# 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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# *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.

# सार

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 ज़ोर दिया गया है। जीए और जीओएए 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 जीओएए (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 डिजाइन 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 डिजाइनों 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*

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|---|---|
| $a_{CIE}$ | 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 $\theta_{in}$ [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 $\theta_{alt}$ |
| $L_v(\theta_{sol}, \theta_{alt}, \chi)$ | 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] |
| $Q_{dfI}(t)$ | Fluctuating Direct Solar Gain or Mean Radiation Heat Transfer through Transparent Surfaces at $t^{th}$ Hour [Wh] |
| $Q_{dmI}$ | Mean Direct Solar Gain or Mean Radiation Heat Transfer through Transparent Surfaces [Wh] |
| $Q_{fc}(t)$ | 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] |
| $Q_{gf}(t)$ | 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] |
| $Q_{mC_u}$ | 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] |
| $T_{fo}(t-\phi_d-\phi_{\mathrm{Y}})$ | Fluctuating Outside Air Temperature at $(t-\phi_d-\phi_{\mathrm{Y}})^{th}$ 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 |
| $X_{n_{ea}}$ | ${n_{ea}}^{th}$ 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** |
| $\alpha$ | Thermal diffusivity [$m^2/s$] |
| $\alpha_{abs_j}$ | Absorptivity of the Surface |
| $\alpha_{lr}$ | Learning rate for Q-learning |
| $\Delta$ | Sky Brightness |
| $\Delta T_m$ | Difference between Hourly Mean Outdoor and Indoor Temperatures [K] |
| $\Delta_{URF}$ | Unit response function time step |
| $\varepsilon$ | Sky Clearness Index |
| $\gamma_{df}$ | Discount Factor for Q-learning |
| $\mu$ | Decrement Response Factor |
| $\mu_j$ | Decrement Response Factor for $j^{th}$ Opaque Surface |
| $\varphi$ | Luminance gradation function |
| $\phi$ | Laplace Transform of Heat Flux Function |
| $\phi_{az}$ | Azimuthal Angle |
| $\phi_d$ | Phase Angle for Decrement Factor |
| $\phi_{ia}$ | Laplace Transform of Heat Flux for Indoor Air |
| $\phi_{j_{harm}}$ | Phase Angle for the $j^{th}$ Harmonic |

| | |
|---|---|
| $\phi_{oa}$ | Laplace Transform of Heat Flux for Outdoor Air |
| $\phi_{RH}$ | RH [in fraction] |
| $\phi_{\mathrm{Y}}$ | Phase Angle for Admittance Factor |
| $\rho$ | Density of a Material [kg/m$^3$] |
| $\theta$ | Laplace transform of temperature function |
| $\theta_{alt}$ | Altitude angle of sky element |
| $\theta_{in}$ | Angle of Incidence |
| $\theta_r$ | Solar Gain Factor for the $r^{th}$ Transparent Surface |
| $\theta_{sol}$ | Solar altitude angle |
| $\chi$ | Arc angle between sky element and the sun |
| $\omega$ | 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 |

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