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Research on Optimization Combination of Heat Transfer Coefficient and Solar Heat Gain Coefficient of Plastic Doors and Windows in Frigid Regions and Carbon Reduction Pathways under the Target of Ultra-Low Energy Consumption

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ABSTRACT In ultra-low energy buildings in frigid regions, plastic doors and windows must simultaneously reduce heat transfer coefficients and optimize solar heat gain coefficients to balance heating demand and carbon reduction objectives. Since solar radiation is fundamentally governed by electromagnetic wave transmission and energy conversion processes, optimizing envelope parameters for efficient electromagnetic energy utilization has become increasingly important in sustainable building engineering. To address the conflict between energy consumption and carbon reduction, this paper constructs an optimal combination of U-value and solar heat gain coefficient together with a carbon reduction pathway. A coupled calculation model of door and window heat transfer and solar heat gain is established using meteorological annual data and an indoor heating setpoint of 20 °C. A two-dimensional parametric grid with U ranging from 0.60 to 1.20 W/(m^2·K) and SHGC ranging from 0.30 to 0.60 is evaluated through dynamic load calculations, while life-cycle carbon emissions are incorporated into a multi-objective optimization framework using a genetic algorithm and weighted entropy method. The results indicate that the optimal interval is U = 0.70–0.80 W/(m^2·K) and SHGC = 0. 45–0.50, reducing life-cycle carbon emissions from 24.8 to 19.9 kgCOe/(m^2·a) and peak heating load from 38.4 to 31.6 W/m^2. The proposed approach provides practical guidance for ultra-low energy building design and electromagnetic radiation-aware solar energy utilization.

INDEX TERMS heat transfer coefficient, solar heat gain coefficient, ultra-low energy building, electromagnetic radiation, carbon reduction

I. RESEARCH BACKGROUND AND CHALLENGES

A. CONSTRAINTS OF ULTRA-LOW ENERGY CONSUMPTION TARGETS ON PLASTIC DOORS AND WINDOWS IN EXTREMELY COLD REGIONS

Under the ultra-low energy consumption constraints of frigid regions, plastic doors and windows, enhanced by thermal-shielding interlayers, serve as the primary control items for managing energy consumption and peak loads during the heating season. The evaluation is no longer limited to meeting the single thermal insulation index, but requires thermal insulation performance and solar heat gain to meet the lower limit of net heating demand and the upper limit of indoor thermal comfort in synergy.

The study proposed to solve the thermal performance of the whole window in a partitioned manner, and to model the glass area and the frame and sash area separately. The heat transfer of the glass was calculated according to the thermal resistance network of the multi-layer structure and the heat transfer of the gas layer was included. The heat conduction of the frame and sash was calculated according to the equivalent heat conduction of the multi-cavity cross section and the steel lining was introduced to correct the thermal bridge. The edge and mullion node were calculated using linear thermal bridge and converted to the average heat transfer level of the whole window [1].

Solar heat gain is achieved by superimposing shortwave transmission and absorption into the room for secondary heat release, and the hourly solar altitude change is processed by the incident angle correction function. Then, the heat transfer and heat gain results are coupled into the hourly room energy balance. The indoor temperature is set at 20 °C. The heating start and stop are triggered by the temperature control hysteresis. The dry bulb temperature and total irradiance are input hourly in the meteorological year and the oriented irradiance decomposition is completed [2]. The net heating demand per unit area and the peak heating load of the heating season are output. At the same time, the incremental carbon emissions at the material end and the carbon emission factors at the operation end are unified to the annual average carbon emission intensity per unit area.

B. THE CONTRADICTION ARISING FROM THE COUPLING OF LOW HEAT TRANSFER COEFFICIENT AND SOLAR HEAT GAIN COEFFICIENT

Maintaining low heat transfer levels while effectively controlling solar heat gain presents a strong coupling contradiction in frigid regions, necessitating the integration of smart phase- multi-layered fiber insulation to balance thermal resistance with dynamic solar modulation. Strengthening insulation often relies on lowemissivity coatings and adjustments to the thickness of the air-filled layer. The coating location and spectral selection lead to a decrease in shortwave transmission, reducing the available solar heat gain during the heating season, thus offsetting the decrease in net heating demand [3,4]. Pursuing higher solar heat gain tends to increase transmission and weaken shading, resulting in delayed nighttime heat dissipation and early morning temperature recovery, raising the peak heating load and increasing the heat source capacity. The study quantifies this contradiction using hourly energy balance, decomposes the incident radiation on the window surface into direct and diffuse radiation according to orientation and time, and obtains the effective transmitted heat by superimposing the incident angle correction. The heat dissipation term is driven by the average heat transfer of the whole window and the indoor and outdoor temperature difference, and equivalent conversion is performed on the thermal bridge of the frame and the edge thermal bridge to avoid misjudging the nodal loss as glass performance. The parameter sweep uses the same building geometry and ventilation permeability settings, and calculates the net heating supply and maximum hourly heating power for the heating season in combination [5,6].

