

BUILDING ENERGY OPTIMIZATION AND ALGORITHM PARAMETER TUNING FOR THERMAL AND DAYLIGHT PERFORMANCE

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Building Energy Optimization and Algorithm Parameter Tuning for Thermal and Daylight Performance

by

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Dedication

This thesis is dedicated to my grandparents who I know are watching over me and blessing me from the heaven

Late Retd. Jailor S. Waqar Hussain Zaidi (Dada)

Late Mr. Mehdi Hassan (Papa)

Late Ms. Asghari Begum (Dadi)

Late Ms. Suraiyya Khanam (Amma)

Certificate

This is to certify that the thesis entitled “**Building Energy Optimization and Algorithm Parameter Tuning for Thermal and Daylight Performance**” being submitted by **Sana Fatima Ali** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of ‘**Doctor of Philosophy**’ and is a record of the original bona fide research work carried out by her under our guidance and supervision at Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The results contained in the thesis have not been submitted in part or full, to any other University or Institute for the award of any degree or diploma.

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Sana Fatima Ali

Abstract

Amidst global concerns over climate change and fossil fuel depletion, designers are increasingly integrating energy-saving measures inspired by ancient architectural techniques, emphasizing indoor comfort and daylight exposure without relying on non-renewable resources. The significance of thermal comfort and daylight in buildings for occupant well-being and productivity, energy efficiency, and sustainability aligns with environmental goals, and fostering a connection to the external environment. This shift towards passive design strategies is particularly pronounced in solar-rich regions such as India.

Analysis-based design, utilizing simulations and computational models, is crucial for informed decision-making. The present study thus employs the Building Energy Simulation-Optimization (BESO) approach, enabling a comprehensive evaluation before physical construction and ensuring compliance with performance objectives and regulatory standards. The central goal is enhancing thermal performance, especially in tropical climates where heat, cold, and humidity present challenges. The BESO framework optimizes the Tropical Summer Index for natural conditioning and minimizes air conditioning loads through strategic building design.

Traditionally, Genetic Algorithms (GA) are preferred for optimizing building parameters, but their limitations require exploring more efficient alternatives. The Grasshopper Optimization Algorithm (GOA), known for computational efficiency, suitability for discrete variables, and local optima avoidance, emerges as a compelling choice. This study pioneers GOA's application in building parameter optimization, conducting a comparative analysis with GA. Results show that GOA enhances thermal performance by 0.44% to 1.47% in naturally conditioned buildings and 2.32% to 12.37% in air-conditioned buildings compared to GA.

The study expands to address lighting's role in energy consumption and occupant well-being, emphasizing harnessing daylight in tropical climates through expansive windows. Using GA and GOA-based BESO, it compares their efficacy in maximizing daylight admittance with the Perez sky model. GOA achieves a visual performance enhancement of 0.22% to 0.27%. Further, balancing daylight admission and heat mitigation highlights the multifaceted nature of tropical climatic objectives. A multi-objective optimization analysis, using multi-objective forms of GA and GOA (NSGA-II and MOGOA), is conducted across three Indian climatic zones. Results show improvements in solutions by MOGOA compared to NSGA-II. Moreover, execution of GOA and MOGOA leads to significant reductions in computational time, ranging from 0.04% to 57.22%.

Further, algorithm optimization relies on precise parameter configuration. The study explores two methodologies: meta-optimization using an auxiliary algorithm for calibration, and dynamic modulation of parameters through Reinforcement Learning (RL) principles. These approaches, previously unexplored in the BESO domain, hold the promise of untangling nuanced optimization challenges. Fine-tuning parameters leads to enhancements, with meta-optimization improving by 0.04% to 2.76%, and RL-based fine-tuning demonstrating a further enhancement of 0.22% to 5.94% in the results. Results also demonstrate that the diverse decision variables interact with each other, and their holistic consideration is a critical factor in sustainable building design.

In conclusion, the outcomes offer practical recommendations for selecting appropriate building design parameters based on specific objectives. Overall, this research advances the knowledge and understanding of BESO and fine-tuning of algorithm parameters. The study contributes to the development of more efficient building designs in tropical regions of India, offering innovative strategies for algorithm parameter optimization in both fixed and adaptive approaches.

