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# Review of Steady-state Building Heat Transfer Algorithms Developed for Climate Zones of India

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## Abstract –

*India is nation of over 1.4 billion people, constituting more than 17% of the global population. The building sector in India accounts for a third of electricity consumption and carbon emissions. To achieve sustainable development, the country needs to prioritize energy-efficient building designs that cater to local climatic conditions. In India, the Energy Conservation Building Code (ECBC) prescribes the use of Envelope Performance Factor (EPF) based on Overall Thermal* Transmittance *Value (OTTV) for building envelope design to minimize the energy consumption of buildings. The OTTV is a measure of the overall thermal transfer through the building envelope, and it is influenced by various parameters such as building orientation, façade area, shading devices and thermal properties of envelope components.*

*This paper delves into the various OTTV-based steady-state heat transfer algorithms developed for Indian climatic zones. The study provides an overview of the different approaches used for developing these algorithms, including energy simulation, parametric studies, and regression analysis. The review also discusses the key input parameters required for the development of these steady-state heat transfer algorithms. The algorithms are compared based on their scope of applicability and development methodology. The review also discusses the limitations associated with the use of these algorithms in accurately predicting the performance of Building Envelope. This paper highlights the importance of steady-state heat transfer algorithms in energy-efficient building design in developing countries like India. It emphasizes on the importance of continued research to refine these algorithms and develop reliable OTTV-based algorithms for Indian climatic zones.*

***Key Words***: OTTV, Buildings, Energy Efficiency, Building Energy Codes, Building Envelope

## 1 INTRODUCTION

Steady-state building physics-based models are simplified mathematical models that are based on the fundamental laws of thermodynamics and heat transfer. These steady-state models are used to predict the thermal performance of building envelopes and to optimize the thermal performance of building envelopes. The equation-based algorithms can be classified into three broad categories based on the approach [1]:

- Analytical approach (includes both dynamic and steady-state models for detailed heat transfer calculations with well-defined boundary conditions)
- Approximation approach (steady-state models for heat load calculations using HDD/CDD)
- Correlational approach (steady-state models for location specific values/curves developed using hourly simulations)

### 1.1 Development of OTTV algorithm

The ASHRAE Standard 90-1975 “Energy Conservation in New Building Design” was the first standard to include Overall Thermal Transmittance Value (OTTV) requirement for upcoming air-conditioned large buildings [2]. The OTTV algorithm proposed by ASHRAE represents the peak rate of heat transmission from the external ambient environment into the building through the exposed envelope components. It represents the rate of heat transfer through the building envelope per unit area, between the inside and outside of the building. It considers the following three heat transfer components to quantify the overall thermal performance of the building envelope:

- Conductive heat transmission via external wall ($Q_{wall.C}$)
- Conductive heat transmission via external fenestration ($Q_{fenestration.C}$)
- Radiative (solar) heat transmission via external fenestration ($Q_{fenestration.R}$)

The simplified OTTV equation developed by ASHRAE is shown in Equation 1.

**Equation 1**

$$OTTV = f\,(Q_{wall.C}\,, Q_{fenestration.C}\,, Q_{fenestration.R})$$

The OTTV approach was further enhanced by incorporating a similar algorithm for heat transmission through roofs and skylights in the revised version of ASHRAE Standard 90A 1980 “Energy Conservation in New Building Design” [3]. The simplified OTTV (roof) equation developed by ASHRAE is illustrated in Equation 2.

**Equation 2**

$$OTTV\ (roof) = f\ (Q_{roof.C}\ , Q_{skylight.C}\ , Q_{skylight.R})$$

Where,

| | |
|---|---|
| $Q_{roof.C}$ | is conductive heat transmission via roof |
| $Q_{skylight.C}$ | is conductive heat transmission via skylight |
| $Q_{skylight.R}$ | is radiative (solar) heat transmission via skylight |

The Overall Thermal Transmittance Value (OTTV) has been an important concept in the building industry for over 40 years. Its main objective is to serve as an indicator of the impact of a building's envelope on the energy used for providing thermal comfort predominantly in air-conditioned buildings. To use OTTV as a measure of thermal performance, it is crucial to have accurate coefficients for each envelope component. The accuracy of these coefficients depends upon how well they are able to represent the interaction of building envelope components with local climate conditions. Recent studies have highlighted the assumptions made by various researchers when computing OTTV coefficients and have emphasized that the calculation of OTTV should be based on heat gains evaluated using fixed thermostat setpoints and air-conditioning operation schedules [4] [5] [6].