C. CHARACTERIZATION OF THE CONFLICT BETWEEN ENERGY CONSUMPTION TARGETS AND CARBON REDUCTION TARGETS

The energy consumption target and carbon reduction target are inconsistent in the optimization of plastic doors and windows. The reduction of heating energy consumption depends on lower heat transfer level and thicker structure. The increase in material usage leads to an increase in carbon emissions from production and transportation. The annual emission reduction brought about by energy saving at the operation end needs a longer time to offset the increase in material end. If the carbon emission factor of the heating heat source is too low, the offset period is lengthened. The order of the schemes in energy consumption and carbon emission evaluation is reversed [7,8] . The conflict characterization adopts a dual ledger accounting with the same parameter combination. The material analysis is based on the hardware decomposition list of profile and glass sealing components, with their mass and unit carbon emission factors converted to a per-unit window area basis. Then, the annual average carbon emission intensity is converted according to the service life. The operation side integrates the hourly heating load to obtain the annual heating demand and multiplies it by the heat source carbon emission factor to obtain the annual emission. The two are added together to form the life-cycle carbon emission intensity and form a two-dimensional evaluation surface with the annual heating demand [9]. After screening multiple combinations, it was found that simply reducing the heat transfer water usually reduces the annual heating demand, but the decrease in life-cycle carbon emission is limited by the increase in the material side. The compromise combination reduces both the annual heating demand and the life-cycle carbon emission.

II. METHODS AND TECHNICAL APPROACH

A. CONSTRUCTION OF A COUPLED CALCULATION MODEL FOR HEAT TRANSFER FROM DOORS AND WINDOWS AND SOLAR HEAT GAIN

The coupled model takes the parallel solution of whole window heat transfer and hourly solar heat gain as input. Geometrically, the window is divided into glass area, frame and sash area and edge node area. Thermally, a multi-layer thermal resistance network is used for the glass and the convection and radiation heat transfer of the gas layer are taken into account. For the frame and sash, a multi-cavity cross section is used for equivalent heat conduction and the thermal bridge caused by the steel lining and drainage cavity is superimposed to correct [10,11]. The linear thermal bridge strength of the node area is obtained by twodimensional steady-state heat transfer numerical calculation and converted to the average heat transfer contribution of the whole window according to the side length, forming a whole window heat transfer characterization consistent with the window size.

The solar heat gain is calculated using a combination of optical and thermal reradiative methods. The incident shortwave is decomposed into transmission and absorption, and the absorbed energy is distributed according to the convective heat transfer coefficient of the inner and outer surfaces and the longwave radiation heat transfer coefficient to obtain the secondary heat released into the room. The incident angle effect is applied to the hourly direct irradiance through the angle correction function and superimposed with the scattered irradiance. External shading and window frame shading are processed according to the projection coefficient to obtain the effective light-receiving area.

The model coupling is achieved through hourly energy balance closure of the room. The heat transfer term is generated by the indoor and outdoor temperature difference and the average heat transfer contribution of the whole window, while the solar heat gain term is generated by the effective irradiance and the heat gain coefficient. At the same time, the inner surface temperature is used to check the risk of radiative heat transfer and cold radiation, so that heat transfer and heat gain can feed back to each other within the same time step and output the hourly heating load for subsequent optimization.

B. SETTING OF METEOROLOGICAL ANNUAL DATA AND INDOOR HEATING CONTROL BOUNDARIES

Meteorological boundaries are driven by hourly data from typical meteorological years, reading dry-bulb temperature, relative humidity, wind speed, atmospheric longwave radiation level, and total solar irradiance on the horizontal surface. Based on the solar position algorithm, the solar altitude angle and azimuth angle are calculated from latitude, longitude, and time zone. The total horizontal irradiance is decomposed into direct and diffuse radiation and converted to vertical planes of each orientation. Ground reflection is given according to the surface albedo to form the shortwave incident flux on the outer surface of the window. At the same time, the convective heat transfer coefficient of the outer surface is calculated from wind speed and outer surface roughness. Longwave radiation heat transfer is corrected by sky effective temperature and perspective factor to ensure that the heat transfer calculation and solar heat gain calculation use the same meteorological time series and the same time step.

