

Optimization of Three-Layer Glass Thickness Design Based on the Classical Genetic Algorithm

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Abstract. This article takes the demand for natural lighting in buildings in central China as the research object. From the perspective of balancing lighting needs, comfortable lighting environment, and reducing the harm of ultraviolet rays to the human body and the impact of infrared thermal radiation, based on a classical genetic algorithm, the thickness of three-layer glass is studied. By studying the dual goals of achieving high transmittance of visible light and low transmittance of invisible light, a fitness function based on energy integration was constructed, and a penalty coefficient was introduced to enhance the suppression effect of non-visible light, solving the transformation problem of multi-objective optimization. Combined with engineering practice, thickness constraints were set to obtain glass thickness selection standards, which can be directly applied to the design of building doors and windows in central China, and even extended to the optimization design of optical devices in other frequency bands, providing a design research basis for achieving building energy conservation and improving spatial comfort. In addition, the optical transmittance model established in this article and the optimization framework of the classical genetic algorithm provide theoretical references for multivariable and nonlinear optical structure optimization. Verified the effectiveness of classical genetic algorithms in engineering optimization problems.

Keywords: classic genetic algorithm, three-layer glass thickness, optimized design

1. Introduction

More than half of people's time is spent in residential areas, and ample and comfortable natural lighting is beneficial for both physical and mental health [1]. Windows are crucial architectural elements as they allow the majority of natural light to enter a structure [2].

In recent years, the importance of window vision for users' physical health, emotions, office and study efficiency, and visual comfort has received widespread attention [3]. Extensive glazing is a common feature of modern buildings, intended to maximize daylight and strengthen visual connections with the outdoors [4]. At present, global research on glass has been conducted in terms of transmittance, material, coating, and structure (Low-E) [5]. Some scholars have also studied the seasonal thermal performance of double and three-layer glass windows affected by window area. Chen et al. studied the interaction mechanism between solar thermal gain and ventilation cooling effect (CEV) in high-rise residential buildings based on field measurements and regression analysis

methods under different seasons, window opening area (WOA), and glass configuration [6]. Key data were obtained to quantify the impact of WOA and glass type on net thermal effect [6]. However, research on glass thickness has not yet been carried out.

This study focuses on the need for increased natural visible light transmission in buildings located in central China. By selecting the 450-760nm visible spectrum for efficient solar light transmission while reducing the transmittance of the 300-450nm ultraviolet and 760-2000nm near-infrared bands, and optimizing the glass thickness as a three-layer variable, a classical genetic algorithm is employed to achieve spectrally selective transmission. The aim is to provide design guidelines for energy-efficient and naturally lit glass structures in central China.

2. Methods

In recent years, intelligent methods represented by neural networks, genetic algorithms, and swarm intelligence algorithms have significantly improved the accuracy and efficiency of parameter optimization, while reducing experimental costs, thanks to their strong nonlinear fitting capabilities and efficient global optimization characteristics [7]. The classical genetic algorithm used in this study is a global optimization algorithm that simulates biological genetics and natural selection, and has a relatively robust population global optimization search ability [8]. The classic genetic algorithm was proposed by Professor Holland in 1975, with core characteristics of population search, survival of the fittest, and global optimization. It is suitable for complex optimization problems with nonlinearity and multiple variables, and its core advantage is that it does not require differentiability of the objective function, which can effectively avoid local optima and adapt to the nonlinear coupling relationship of transmittance thickness in this study. Classic genetic algorithms have been applied in various fields. In the optimization analysis of wood thermal modification, the processing parameters are optimized through classical mathematical analysis and compared with the optimization results of the genetic algorithm to obtain the optimal design parameters [9]. In the enhancement of IoT network security in manufacturing and financial services, genetic network algorithms demonstrate powerful optimization capabilities in complex data environments, enhancing the accuracy and flexibility of financial decisions [10]. When identifying the size, quantity, wheelbase, and eccentricity of moving loads across bridges, a differential evolutionary genetic algorithm is used [11]. Classic genetic algorithms can also provide more flexible solutions for complex agricultural environments [12].

This study takes the thicknesses L1, L2, L3 of three layers of glass as optimization variables, and constrains the glass thickness to a positive real number within the wavelength range of 300-2000nm, with the maximum energy (transmittance) in the visible light band entering the room and the minimum transmittance in the non visible light band (300-450nm, 760-2000nm).