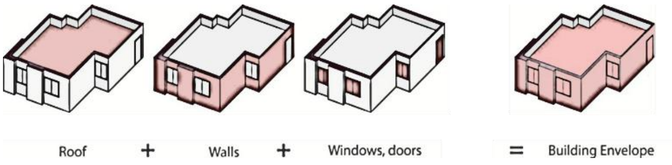

**Fig. 1:** Components of Building Envelope for OTTV **[7]**

Hui (1997) argues that an OTTV based performance standard should be the first step toward the development of a national building energy code [6]. W. K. Chow & K. T. Chan (1995) have discussed the application of the Overall Thermal Transfer Value (OTTV) equation to evaluate the cooling load of buildings [8]. The study found that the Window-to-Wall Ratio (WWR) and Solar Heat Gain Coefficient (SHGC) are significant factors in determining the thermal performance of building envelopes. The sensitivity of these parameters can provide guidance to building designers on how to optimize the thermal performance of building envelopes and make trade-offs among parameters to meet desired heat transfer limits. However, the study also found that the OTTV equation does not fully reflect the effects of wall absorptance and heat capacity. To account for this, the authors propose modifying the OTTV equation by adding a correction factor to the term $T_{Deq}$ [8].

J. Vijayalaxmi (2010) suggests that certain design modifications at an early stage can significantly reduce the OTTV value [9]. It also suggests that the OTTV value at the time of maximum solar radiation intensity is a good benchmark for evaluating the thermal performance of building envelopes in hot-humid and hot-dry countries. However, this benchmark may not be suitable for cold climates, where the focus should be on reducing heating loads. Additionally, the author suggests that early design stage options for varying walling material and glazing type for wall orientation where the OTTV is high should be considered as preventive measures for reducing heat gain and load on air conditioners [9].

## 2 OTTV IN BUILDING ENERGY CODES

Singapore became the first country to include OTTV requirements in their building regulations in 1979 for air-conditioned buildings. Subsequently in 2004, it was superseded by a revised algorithm “Roof Thermal Transfer Value” (RTTV) and “Envelope Thermal Transfer Value” (ETTV) in favour of an improved representation of fenestration solar gains [10]. A similar OTTV based algorithm (RETV) was incorporated in 2008 by Building and Construction Authority, Singapore to include residential buildings as well [11].

Residential Envelope Transmittance Value (RETV) is based on the concept of Overall Thermal Transfer Value (OTTV) developed by ASHRAE as it represents the average rate of heat transmission from the external ambient environment into the building through the exposed envelope components. Higher heat gain taking place through the building envelope would translate into a higher RETV value. A number of countries such as India, Singapore, Thailand and Hong Kong have used RETV in their building codes [6]. Unfortunately, there isn't much information in the literature on the precise methods employed by these nations to develop the algorithm and compute the coefficients. The OTTV based algorithms have been developed for integration in nation building energy codes of Singapore (2008), Hong Kong (2019), Thailand (2017), Malaysia (2007), Indonesia (2011), Jamaica (1994), Vietnam, Sri Lanka (2009), Mauritius, Pakistan (1990) and Egypt (2005) among others.

A comparison of algorithms developed by countries having comparable climatic conditions is listed in Table 1.

**Table 1:** Comparison of OTTV algorithms incorporated in building energy codes

| Country | Code | Equation | Limit |
|---|---|---|---|
| Singapore | Code on Envelope Thermal Performance | $ETTV = 12(1\text{-}WWR)U_w + 3.4(WWR)U_f + 211(WWR)(CF)(SC)$ | 50 $W/m^2$ |
| | | $RTTV = 12.5\ (1\text{-}SRR)U_r$ | 50 |