The indoor heating control boundary employs constant temperature control and hysteresis triggering logic. The target indoor air temperature is set at 20 °C, and a minimum start-stop interval is defined to suppress numerical oscillations caused by frequent start-stop cycles. The heating system is input as an ideal heat source to directly map window parameter changes to load changes without introducing equipment efficiency disturbances. Internal heat gain is given based on occupancy and lighting power density, and a work/rest period curve is set. Infiltration ventilation is converted into hourly ventilation volume using a pressure difference and wind pressure coupling model and superimposed with the mechanical fresh air setting. Indoor longwave radiation heat transfer is closed-loop based on the building envelope surface temperature and mean radiation temperature.

Window opening and shading behaviors are kept to a fixed rule to avoid the behavior parameters masking the thermal coupling effect of doors and windows. The hourly indoor temperature deviation and heating input power are output as boundary constraints for the subsequent objective function.

C. PARAMETER GRID SETTING AND DYNAMIC LOAD CALCULATION

The parametric mesh is constructed as a two-dimensional discrete set around the overall window insulation level and solar heat gain level. The value range covers the commonly used design range of ultra-low energy consumption doors and windows and is set with equal interval step size. The mesh points are mapped oneto-one with the feasible structures to avoid falling into unmanufacturable areas. Each mesh point obtains a consistent combination of glass configuration and profile cavity thermal resistance through back calculation of the construction parameters. At the same time, the same node library is used for edge thermal bridges and mullion nodes to ensure that the differences between different mesh points are only caused by changes in the target parameters. The window-to-wall ratio is kept constant to isolate the parameter coupling effect. Dynamic load calculation uses hourly heat balance as the solution unit, with the time step consistent with annual meteorological data. The heat transfer term is generated from the indoor-outdoor temperature difference and the whole-window heat transfer characteristic. The solar heat gain term is generated from hourly directional irradiance and heat gain characteristic, superimposed with indoor heat gain and ventilation infiltration load. Indoor air temperature is updated by integrating sensible heat capacity and heat transfer flux and is constrained by heating control logic. To reduce numerical errors, time interpolation is used to smooth abrupt changes in solar irradiance at sunrise and sunset. A minimum running time is introduced for heating start-up and shutdown, and a threshold is set for the indoor temperature iteration convergence criterion.

D. CONSTRUCTION OF THE OBJECTIVE FUNCTION FOR CARBON EMISSIONS THROUGHOUT THE LIFE CYCLE

The carbon emission target for the entire life cycle is measured by the average annual carbon emission intensity per unit window area. The material side adopts the list method, and the mass is converted from the list of cross-sectional dimensions and lengths and corrected according to the loss rate. The carbon emission factor is taken from the traceability database and distinguishes the proportion of virgin materials and recycled materials. Composite components are treated according to mass allocation.

The manufacturing end is calculated by multiplying the power and heat consumption intensity by the regional power grid emission factor, with glass deep processing and profile extrusion included separately, and the surface coating and gas filling processes are checked by the process energy consumption intensity and combined into the manufacturing end [12].

The transportation end is calculated in ton-kilometers based on the mode of transport and distance, and the loading rate is added for correction. The installation end is calculated based on the energy consumption of on-

TABLE 1. Configuration and Constraint Settings of Multi-Objective Genetic Algorithm

Parameters	Set up	Target	Remark
Population size	120	Non-dominated sorting	Coverage control
Crossover probability	0.90	Cross operator	Adaptive decay
Mutation probability	0.10	Mutation Operator	Reflection Repair
Elite ratio	0.10	Retention strategy	Anti-degradation
Termination conditions	Super-volume increment threshold	Convergence Criterion	Continuous generation determination

site auxiliary materials and machinery, and is repeatedly calculated at the replacement cycle. The carbon emission at the operating end is obtained by multiplying the annual heating demand calculated from the dynamic load with the heat source carbon emission factor. The heat source factor is given according to the heating system type and regional energy supply structure and is isolated from interannual variation scenarios.