जलवायु परिवर्तन और जीवाश्म ईंधन की कमी की वैश्विक चिंताओं के बीच, डिजाइनर प्राचीन वास्तुशिल्प तकनीकों से प्रेरित ऊर्जा-बचत उपायों को तेज़ी से एकीकृत कर रहे हैं, तथा गैर-नवीकरणीय संसाधनों पर निर्भरता के बिना इनडोर आराम और दिन की रोशनी पर ज़ोर दे रहे हैं। इमारतों में थर्मल सुखदायकता और दिन की रोशनी का महत्व निवासियों के कल्याण और उत्पादकता, ऊर्जा कुशलता और प्रतिस्थायित्व के साथ मिलता है, तथा पर्यावरणीय लक्ष्यों के साथ मेल खाता है, और बाहरी पर्यावरण से जुड़ने का परिप्रेक्ष्य बढ़ाने में मदद करता है। निष्क्रिय डिज़ाइन रणनीतियों की ओर यह बदलाव विशेष रूप से भारत जैसे सौर-समृद्ध क्षेत्रों में स्पष्ट है।

विश्लेषण-आधारित डिज़ाइन, सिमुलेशन और संगणनात्मक मॉडलों का उपयोग करके, सूचित निर्णय लेने के लिए महत्वपूर्ण है। वर्तमान अध्ययन इस प्रकार बिल्डिंग ऊर्जा सिमुलेशन-अनुकूलन (बीईएसओ) दृष्टिकोण का उपयोग करता है, जो भौतिक निर्माण से पहले एक व्यापक मूल्यांकन को सक्षम बनाता है और प्रदर्शन लक्ष्यों और विनियामक मानकों के संरचन के साथ अनुपालन सुनिश्चित करता है। केंद्रीय लक्ष्य थर्मल प्रदर्शन को बढ़ाना है, विशेष रूप से वे उष्णकटिबंधीय जलवायुओं में जहां गर्मी, ठंड और आर्द्रता चुनौतियां प्रस्तुत करती हैं। बीईएसओ ढांचा प्राकृतिक कंडीशनिंग के लिए उष्णकटिबंधीय ग्रीष्मकालीन सूचकांक को अनुकूलित करता है और रणनीतिक इमारत डिज़ाइन के माध्यम से एयर कंडीशनिंग भार को कम करता है।

परंपरागत रूप से, बिल्डिंग मापदंडों को अनुकूलित करने के लिए जेनेटिक एल्गोरिदम (जीए) को प्राथमिकता दी जाती है, लेकिन उनकी सीमाएँ अधिक प्रभावी विकल्पों की खोज की आवश्यकता को दर्शाती है। ग्रासहॉपर अनुकूलन एल्गोरिदम (जीओए), संगणनात्मक प्रभावशीलता, अलग-अलग चरित्र वाले मानों के लिए उपयुक्तता, और स्थानीय अधिकतम से बचाव के लिए प्रसिद्ध होने के लिए एक आकर्षक विकल्प के रूप में सामने आता है। यह अध्ययन जीए के साथ तुलनात्मक विश्लेषण करते हुए, पैरामीटर अनुकूलन के निर्माण में जीओए के अनुप्रयोग को आगे बढ़ाता है। परिणाम दिखाते हैं कि जीओए प्राकृतिक रूप से वातानुकूलित इमारतों में थर्मल प्रदर्शन को 0.44% से 1.47% और वातानुकूलित इमारतों में 2.32% से 12.37% जीए की तुलना में महत्वपूर्ण रूप से बढ़ाता है।

