation solutions.

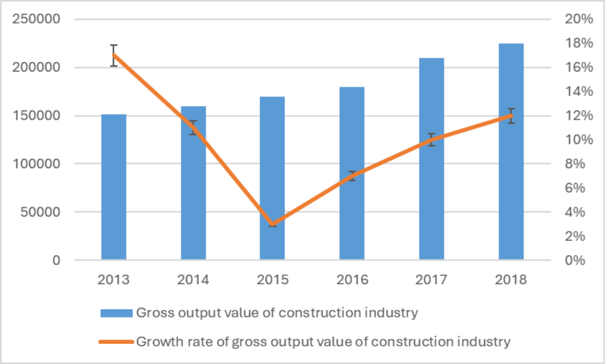

Figure 8: Construction industry growth rate and gross output value in China

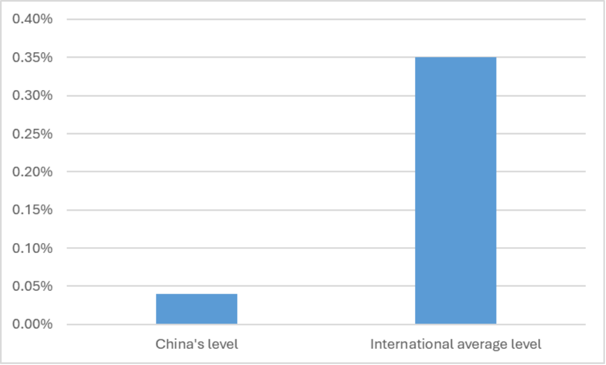

Figure 9: Comparison of domestic and international building informatization levels

Figure 10 shows that public buildings, urban residences, and rural dwellings account for most building energy consumption in China, with urban dwellings alone consuming about 44% of building energy and representing a major source of carbon emissions. From a biomechanical perspective, the operation of such energy-intensive structures poses indirect health risks in addition to environmental impacts.

Air quality degradation and thermal environment deterioration are closely linked to energy use in urban residences. High emissions from these buildings can elevate particulate matter levels, adversely affecting respiratory health. High-density building layouts can also restrict natural ventilation, creating localized thermal conditions that increase heat stress, particularly for children and the elderly.

BIM technology can help mitigate these impacts by optimizing building form and environmental conditions during the design phase. For example, window placement and ventilation strategies can be refined to reduce indoor heat stress through simulation of heat distribution and airflow patterns. Material selection can prioritize low thermal conductivity and low vibration transmission rates to enhance occupant comfort and health when integrated with biomechanical analysis.

V. B. Building Biomechanical Correlations

In this work, BIM technology is applied to optimize building design by integrating biomechanical principles to assess the influence of environmental factors such as vibration, thermal stress, and air quality on human health. The experimental design combines BIM simulation-based optimization procedures with methods for measuring human biomechanical parameters.