E. MULTI-OBJECTIVE GENETIC ALGORITHM SOLUTION AND PARETO SOLUTION SET ACQUISITION

The multi-objective genetic algorithm encodes the combination of door and window parameters into continuous genes and applies manufacturability constraints. The initial population adopts Latin hypercube sampling to cover the design domain. The fitness is composed of annual heating demand and annual average carbon emission intensity, plus peak load and minimum inner surface temperature penalty terms. The nondominated sorting obtains the rank and the crowding degree maintains the discreteness of the solution. Crossover employs a simulated binary operator and converges adaptively with each algebra. Mutation uses polynomial perturbation and performs reflective repair on individuals that exceed the limits. Constraint violations are handled through feasibility-first rules to advance the search along the feasible boundary. Elite retention copies the frontier solution into the next generation to avoid degradation. The termination criterion is triggered when the frontier hypervolume increment is below a threshold and continues for several generations. The output is a non-dominated solution set, and duplicate solutions are merged according to a distance threshold to form a Pareto solution set for subsequent compromise selection. Its specific configuration and constraints are shown in Table 1.

Table 1 shows the solver parameters and constraint handling interface. The population size and crossover mutation intensity jointly determine the frontier exploration width. The elite ratio is used to lock the obtained non-dominated solutions. The termination condition is replaced by frontier morphology changes to avoid overcomputation.

TABLE 2. Weighted Entropy Method Screening Process and Parameter Settings

Link	Enter	Output	Key points of handling
Normalization	Original matrix of indicators	Dimensionless matrix	Cost-based homogenization
Entropy calculation	Dimensionless matrix	Entropy vector	Add the smallest positive number
Weight fusion	Entropy weights and preference weights	Overall weight	Convex combination constraints
Rating and sorting	Comprehensive weights and matrices	Score sequence	Penalty items enlarged
Feasible Filtering	Score sequence	compromise	Threshold elimination

F. WEIGHTED ENTROPY METHOD FOR COMPROMISE SCHEME SELECTION

The weighted entropy method is used to compress the Pareto solution set into a single compromise solution, with the input being the evaluation matrix for each non-dominated solution. Data preprocessing employs interval normalization and introduces minimal positive numbers to prevent logarithmic singularities caused by zero values. Information entropy is calculated based on the sample proportion to obtain the dispersion coefficient; indicators with higher dispersion have greater weights to reflect their discriminative ability. The weight fusion adopts a convex combination of subjective and objective factors. The subjective weight comes from the target preference of ultra-low energy consumption and carbon reduction constraints, while the objective weight comes from entropy weight. After combination, a weighted comprehensive score is calculated for each solution and sorted according to the score.

To avoid the compromise solution falling on the constraint boundary, the penalty term is amplified twice and a feasibility screening threshold is set before sorting. The top-ranked solutions are output and their normalized contributions on each indicator are recorded for sensitivity interpretation. The weighted entropy method screening process and parameters are shown in Table 2.

The data flow corresponding to Table 2 ensures that the weights are driven by the discreteness of the samples and are compatible with engineering preferences. The penalty terms and thresholds transform comfort and load constraints into screening conditions, avoiding the inclusion of infeasible solutions due to reliance solely on scores.

III. RESULTS AND OPTIMAL COMBINATIONS

A. OPTIMAL U VALUE AND SHGC INTERVAL

After feasibility screening, the Pareto solutions exhibit a banded distribution. Solutions within the band show simultaneous reductions in annual heating demand and average annual carbon emission intensity, with peak loads under control. Solutions outside the band show improvement in one indicator accompanied by a rebound in another. The compromise solution selection uses weighted entropy scoring and sets a threshold for the lowest deviation of the inner surface temperature. The optimal range falls within

TABLE 3. Representative Combinations and Evaluation Indicators for Optimal Intervals

Combination	Heat transfer coefficient W/(m^2·K)	SHGC	Net heating supply during the heating season (kWh/(m^2·a))
A	0.80	0.45	42.7
B	0.75	0.50	41.3
C	0.70	0.55	41.9
D	0.90	0.35	48.9
E	1.10	0.35	52.6

the coupling region of low heat transfer and moderate solar heat gain, reflecting a balance between daytime heat gain compensation and nighttime heat dissipation suppression during the heating season. Statistical analysis of the density and score distribution of the frontier solutions shows that heat transfer levels are concentrated between 0.70 and 0.80 W/(m^2·K), and solar heat gain is concentrated between 0.45 and 0.50. Solutions outside the range either have insufficient net heating reduction due to low transmission or experience a peak rebound due to high transmission, pushing up carbon emissions at the operating end.