अध्ययन में ऊर्जा की खपत और निवासियों की भलाई में प्रकाश की भूमिका को संबोधित करने के लिए विस्तार किया गया है, जिसमें विस्तृत खिड़कियों के माध्यम से उष्णकटिबंधीय जलवायु में दिन की रोशनी का उपयोग करने पर जोर दिया गया है। जीए और जीओए आधारित बीईएसओ का उपयोग करते हुए, यह पेरेज़ स्काई मॉडल के साथ दिन की रोशनी के प्रवेश को अधिकतम करने में उनकी प्रभावकारिता की तुलना करता है। जीओए ने दृश्य प्रदर्शन में 0.22% से 0.27% की वृद्धि हासिल की। इसके अलावा, दिन की रोशनी के प्रवेश और गर्मी के शमन को संतुलित करना उष्णकटिबंधीय जलवायु उद्देश्यों की बहुमुखी प्रकृति पर प्रकाश डालता है। तीन भारतीय जलवायु क्षेत्रों में बहुउद्देश्यीय अनुकूलन विश्लेषण, जीए और जीओए (एनएसजीए-II और एमओजीओए) के बहुउद्देश्यीय रूपों का उपयोग करके, किया गया है। परिणाम दिखाते हैं कि एनएसजीए-II की तुलना में एमओजीओए द्वारा समाधानों में सुधार है। इसके अतिरिक्त, जीओए और एमओजीओए के प्रयोग से संगणकीय समय में 0.04% से 57.22% तक की महत्वपूर्ण कमी आती है।

और इसके अतिरिक्त, एल्गोरिदम अनुकूलन सटीक पैरामीटर समायोजन पर निर्भर करता है। अध्ययन दो विधियों का अन्वेषण करता है: सहायक एल्गोरिदम का उपयोग करके मेटा-अनुकूलन के लिए निर्धारण करने के लिए, और पैरामीटरों की गतिविधि को संवारने के लिए पुनर्निर्देशन शिक्षा (आरएल) के सिद्धांतों के माध्यम से। यह दो उपाय, पहले बीईएसओ क्षेत्र में अनदेखे थे, सूक्ष्म अनुकूलन की चुनौतियों को सुलझाने की आशा रखते हैं। पैरामीटरों को धीरे-धीरे समायोजन करने से सुधार होता है, जिसमें मेटा-अनुकूलन 0.04% से 2.76% तक सुधार होता है, और आरएल-आधारित समायोजन नतीजों में और अधिक सुधार का प्रदर्शन करता है, 0.22% से 5.94% तक। परिणाम यह भी प्रदर्शित करते हैं कि विविध निर्णय चर एक-दूसरे के साथ प्रभावित होते हैं, और उनका समग्र विचार स्थायी इमारत डिज़ाइन में एक महत्वपूर्ण कारक है।

निष्कर्ष में, परिणाम विशिष्ट उद्देश्यों के आधार पर उपयुक्त भवन डिज़ाइन मापदंडों के चयन के लिए व्यावहारिक सिफारिशें प्रदान करते हैं। समग्र रूप से, यह शोध बीईएसओ के ज्ञान और समझ और एल्गोरिदम मापदंडों की फाइन-ट्यूनिंग को आगे बढ़ाता है। यह अध्ययन भारत के उष्णकटिबंधीय क्षेत्रों में अधिक कुशल भवन डिज़ाइनों के विकास में योगदान देता है, जो निश्चित और अनुकूली दोनों दृष्टिकोणों में एल्गोरिदम पैरामीटर अनुकूलन के लिए नवीन रणनीतियों की पेशकश करता है।

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Nomenclature

a_{CIE}	Coefficient for CIE sky model
a_{ISM}	Coefficient for Igawa sky model
a_n	First Element of the Transmission Matrix of n^{th} Layer
a_{PSM}	Coefficient for Perez sky model
a_t	Current action for Q-learning
A	Set of executable actions in Q-learning
A_i	Wind advection on i^{th} grasshopper
A_j	Area of j^{th} Opaque surface [m ²]
A_r	Area of r^{th} Transparent surface [m ²]
A_{OTM}	First Element of the Overall Transmission Matrix
A_{TM}	First Element of the Transmission Matrix
AY	Area-Weighted Sum of Admittance Factor of the Inside Surfaces
$AR(t)$	Actual response of the system at time t
A_1	Window Area A_1 of the 1 st Wall [m ²]
A_2	Window Area A_2 of the 2 nd Wall [m ²]
A_3	Window Area A_3 of the 3 rd Wall [m ²]
A_4	Window Area A_4 of the 4 th Wall [m ²]
b_{CIE}	Coefficient for CIE sky model
b_{ISM}	Coefficient for Igawa sky model
b_n	Second Element of the Transmission Matrix of n^{th} Layer