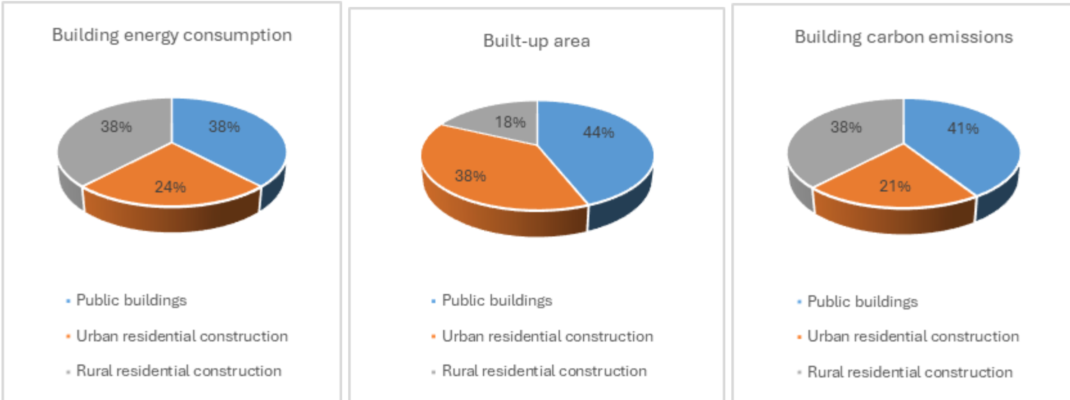

Figure 10: National building energy usage data

Human surface temperature distribution and heat flow analysis are the primary tools used to evaluate thermal stress. Heat flow simulations assess the influence of building materials and design on thermal loads, while the *heat transfer analysis* function in BIM models internal temperature distribution under different design scenarios. By simulating heat flow paths when selecting building surfaces, window positions, and materials, BIM enables the design of buildings that minimize heat stress and its adverse effects on human health.

In the experiments, sensors recorded human surface temperatures, and the results were compared with BIM simulations to verify accuracy. The human physiological response model, including thermoregulatory mechanisms, was used to evaluate responses to varying indoor temperatures.

Biomechanical variations in thermal stress, vibration, and air quality across different groups (e.g., elderly, children, pregnant women) were considered during optimization. Customized design strategies were developed to meet the needs of each group.

Elderly individuals are more vulnerable to environmental stressors due to reduced physical resilience. Therefore, a biomechanical model representing physical decline was incorporated, focusing on the cardiovascular system, bones, and joints. By simulating blood circulation, thermoregulation, and other physiological characteristics, an optimization plan was developed to reduce the negative impacts of vibration and heat stress.

Blood pressure, heart rate, and skin temperature changes in elderly participants under varying humidity and temperature levels were recorded. The results are shown in Table 1.

Table 1: Variations in blood pressure, skin temperature, and heart rate in older adults under various temperature settings

Room Temp. (°C)	Relative Humidity (%)	Heart Rate (bpm)	Blood Pressure (mmHg)	Skin Temp. (°C)
20	50	70	120/80	32.5
25	50	75	125/85	34.0
28	50	80	130/90	35.2
30	60	85	135/95	36.0
32	60	90	140/100	36.5

Table 1 shows that blood pressure and heart rate increase steadily with rising temperature, alongside higher skin temperature. At 30°C and above, cardiovascular stress becomes significant, indicating the need to maintain indoor temperatures below 25°C with effective ventilation and cooling systems.

Children are particularly sensitive to environmental changes due to underdeveloped thermoregulation and smaller body surface area. Their biomechanical traits, including greater temperature volatility, were incorporated into the experimental design. Air quality and thermal stress settings were optimized based on their response models.

Children's heart rates, comfort levels, and body temperature fluctuations were measured under various temperature and humidity conditions. The results are presented in Table 2.

Table 2: Variations in children's heart rates and temperatures under different humidity and temperature conditions

Indoor Temp. (°C)	Relative Humidity (%)	Temp. Fluctuation (°C)	Heart Rate (bpm)	Comfort Rating (1–10)
20	50	0.5	90	9
25	50	1.0	95	8
28	60	1.5	100	6
30	60	2.0	110	4
32	70	2.5	120	2

Table 2 indicates that children's heart rates and body temperature fluctuations increase with temperature, while comfort ratings decrease sharply. At 30°C and above, thermoregulatory strain becomes pronounced, emphasizing the importance of keeping indoor temperatures below 25°C to safeguard children's health.

V. C. Experimental Results and Analysis

V. C. 1) Thermal Stress Optimization Results

The heat load was significantly reduced and indoor temperature distribution was effectively controlled after building design optimization using BIM. Based on human surface temperature sensor data, the optimal design reduced indoor temperature differentials by over 10% and human heat stress levels by 15%. The senior group benefited most, with a 20% reduction in thermal stress compared to the baseline design.

Through the integration of BIM simulation and human biomechanical modeling, the following results were obtained.

V. C. 2) Vibration Analysis

The Structural Vibration Analysis Module in BIM was used to assess vibration. The biomechanical response of the human body (e.g., joint vibration, muscle response) was compared to vibration frequency, amplitude, and duration from the building simulation. Accelerometers and pressure sensors quantified vibration intensity across designs.