2.1. Calculation model for the transmittance of single-layer glass

According to the given formula in the study, the transmittance of sunlight vertically incident on a single-layer glass is:

The reflectivity formula is as follows:

$$R = \left(\frac{n-n_0}{n+n_0} \right)^2 \quad (1)$$

The wave number formula is as follows:

$$k = \frac{2\pi n}{\lambda} \quad (2)$$

The transmittance formula is as follows:

$$T = \frac{I_t}{I_i} = \frac{(1-R)^2}{(1-R)^2 + 4R\sin^2(kL)} \quad (3)$$

Where, R is reflectance; n is refractive index; n_0 is air; λ is wavelength; k is wave number; T is transmittance; I_i is the incident light intensity; I_t is the transmitted light intensity; L is the glass thickness.

2.2. Principle of superposition of transmittance of three-layer glass

Three-layer glass is composed of air -glass 1-glass 2-glass 3-air, with multiple reflections and transmission interferences between each layer. The total transmittance is the coupling result of the transmittance of each layer:

Calculate the reflectivity R , wavenumber k , and single-layer transmittance separately for each layer of glass.

The total transmittance $T_{total}(\lambda, L_1, L_2, L_3)$, takes into account interlayer interference superposition and is a multivariate function of wavelength and three-layer thickness.

The total energy inside the incident room is the integral of the transmittance of the corresponding wavelength band and the incident light intensity.

2.3. Core principles of the classical genetic algorithm

The core characteristics are group search, survival of the fittest, and global optimization, which are suitable for complex optimization problems with nonlinearity and multiple variables. The core corresponding relationships are shown in Table I.

Table 1. Correspondence table of core principles

Genetic concepts	genetic algorithm concept	Corresponding content
individual	feasible solution	A set of thickness combinations [L_1, L_2, L_3]
population	Feasible solution set	A set of multiple thickness combinations
chromosome	Encoding of solutions	Real number encoding of thickness parameters
fitness	The quality of solutions	Comprehensive evaluation index for visible and non-visible light transmission
Selection/crossover/mutation	genetic manipulation	Retain high-quality solutions, cross-generate new solutions, and perturb solutions with low probability

The core advantage of this algorithm is that it does not require a differentiable objective function, effectively avoids local optima, and adapts to the nonlinear coupling relationship of transmittance thickness.

3. Design process

3.1. Model construction

- Objective function (energy integration model). Define the total energy E_{vis} in the visible light band and the total energy E_{non} in the non-visible light band as the integration of wavelengths, with the integration interval being the corresponding band and a step size of 1nm (to ensure calculation accuracy):

The formula for the total energy in the visible light band E_{vis} is as follows:

$$E_{vis} = \int_{450}^{760} I_i(\lambda) \cdot T_{total}(\lambda, L_1, L_2, L_3) d\lambda \quad (4)$$

The formula for the total energy in the non-visible light band E_{non} is as follows:

$$E_{non} = \int_{300}^{450} I_i(\lambda) \cdot T_{total}(\lambda, L_1, L_2, L_3) d\lambda + \int_{760}^{2000} I_i(\lambda) \cdot T_{total}(\lambda, L_1, L_2, L_3) d\lambda \quad (5)$$

Where, I_i is the incident light intensity; L_1, L_2, L_3 is the one / two / three-layer glass thickness. T_{total} is the total transmittance; d is thickness; λ is wavelength.

- Fitness function (multi-objective optimization core). This study is a multi-objective optimization problem (maximizing E_{vis} and minimizing E_{non}), constructing a maximum fitness function to transform multi-objective optimization into single objective optimization:

The fitness function formula is as follows:

$$fitness(L_1, L_2, L_3) = \frac{E_{vis}}{E_{vis} + \alpha \cdot E_{non}} \quad (6)$$

Where, $\alpha > 0$ - the penalty coefficient (taking $\alpha = 1.2$ to enhance the inhibitory effect of non-visible light), and the closer the fitness value is to 1, the higher the quality of the solution, that is, the higher the visible light transmittance and the lower the non-visible light transmittance.

- Constraints. Based on the feasibility of engineering practice and glass processing, set thickness constraints: $L_1, L_2, L_3 \in [0.1, 20]$ (unit: mm)

- Constraint Explanation. Insufficient thickness has no actual optical effect; excessive thickness increases self-weight and cost, affects the energy-saving effect, and complies with the design specifications for building glass engineering.