Table 3 shows that the net heat supply decreases from 52.6 to 41.3 when moving from E to B. The net heat supply at C increases to 41.9 due to higher solar heat gain under lower heat transfer conditions. The net heat supply at A increases compared to B and corresponds to lower solar heat gain. Thus, the optimal interval converges to the neighborhood of B.

B. CHANGES IN NET HEATING DEMAND DURING THE HEATING SEASON

The net heating demand during the heating season is obtained by integrating the hourly heating input power and normalizing it by building area. The calculation process maintains the same window-to-wall ratio and orientation for the same meteorological year and the same ventilation and infiltration settings, so that the difference is caused only by the combination of heat transfer from doors and windows and solar heat gain. Net heating supply is determined by two competing factors: at night and during periods of low solar radiation, building envelope heat dissipation dominates, while during clear daytime periods, transmitted heat gain offsets the heating input. The combined effect of these two factors creates a nonlinear response to both heat transfer and solar heat gain levels. The baseline net heating supply is 52.6 kWh/(m^2·a). When heat transfer decreases but solar heat gain remains low, the net heating supply drops to 48.9 kWh/(m^2·a), with the decrease limited by insufficient daytime heat gain.

After optimizing both heat transfer and solar heat gain, the net heating output decreased to 41.3 kWh/(m^2·a), a 21.5% reduction from the baseline. This corresponds to a shorter daytime heating input period on sunny days and a decrease in nighttime warming demand. After further increasing solar heat gain and reducing heat transfer, the net heating output rebounded to 41.9 kWh/(m^2·a), reflecting the additional heating compensation brought about by the time mismatch between daytime gains and nighttime heat dissipation.

C. CARBON EMISSION CHANGES THROUGHOUT THE LIFE CYCLE

The carbon emissions throughout the entire life cycle are summarized on an annual average basis per unit window area. Material manufacturing, transportation, installation and replacement form carbon emissions at the material end. The carbon emissions at the operation end are calculated based on the hourly heating load and added to the carbon emissions at the material end to obtain the total. Comparing different parameter combinations, it can be seen that the carbon emissions at the material end increase with the strengthening of insulation. This is due to the deepening of the profile cavity, the increase in steel lining configuration and the increase in energy consumption of glass layers and deep processing. The carbon emissions at the operation end decrease as the net heating supply decreases during the heating season. The combination of the two forms a minimum value range rather than a monotonic decrease.

The baseline combination has a total carbon emission of 24.8 $kgCO_2e$/(m^2·a). In combinations with reduced heat transfer but low solar heat gain, the decrease in total carbon emission is limited, and the proportion of material-related emissions increases. The compromise combination with synergistic optimization of heat transfer and solar heat gain has a total carbon emission of 19.9 $kgCO_2e$/(m^2·a), a 19.8% reduction relative to the baseline. This corresponds to a situation where emission reduction at the operational end is dominant, and the increase in material-related emissions does not offset the reduction at the operational end. Combinations that continue to reduce heat transfer and increase solar heat gain show a rebound in total carbon emissions, with a narrowing of the reduction at the operational end and an expansion of the increase in material-related emissions. This results in the lowest point of total carbon emission in the frontier solution not completely coinciding with the lowest point of net heat supply.

D. PEAK HEATING LOAD VARIATION

Peak heating load is the maximum value of hourly heating input power and normalized according to building area. It is used to characterize the demand for heat source installed capacity and terminal heating capacity. The peak occurs during the period of superposition of low outdoor temperature and low radiation, and the indoor temperature control hysteresis triggers continuous heat replenishment. The proportion of heat loss through doors and windows increases, so it is more sensitive to the heat transfer level. At the same time, the solar heat gain level indirectly affects the peak through daytime heat storage and nighttime temperature recovery.

The baseline combination peak value is 38.4 W/m^2, which drops to 35.6 W/m^2 when heat transfer is reduced and solar heat gain is low. The decrease in peak value is mainly due to reduced heat dissipation from windows at night.

The compromise combination of optimized heat transfer and solar heat gain reduces the peak value to 31.6 W/m^2, corresponding to a narrower drop in indoor temperature and a reduction in the number of hysteresis triggers.

The solar heat gain further increased, and the combined peak value with lower heat transfer rose to 32.1 W/m^2. This was manifested as increased heat gain during the day leading to a change in the nighttime temperature control heat replenishment rhythm, resulting in more concentrated short-term heat replenishment.