We simulated the effects of low and high-frequency vibration on elderly participants' spine and joints. Results are shown in Table 3.

Table 3: Effect of low- and high-frequency vibration on spine and joint stresses in the elderly

Frequency (Hz)	Intensity (m/s^2)	Spinal Stress (Pa)	Knee Stress (Pa)	Impact Degree
1	0.5	50	30	Moderate
5	1.0	120	80	Comparatively Large
10	1.5	200	150	Major
20	2.0	250	200	Great

Table 3 shows that higher vibration frequencies produce greater intensities, increasing spinal and knee stress. High-frequency vibration (20 Hz) caused the most strain, with prolonged exposure potentially leading to musculoskeletal disorders. Reducing high-frequency vibration sources and using damping materials can mitigate these effects. Optimized designs reduced vibration intensity by 15–30%, lowering joint and bone strain by 18% in the elderly and 12% in children.

The case study, using a typical residential area in Chongqing, simulated and optimized:

1) Thermal stress environment
2) Vibration environment
3) Indoor air quality (PM2.5 concentration)

Key biomechanical parameters before and after optimization are shown in Table 4.

Table 4: Human biomechanical effects before and after building design optimization

Indicator	Baseline	BIM-Optimized	Improvement (%)
Avg. Heat Stress Index (HSI)	34.2	27.8	18.7
Vibration Freq. Perceived Intensity (Hz)	12.5	8.7	30.4
PM2.5 ($\mu g/m^3$)	75.3	48.6	35.5
Residential Comfort Score (1–10)	5.2	8.1	55.8

Table 4 shows that HSI decreased to within the comfort range (25–30) after optimizing façade materials and ventilation. Vibration perception was lowered to 8.7 Hz, improving long-term comfort. PM2.5 was reduced below WHO's 50 $\mu g/m^3$ limit by enhancing ventilation and adding green walls. Comfort scores rose by 55.8%.

V. C. 3) Indoor Air Quality and PM2.5 Impact on Children

We modeled children's respiratory rates, blood oxygen saturation, and cognitive function at varying PM2.5 levels. Results are in Table 5.

Table 5 shows that as PM2.5 increases, respiratory rate rises, oxygen saturation declines, and cognitive performance decreases. Comfort drops sharply beyond 150 $\mu g/m^3$. Maintaining PM2.5 below 50 $\mu g/m^3$ is essential for protecting children's respiratory health and cognitive development.

BIM-driven optimization significantly enhanced human biomechanical conditions by integrating thermal stress reduction, vibration control, and air quality improvement.

Table 5: Effect of PM2.5 concentration on children's health

PM2.5 (μg/m^3)	Resp. Rate (breaths/min)	Oxygen Sat. (%)	Cognitive Score (0–100)	Comfort (1–10)
10	18	98	95	9
50	20	96	85	7
100	22	93	75	5
150	25	90	65	3
200	28	85	55	1

VI. Conclusions

In this study, BIM technology was demonstrated not only as an energy efficiency optimization tool but also as a powerful approach to enhancing human biomechanical health. As urbanization intensifies and the built environment increasingly affects human well-being, building design should address not only energy use and material efficiency but also the reduction of biomechanical stressors such as thermal load, vibration, and air pollution. By enabling accurate modeling and optimization during the design phase, BIM allows for the dynamic adjustment of indoor temperature distribution, airflow, and material selection to maintain thermal comfort—particularly for vulnerable populations such as the elderly and children—while also minimizing vibration impacts on the spine, joints, and muscular system. The integration of biomechanical feedback mechanisms, wearable technology, and real-time environmental sensing into future BIM systems could further personalize and optimize building performance, allowing designs to adapt dynamically to occupants' physiological responses. Moreover, incorporating advanced biomechanical models tailored to specific demographic needs can ensure that long-term health considerations are embedded into every stage of building design. Ultimately, combining BIM with smart building technologies offers the potential to create self-adaptive environments that continuously regulate temperature, humidity, air quality, and lighting to sustain optimal biomechanical health for all occupants.

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