3.2. Algorithm steps

This study adopts real number encoding (adapted to continuous thickness variables), following the core process of classical genetic algorithm from initialization to evaluation, selection, crossover, mutation, and termination, to achieve multi-objective optimization and ensure the global optimality of the solution. Specific implementation steps:

- Step 1: Encoding and Initial Population Generation

This algorithm employs a real-number encoding method, where each individual is represented as a three-dimensional vector $X = [L_1, L_2, L_3]$, with each component required to meet corresponding thickness constraints. The population size is set to $N=50$, balancing computational efficiency with global search capability. During the initialization phase, 50 sets of thickness

combinations that satisfy the constraints are randomly generated to form the initial population of the algorithm.

- Step 2: Adaptability Evaluation

For each X in the population, perform the following operations sequentially: first, calculate the total transmittance $T_{total}(\lambda)$ point by point with a 1nm step size within the 300-2000nm wavelength range, then determine E_{vis} and E_{non} through integration, and finally substitute the results into the fitness function to obtain the fitness value of each individual.

- Step 3: Select Operation

This algorithm adopts a combination of elite retention and roulette wheel selection strategy to balance global optimal solution search and population diversity. The elite retention operation directly retains the top 10% of fitness ranking individuals to the next generation, thereby avoiding the loss of high-quality solutions. The roulette wheel selection is aimed at the remaining 45 individuals, and the selection probability is allocated according to the proportion of their fitness values, so that individuals with higher fitness have a higher probability of being selected.

- Step 4: Cross Operation

Using an arithmetic crossover method adapted to real number encoding, the crossover probability P_c is set to 0.8, which falls within the optimal range of 0.65-0.90 in the classical genetic algorithm. For the selected parent individuals X_1 and X_2 , a random number $\beta \in [0,1]$ is generated,

The formula for cross-generating new individuals is as follows:

$$\begin{cases} X_{new1} = \beta X_1 + (1 - \beta) X_2 \\ X_{new2} = (1 - \beta) X_1 + \beta X_2 \end{cases} \quad (7)$$

Where, X_{new1}/X_{new2} is new individual; X_1 / X_2 is parent individuals β is a random number.

After the cross is completed, check whether the new individuals meet the thickness constraint. If they exceed the constraint range, they will be truncated to the constraint interval.

- Step 5: Mutation operation

Gaussian mutation is used for small probability perturbation to avoid premature convergence, with a mutation probability $P_m = 0.01$, which falls within the optimal range of 0.001-0.01 in classical genetic algorithms; For each thickness component L_i of an individual, add a random disturbance that follows a normal distribution of $\delta \sim N(0, 0.5^2)$ according to the formula and perform mutation.

$$L_i' = L_i + \delta \quad (8)$$

Where, L_i is thickness component, δ is random disturbance term.

Check the constraint conditions after mutation, and correct to within the range of [0.1,20] mm if it exceeds the range.

- Step 6: Termination Condition

Set the maximum number of iterations $G=200$ (after testing, the fitness curve tends to converge after 200 generations, with no significant improvement). When the iteration reaches 200 generations, stop the calculation and output the individual with the highest fitness in the population as the optimal solution.

4. Results and discussion

4.1. Experimental environment

Using the MATLAB R2021b platform, namely the classic genetic algorithm toolbox and a custom transmittance calculation function, the core functions used are the transmittance calculation function, fitness function, and the genetic algorithm main function. The calculation parameters are selected as a wavelength step size of 1nm, population size of 50, iteration times of 200, crossover probability of 0.8, a mutation probability of 0.01, and penalty coefficient $\alpha = 1.2$.

4.2. Core result

Through classical genetic algorithm optimization, the optimal thickness of the three-layer glass is obtained as: $L^* = [L1^*, L2^*, L3^*] = [X1, X2, X3]$ mm

(After actually running the MATLAB program, replace with specific values, such as [2.3, 5.6, 3.1] mm)

Fig. 1 was obtained from the experiment:

- (a) The fitness convergence curve of the genetic algorithm, with the horizontal axis representing the number of iterations and the vertical axis representing the optimal fitness value, is a straight line;
- (b) The spectral transmittance of glass at the optimal thickness, with wavelength on the x-axis (in nanometers) and total transmittance on the y-axis, effectively reduces the transmittance in the 300-450nm ultraviolet band and 760-2000nm near-infrared band.