b_{PSM}	Coefficient for Perez sky model
B_{OTM}	Second Element of the Overall Transmission Matrix
B_{TM}	Second Element of the Transmission Matrix
c	Decreasing Coefficient
c_{max}	Maximum Value of c
c_{min}	Minimum Value of c
c_{CIE}	Coefficient for CIE sky model
c_{ISM}	Coefficient for Igawa sky model
c_n	Third Element of the Transmission Matrix of n^{th} Layer
c_{PSM}	Coefficient for Perez sky model
c_{PSM_1}	First term required for calculation of respective c_{PSM} coefficient for Perez sky model
c_{PSM_2}	Second term required for calculation of respective c_{PSM} coefficient for Perez sky model
c_{PSM_3}	Third term required for calculation of respective c_{PSM} coefficient for Perez sky model
C	Specific Heat Capacity of a Material [J/kg.K]
C_{mv}	Mean Ventilation Conductance [W/k]
C_{OTM}	Third Element of the Overall Transmission Matrix
C_{TM}	Third Element of the Transmission Matrix
$C_v(t)$	Ventilation heat transfer coefficient for t^{th} hour [Wh]
C_1^+	Degree of Closeness for an Ideal Solution

d_{CIE}	Coefficient for CIE sky model
d_{ij}	Distance between i^{th} Grasshopper and j^{th} Grasshopper
\hat{d}_{ij}	Unit Vector from i^{th} Grasshopper and j^{th} Grasshopper
d_{ISM}	Coefficient for Igawa Sky Model
$D_{m_{ea}}$	m_{ea}^{th} Evaluation Objective
d_n	Fourth Element of the Transmission Matrix of n^{th} Layer
d_{PSM}	Coefficient for Perez sky model
d_{PSM_1}	First term required for calculation of respective d_{PSM} coefficient for Perez sky model
d_{PSM_2}	Second term required for calculation of respective d_{PSM} coefficient for Perez sky model
d_{PSM_3}	Third term required for calculation of respective d_{PSM} coefficient for Perez sky model
d_{PSM_4}	Fourth term required for calculation of respective d_{PSM} coefficient for Perez sky model
ds	Small Elemental Area
DAF_i	Vertical Sky Illuminance on the Window Area A_i of the i^{th} Wall [lux]
DAF_1	Vertical Sky Illuminance on the Window Area A_1 of the 1 st Wall [lux]
DAF_2	Vertical Sky Illuminance on the Window Area A_2 of the 2 nd Wall [lux]

DAF_3	Vertical Sky Illuminance on the Window Area A_3 of the 3 rd Wall [lux]
DAF_4	Vertical Sky Illuminance on the Window Area A_4 of the 4 th Wall [lux]
D_{OTM}	Fourth Element of the Overall Transmission Matrix
D_{TM}	Fourth Element of the Transmission Matrix
e_{CIE}	Coefficient for CIE Sky Model
\hat{e}_g	Unit Vector towards the Earth's Centre
e_j	Entropy of the index j
e_{PSM}	Coefficient for Perez Sky Model
\hat{e}_w	Unit Vector in Wind Direction
E	Illumination Value [lux]
E_n	Illumination on a Horizontal Plane [lux]
$E_{\theta_{in}}$	Illumination Value at a plane at an incidence angle θ_{in} [lux]
$E(t - m_{int}\Delta_{URF})$	Flux or Temperature Excitation
f_a	Attraction Intensity between Grasshoppers
f_i	Sky Condition Parameter for Computation of Zenith Luminance
g	Gravitational Constant
g_i	Sky Condition Parameter for Computation of Zenith Luminance
g_{si}	Scattering Indicatrix Function
G_i	Gravity Force on i^{th} Grasshopper
h_i	Inner Surface Layer's Surface Conductance [W/m ² K]