The peak value change is not completely synchronized with the net heat supply change. The peak value is more sensitive to heat transfer and has a bidirectional effect on solar heat gain. Therefore, the compromise range is further converged to heat transfer of 0.70 to 0.80 W/(m^2·K) and solar heat gain of 0.45 to 0.50 by the peak value constraint.

IV. CARBON REDUCTION PATH OUTPUT

A. FRAMEWORK FOR COMPARISON BETWEEN BASELINE AND OPTIMIZED SCHEMES

The comparison process is divided into three parallel links. The thermal link outputs the hourly heating load and summarizes the net heating supply and peak load of the heating season. The link outputs a unit area mass list and maps it to the carbon emissions of materials and manufacturing. The operation link converts the net heating supply of the heating season into operation carbon emissions and adds them to the carbon emissions of the material end on an annual average basis.

The difference decomposition uses contribution rate accounting, breaking down the total carbon emission difference into material-side increments and operation-side reductions, and simultaneously providing the offset ratio to determine whether the optimization falls into the material-side increment-dominant zone. The framework output is presented in parallel with three types of indicators: net heating supply during the heating season decreased from 52.6 to 41.3 kWh/(m^2·a), peak emissions decreased from 38.4 to 31.6 W/m^2, and lifecycle carbon emissions decreased from 24.8 to 19.9 kgCO_2e/(m^2·a), supporting the verifiability of the carbon reduction path.

B. CARBON REDUCTION PATH DRIVEN BY DOOR AND WINDOW PARAMETER COMBINATIONS IN THE OPERATIONAL PHASE

The carbon reduction path during operation focuses on shaping the hourly heating load curve through the combination of door and window parameters.This is achieved by minimizing heat-loss fluctuations and optimizing the timing of solar heat utilization, thereby reducing heating demand and flattening peak load variations. The implementation of this path extends from the thermal parameters of doors and windows to feasible configurations at the structural level. On the insulation side, the selection of interglazing gas and lowemissivity coating surfaces reduces nighttime heat transfer. On the frame and sash side, multi-cavity cross-sections and steel-lined partitions suppress linear thermal bridges. On the installation side, opening connection nodes are included in thermal bridge control, and the sealing system is continuously verified to reduce the additional load from infiltration ventilation.

The heat gain side improves effective transmission during the heating season through spectral selection and angle response verification, and constrains the projection coefficient of window frame shading and external obstruction, so that the daytime heat gain enters the room and participates in the heat storage and release process of the building envelope surface and indoor air, thereby reducing the number of times the temperature control hysteresis triggers the reheating.

The operational accounting maps changes in door and window parameters to the input power sequence of the heating system, calculates operational carbon emissions based on the same heat source emission factor, and compares them with the baseline operating conditions. The path evaluation also checks the lower limit of indoor surface temperature and the upper limit of peak load to ensure that carbon reduction comes from load reduction rather than comfort sacrifice.

V. CONCLUSION

In frigid regions, plastic doors and windows exhibit a strong coupling between heat transfer reduction and solar heat gain control under ultra-low energy consumption constraints, requiring the synergy of high-density insulating membranes and thermal-regulating fibers to optimize the building envelope's overall energy efficiency. Unilaterally pursuing either insulation or heat gain can lead to insufficient net heat gain utilization and peak load redistribution during the heating season, ultimately impacting life-cycle carbon emissions. This paper establishes a coupled calculation of heat transfer and solar heat gain, incorporating hourly boundaries and constant-temperature heating control for typical meteorological years. Energy consumption response surfaces are obtained through two-dimensional parametric meshes and dynamic load simulations. Life-cycle assessments are constructed by unifying material-side and operational-side carbon emissions to the same functional unit. A multi-objective genetic search is used to obtain non-dominated solution sets, and a weighted entropy method is employed to fuse engineering preferences and information dispersion to lock in compromise solution intervals. This forms an operational-stage carbon reduction path driven by door and window parameter combinations and provides screening criteria consistent with installed capacity constraints. However, the limitations lie in the insufficient exploration of regional differences in material carbon emission factors and the impact of varying actual door and window permeability under different operating conditions. Future research will introduce multi-city climate zones, heat source structure scenarios, and uncertainties related to node construction quality to improve the extrapolability of the conclusions.

AUTHOR CONTRIBUTIONS

Meng Zhang designed, collected and analyzed the data, and drafted the manuscript. Meng Zhang conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Meng Zhang participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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