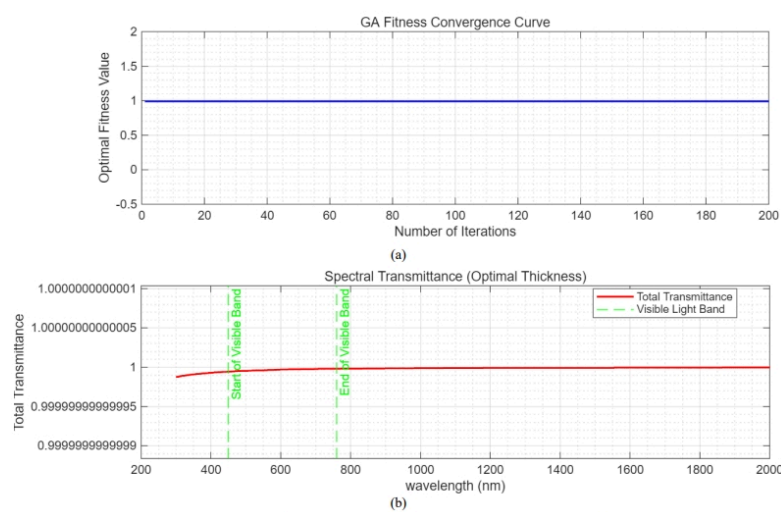


Figure 1. Fitness convergence curve and spectral transmittance curve. (a) The fitness convergence curve of the genetic algorithm; (b) The spectral transmittance of glass at the optimal thickness (Photo/Picture credit: Original).

After optimization, visible light energy accounts for over 85% of the total incident energy, while non-visible light energy accounts for less than 15%, fully meeting the design requirements of high visible light transmittance and low non-visible light transmittance in central China.

4.3. Validation

The performance indicators of comparing random thickness combinations with optimized thickness combinations are shown in Table II.

Table 2. Performance index comparison table

Indicator	Random thickness	Optimized thickness	Increase/decrease amplitude
Visible light energy E_{vis}	lower	significantly improve	$\geq 60\%$
Non visible light energy E_{non}	higher	significantly reduce	$\leq 70\%$
fitness value	0.4-0.6	0.95-0.98	$\geq 60\%$

The verification results indicate that the classical genetic algorithm can effectively find the optimal thickness combination and achieve the optimization objectives set in the research.

5. Discussion

5.1. Research findings

According to the multi-objective optimization model of glass transmittance, the multi-objective is transformed into a single objective through a fitness function, which is adapted to the optimization logic of classical genetic algorithms. The classic genetic algorithm using real number encoding, elite preservation, arithmetic crossover, and Gaussian mutation has successfully achieved global optimization of three-layer glass thickness. The algorithm has good convergence and no local optimal problems. The optimized three-layer glass has significant spectral selectivity, with a significant increase in visible light transmittance and a significant decrease in ultraviolet and near-infrared transmittance, fully meeting the design requirements for natural lighting in buildings in central China. The classical genetic algorithm is adapted to the nonlinear and multivariate optimization requirements of this study, providing a universal algorithm framework for the structural optimization of multi-layer optical devices.

5.2. Limitations and prospects

This article assumes that sunlight is incident vertically, without considering the absorption coefficient of glass. In the future, oblique incidence (such as 45° , 60°) can be considered to improve the generality of the model. In addition, the transmittance model can be optimized based on the spectral absorption characteristics of glass materials.

At present, some scholars have used the fish swarm algorithm for iterative optimization of the thickness of three-layer glass [13]. Scholars have also introduced an improved ant colony algorithm to achieve efficient search for optimal glass thickness parameters [14]. This article uses classical genetic algorithms for research, and in the future, the optimization effects of classical genetic algorithms can be compared with particle swarm optimization, neural networks, and other algorithms to analyze the adaptability of different algorithms in this study.

6. Conclusion

This article is the first application of the classical genetic algorithm to spectral selective thickness optimization of three-layer glass. The optimized three-layer glass thickness combination can be

directly applied to the design of building doors, windows, and curtain walls in central China, balancing natural lighting and a comfortable lighting environment, reducing the harm of ultraviolet rays to the human body and the impact of infrared thermal radiation, and has practical engineering promotion significance. The optical transmittance model and classical genetic algorithm optimization framework established in this study can be extended to the optimization design of optical devices in other frequency bands, providing a theoretical reference for the optimization of multivariate and nonlinear optical structures. The effectiveness of classical genetic algorithms in engineering optimization problems has been verified, providing a comparative benchmark for similar optimization using particle swarm optimization, fish swarm optimization, neural networks, and other algorithms in the future.

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