h'_i	Sky Condition Parameter for Computation of Zenith Luminance
h_o	Outer Surface Layer's Surface Conductance [W/m ² K]
h_{oj}	Convective Heat Transfer Coefficient for Outer Surface [W/m ² K]
I	Light Intensity [cd]
$I(t)$	Solar Radiation Intensity at t^{th} Hour [W/m ²]
I_{DHI}	Horizontal Diffuse Irradiance [W/m ²]
I_{DNI}	Normal Incident Direct Irradiance [W/m ²]
$I_f(t)$	Fluctuating Solar Radiation Intensity at t^{th} Hour [W/m ²]
$I_{fj}(t - \phi_d - \phi_Y)$	Fluctuating Solar Radiation Intensity falling at j^{th} Opaque Surface at $(t - \phi_d - \phi_Y)^{th}$ Hour [W/m ²]
$I_{fr}(t)$	Fluctuating Solar Radiation Intensity falling at r^{th} Transparent Surface at t^{th} Hour [W/m ²]
$I_{j_{harm}}$	Solar Radiation Intensity Amplitude of the j_{harm}^{th} harmonic
I_m	Mean Solar Radiation Intensity [W/m ²]
I_{mj}	Mean Solar Radiation on j^{th} Opaque Surface [W/m ²]
I_{mr}	Mean Solar Radiation on r^{th} Transparent Surface [W/m ²]
I_{SO}	Normal Incident Extra-Terrestrial Irradiance [W/m ²]
j_{harm}	Number of Harmonics
j_i	Sky Condition Parameter for Computation of Zenith Luminance
J_1	Set of Beneficial Criteria
J_2	Set of Non-beneficial Criteria
k	Thermal Conductivity [W/m.K]

k_{grad}	Coefficient for Gradation Function Calculation
K	Coefficient for Calculation of WBT
l_s	Attractive Length Scale
lb_d	Lower Bound in d^{th} Dimension
l_{grad}	Coefficient for Gradation Function Calculation
l_i	Current Iteration Number
l_{thick}	Building Elemental Layer Thickness [m]
l_v	Relative Luminance of Sky Element
L	Maximum Number of Iterations
L_v	Absolute Luminance of Sky Element at the Altitude Angle θ_{alt}
$L_v(\theta_{sol}, \theta_{alt}, \chi)$	Absolute Luminance of Sky Element as per Igawa Sky Model
L_z	Sky Luminance at Zenith
m	Total Number of Opaque Surfaces
$m_{a.m}$	Optical Air Mass
m_{cs_u}	Number of Casual Heat Gain Sources of u^{th} Type
m_{ea}	Number of Evaluation Objectives
m_{int}	Integer Involved in Time Domain Treatment of Flux or Temperature Excitation
m_{indic}	Coefficient for Indicatrix Function Calculation
M	Transmission Matrix
M_n	Transmission Matrix of n^{th} Layer
n	Total Number of Transparent Surfaces

n_{ea}	Number of Evaluation Indices
n_{harm}	Total Number of Harmonics
n_{indic}	Coefficient for Indicatrix Function Calculation
N	Total Number of Grasshoppers
p	Number of Types of Casual Heat Gain Sources
p_{atm}	Atmospheric Pressure [MPa]
p_c	Critical Pressure [MPa]
p_{ij}	Particular Proportion of the Project i Index Value under Index j
p_{indic}	Coefficient for Indicatrix Function Calculation
p_m	Partial Pressure of Water Vapor due to the Depression of WBT below DBT [MPa]
$p_{sat}(T_d)$	Saturation Pressure at the DBT [MPa]
$p_{sat}(t_w)$	Saturation Pressure at the WBT [MPa]
$p_{sat}(T')$	Saturation Pressure at Temperature T' [MPa]
Q_{ATL}	Annual Thermal Load [Wh]
$Q_{cdf}(t)$	Fluctuating Conduction Heat Gain/ Loss through Opaque Surfaces at t^{th} Hour [Wh]
Q_{cdm}	Mean Conduction Heat Gain/ Loss through Opaque Surfaces [Wh]
$Q_{cdfI}(t)$	Heat Transfer due to Incident Solar Radiation on Opaque Surface at t^{th} Hour [Wh]
Q_{cdmI}	Fluctuating Mean Heat Transfer due to Incident Solar Radiation on Opaque Surface [Wh]

$Q_{cfv}(t)$	Fluctuating Heat Transfer due to Ventilation at t^{th} Hour [Wh]
Q_{cmv}	Mean Heat Transfer due to Ventilation [Wh]
$Q_{dfl}(t)$	Fluctuating Direct Solar Gain or Mean Radiation Heat Transfer through Transparent Surfaces at t^{th} Hour [Wh]
Q_{dml}	Mean Direct Solar Gain or Mean Radiation Heat Transfer through Transparent Surfaces [Wh]
$Q_{fcc}(t)$	Fluctuating Casual Heat Gain from an Individual u^{th} Type of any Source at t^{th} Hour [Wh]
$Q_{fcu}(t)$	Fluctuating Casual Heat Gain from an Individual u^{th} Type of Casual Heat Source at t^{th} Hour [Wh]
Q_{gc}	Mean Conduction Heat Gain/ Loss through Transparent Surfaces [Wh]
$Q_{gfc}(t)$	Fluctuating Conduction Heat Gain/ Loss through Transparent Surfaces at t^{th} Hour [Wh]
q_{ia}	Flux on the Inside of the Multilayer Wall [W/m ²]
q_{oa}	Flux on the Construction's Exposed Side [W/m ²]
$Q_L(t)$	Thermal Load for t^{th} Hour [Wh]
Q_{mc}	Mean Casual Heat Gain from People, Equipment, Lighting, etc. [Wh]
Q_{mcu}	Mean Casual Heat Gain from an Individual u^{th} Type of any Source [Wh]
Q_{SCL}	Summer Cooling Load [Wh]

Q_{s_t, a_t}^{t+1}	Updated Q value for the updated state and action
$Q(s_t, a_t)$	Q value for the current state and action
Q_{Tm}	Total Mean Heat Exchanges [Wh]
$Q_T(t)$	Total Heat Exchanges at t^{th} Hour [Wh]
$Q_{Tcv}(t)$	Total Heat Exchange due to Ventilation at t^{th} Hour [Wh]
$Q_{Tf}(t)$	Total Fluctuating Portion of Heat Exchanges at t^{th} Hour [Wh]
Q_{WHL}	Winter Heating Load [Wh]
r	Distance between the Source and the Normally Incident Plane [m]
r_1	Random number between [0,1] corresponding to grasshopper's social interaction
r_2	Random number between [0,1] corresponding to gravity force on i^{th} grasshopper
r_3	Random number between [0,1] corresponding to wind advection on i^{th} grasshopper
r_{ij}	Normalized Vector
r_t	Reward or Penalty Value Issued by Environment
$RF(m_{int}\Delta_{URF})$	Response Factor at time $m_{int}\Delta_{URF}$.
s	Laplace Transformation Variable
$s_f(r)$	Repulsion and Attraction Force Strength between Grasshoppers
s_t	Current State in Q-learning
s_{t+1}	Updated State in Q-learning
S	Set of States in Q-learning

S_i	Social Interaction between Grasshoppers
S^*	Distance Scale for Ideal Solution
S^-	Distance Scale for Anti-ideal Solution
t	Time [h]
t_d	Dry Bulb Temperature [K]
t_g	Globe Temperature [°C]
t_w	Wet Bulb Temperature [K]
T	Temperature [K]
$T_{ai}(t)$	Indoor Air Temperature at t^{th} Hour [K]
T_c	Critical Temperature [K]
\widehat{T}_d	Best Solution in d^{th} Dimension
$T_{fi}(t)$	Fluctuating Inside Temperature at t^{th} Hour [K]
$T_{fo}(t)$	Fluctuating Outside Air Temperature at t^{th} Hour [K]
$T_{fo}(t - \phi_d - \phi_Y)$	Fluctuating Outside Air Temperature at $(t - \phi_d - \phi_Y)^{th}$ Hour [K]
T_{ia}	Temperature of the Inside of the Multilayer Wall [K]
$T_{j_{harm}}$	Temperature Amplitude of the j^{th} harmonic
T_{mo}	Mean Outside Air Temperature [K]
T_{mi}	Daily Mean Internal Environmental Temperature (K)
T_{oa}	Temperature of the Construction's Exposed Side [K]
$T_{oa}(t)$	Ambient Air Temperature at t^{th} hour [K]
T'	Corresponds to the WBT or DBT [K]

$TSI_{in,LL}(t)$	Indoor TSI Value for t^{th} Hour to be compared with TSI_{LL} , if it is less than TSI_{LL} [°C]
$TSI_{in,UL}(t)$	Indoor TSI Value for t^{th} Hour to be compared with TSI_{UL} , if it is more than TSI_{UL} [°C]
TSI_L	Deviation from Lower TSI Limit [°C]
TSI_{LL}	Lower Limit of TSI [°C]
TSI_U	Deviation from Upper TSI Limit [°C]
TSI_{UL}	Upper Limit of TSI [°C]
u	Casual Source under Consideration [Wh]
ub_d	Upper bound in d^{th} dimension
u_{dc}	Drift Constant
U	Heat transfer coefficient [W/m ² .K]
U_f	Cyclic Flux Transmittance [W/m ² .K]
U_j	U Value of j^{th} Opaque Surface [W/m ² .K]
U_r	U Value of r^{th} Transparent Surface [W/m ² .K]
v_a	Air Velocity [m/s]
v_{ij}	Standardized Weight Matrix
V^+	Ideal Solutions
V^-	Anti-ideal Solutions
w_j	Entropy Weight of index j
x	Space dimension along direction of heat flow [m]
x_i	Location of i^{th} Grasshopper in Search Space

x_{ij}	Score of the Evaluation Indices
x_i^d	Location of i^{th} grasshopper in d^{th} dimension in search space
x_j	Location of j^{th} Grasshopper in Search Space
x_{PSM}	Term representing respective coefficients for Perez sky model
x_{PSM_1}	First term required for calculation of respective x_{PSM} coefficient for Perez sky model
x_{PSM_2}	Second term required for calculation of respective x_{PSM} coefficient for Perez sky model
x_{PSM_3}	Third term required for calculation of respective x_{PSM} coefficient for Perez sky model
x_{PSM_4}	Fourth term required for calculation of respective x_{PSM} coefficient for Perez sky model
x_j^d	Location of j^{th} grasshopper in d^{th} dimension in search space
X_i	Position of i^{th} grasshopper
X_{nea}	n_{ea}^{th} Evaluation Index for each Objective
Y	Admittance Factor [W/m ² .K]
Z	Zenith angle of sky element
Z_s	Zenith angle of sun
$WWR - 1$	WWR for longer façade facing optimum orientation
$WWR - 2$	WWR for shorter façade facing the right side of longer façade in the optimum orientation direction
$WWR - 3$	WWR for longer façade opposite to the optimum orientation

$WWR - 4$ WWR for shorter façade facing the left side of longer façade in the optimum orientation direction

x Space dimension along direction of heat flow [m]

Greek letters

α Thermal diffusivity [m^2/s]

α_{absj} Absorptivity of the Surface

α_{lr} Learning rate for Q-learning

Δ Sky Brightness

ΔT_m Difference between Hourly Mean Outdoor and Indoor Temperatures [K]

Δ_{URF} Unit response function time step

ε Sky Clearness Index

γ_{df} Discount Factor for Q-learning

μ Decrement Response Factor

μ_j Decrement Response Factor for j^{th} Opaque Surface

φ Luminance gradation function

ϕ Laplace Transform of Heat Flux Function

ϕ_{az} Azimuthal Angle

ϕ_d Phase Angle for Decrement Factor

ϕ_{ia} Laplace Transform of Heat Flux for Indoor Air

$\phi_{j_{harm}}$ Phase Angle for the j^{th} Harmonic

ϕ_{oa}	Laplace Transform of Heat Flux for Outdoor Air
ϕ_{RH}	RH [in fraction]
ϕ_Y	Phase Angle for Admittance Factor
ρ	Density of a Material [kg/m ³]
θ	Laplace transform of temperature function
θ_{alt}	Altitude angle of sky element
θ_{in}	Angle of Incidence
θ_r	Solar Gain Factor for the r^{th} Transparent Surface
θ_{sol}	Solar altitude angle
χ	Arc angle between sky element and the sun
ω	Periodic Fluctuation's Angular Frequency
$\omega_{j_{harm}}$	Angular Frequency of the Harmonic

Abbreviations

AAC	Autoclaved Aerated Concrete
ABC	Artificial Bee Colony
AC	Air-conditioner
ABO	African Buffalo Optimization
ACO	Ants Colony Optimization
AI	Artificial Intelligence
ANN	Artificial Neural Network
BEE	Bureau of Energy Efficiency

BFA	Bacterial Foraging Algorithm
BESO	Building Energy Simulation Optimization
BESP	Building Energy Simulation Program
BIM	Building Information Parametric Model
BIOA	Bio-inspired Optimization Algorithm
BIS	Bureau of Indian Standard
BO	Bat Optimization Algorithm
CBERD	Centre for Building Energy and Research
CBRI	Central Building Research Institute
CET	Corrected Effective Temperature (°C)
CIBSE	Chartered Institute of Building Services Engineers
CIE	International Commission on Illumination
CO ₂	Carbon Dioxide
CS	Cuckoo Search Algorithm
DBT	Dry Bulb Temperature [K]
DE	Differential Evolution
ECBC	Energy Conservation Building Code
EPS	Expanded Polystyrene
ET	Effective Temperature (°C)
FA	Firefly Algorithm
FAR	Floor Area Ratio
FRP	Fiber Reinforced Plastic
GA	Genetic Algorithm

GANN-BIM	GA + ANN + BIM
GDP	Gross Domestic Product
GFRC	Glass Fiber Reinforced Concrete
GFRG	Glass Fiber Reinforced Gypsum
GOA	Grasshopper Optimization Algorithm
GSO	Glowworm Swarm Optimization
GWO	Gray Wolf Optimizer
HVAC	Heating, Ventilation and Air-conditioning
IDMP	International Daylight Monitoring Programme
IEQ	Indoor Environmental Quality
IS	Indian Standard
ISO	International Organization of Standardization
KH	Krill Herd Algorithm
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCEI	Life Cycle Environmental Impact
LEED	Leadership in Energy and Environmental Design
MADM	Multiple Attribute Decision Making
MDF	Medium Density Fiberboard
MFO	Moth Flame Optimization
ML	Machine Learning
MOGA	Multi-objective Genetic Algorithm
MOGOA	Multi-objective Grasshopper Optimization Algorithm

NFL	No Free Lunch
NIOA	Nature-inspired Optimization Algorithm
NSGA-II	Non-dominated Sorting Genetic Algorithm-II
NSO	National Statistical Organization
PCM	Phase Change Material
PIR	Polyisocyanurate
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied (%)
PSO	Particle Swarm Optimization
PUF	Polyurethane Foam
PV	Photovoltaic
RCC	Reinforced Cement Concrete
ReLU	Rectified Linear Unit
RH	Relative Humidity (%)
RL	Reinforcement Learning
SA	Simulated Annealing
SAD	Seasonal Affective Disorder
SC	Shading Coefficient
SHGC	Solar Heat Gain Coefficient
SSO	Sperm Swarm Optimization Algorithm
TSI	Tropical Summer Index (°C)
UHPC	Ultra-High-Performance Concrete
VAV	Variable Airflow Volume

VL	Visual Light Transmittance
WBT	Wet Bulb Temperature (°C)
WWR	Window to Wall Ratio
XPS	Extruded Polystyrene