| Country | Code | Equation | Limit |
|---|---|---|---|
| | for Buildings [11] | + 4.8(SKR)$U_s$ + 485(SRR)(CF)(SC) | W/m² |
| | | RETV = 3.4(1-WWR)$U_w$ + 1.3(WWR)$U_f$ + 58.6(WWR)(CF)(SC) | 25 W/m² |
| Malaysia | Code of Practice on Energy Efficiency and Use of Renewable Energy for Non-Residential Buildings [12] | OTTV = 15 × α × (1-WWR)$U_w$ + 6 × (WWR)×$U_f$ + (194×CF×WWR×SC) | 50 W/m² |
| Hong Kong | Code of Practice for Overall Thermal Transfer Value in Buildings [13] & [14] | $OTTV_{wall}$ = $U_w$ × $TD_{EQw}$ × α (1-WWR) + (SF×SC×WWR)<br>Where,<br>$TD_{EQw}$ varies between 1.4 to 7.5 depending upon orientation and density of wall construction; and SF varies between 104 to 202 depending upon orientation | 21 W/m² for building tower; and 50 W/m² for podium |
| | | $OTTV_{roof}$ = α × $U_r$ × $TD_{EQr}$ (1-SRR) + (264 × SC × SRR)<br>Where,<br>$TD_{EQw}$ varies between 7.9 to 18.6 depending upon density of roof construction | |
| Pakistan | Building Energy Code of Pakistan [15] | $OTTV_{wall}$ = $U_w$ × $TD_{EQw}$ × (1-WWR) + (SF×SC×WWR) + $U_g$×ΔT×(WWR)<br>Where,<br>$TD_{EQw}$ varies depending upon density of wall construction; ΔT is difference between indoor and outdoor temperatures; and SF varies between 104 to 561 depending upon orientation and climate zone | 91 – 101 W/m² |
| | | $OTTV_{roof}$ = $U_r$ × $TD_{EQr}$ (1-SRR) + (471×SC×SRR) + $U_s$×ΔT×(SRR)<br>Where,<br>$TD_{EQr}$ varies depending upon density of roof construction; and ΔT is difference between indoor and outdoor temperatures | 26.8 W/m² |
| Sri Lanka | Code of practice for energy efficient buildings in Sri Lanka [16] | OTTV = 19.3 × α × $U_w$ × (1-WWR) + 3.6 × $U_f$ × (WWR) + 186 × (SC×CF ×WWR)<br>Where,<br>CF varies between 0.79 to 1.34 depending upon the orientation; and SC varies depending upon the projection factor and type of shading device | 50 W/m² |
| Jamaica | Jamaica National Building Code-Volume 2: Energy Efficiency Building Code, Requirements and Guidelines [17] | $OTTV_w$ = ($TD_{eq}$ – DT) × CF × α × $U_w$ × (l-WWR) + DT × $U_w$ × (1-WWR) + (372 × CF × SC × WWR) + (DT × $U_f$ × WWR)<br>Where,<br>$TD_{EQw}$ varies between 10.6 – 24.4 depending upon density of wall construction; DT varies between 6.1 – 9.4 depending upon climatic zone; and CF varies between 0.58 to 1.36 depending upon the orientation | 55.1 – 67.7 W/m² |
| | | $OTTV_r$ = ($TD_{eq}$ – DT) × α × $U_r$ × (l-SRR) + DT × $U_r$ × (1-SRR) + (138 × SC × SRR) + (DT × $U_s$ × SRR)<br>Where,<br>$TD_{EQw}$ varies between 16.1 – 38.9 depending upon density and U-value of roof construction; and DT varies between 6.1 – 9.4 depending upon climatic zone | 20 W/m² |

Almost a decade after introducing OTTV, with the progress in access to computational resources and simulation tools ASHRAE discarded the Overall Thermal Transfer Value (OTTV) compliance approach in favour of the Energy Cost

Budget method and more advanced whole building energy simulation. Nevertheless, many countries (predominantly Asian countries) continued with the development of nation specific OTTV algorithms and incorporated them in their respective building codes with varying levels of stringency and enforcement (voluntary or mandatory) [7]. Interestingly, there are several advantages of using steady-state heat transfer models for optimizing building envelope performance over advanced building energy simulation software:

1. Simplicity: Steady-state heat transfer models are relatively simple to understand and use, and they do not require specialized knowledge or skills to implement. This can make them more accessible to building designers and engineers in developing countries, who may not have the resources or expertise to use advanced building energy simulation software.
2. Low Computational Requirements: Steady-state heat transfer models require less computational resources compared to advanced building energy simulation software, which means they can be run on lower-end computers and can be used in areas where computational resources are limited.
3. Low Cost: Steady-state heat transfer models are typically less expensive than advanced building energy simulation software, which can make them more accessible to organizations and individuals in developing countries.
4. Easy to Validate: The results of steady-state heat transfer models are relatively easy to validate using simple spreadsheet based tools.
5. Easy to Use: Steady-state heat transfer models are easy to use and do not require advanced technical knowledge, they can be implemented by building designers and engineers with basic understanding of heat transfer principles.
6. Easy to Modify: Steady-state heat transfer models are relatively easy to modify to reflect changes in building design, construction materials, and external climate conditions.
7. Good for Benchmarking: Because steady-state heat transfer models are relatively simple, they can be used to establish a benchmark for building envelope thermal performance. This can help to identify areas where improvements are needed and to evaluate the effectiveness of different design options.

The major limitation of OTTV based approach is its reliance on steady-state heat transfer calculations, which don't accurately represent the dynamic thermal behaviour of building envelope components. This can also lead to oversimplification of building envelope thermal performance, as it does not account for the impact of variance in internal loads, operation schedules and ventilation gains on energy consumption of air-conditioning systems for providing thermal comfort to the occupants. Hence, few developed nations along with ASHRAE shifted toward more advanced methods in their building codes, such as building energy simulations, that provide a more accurate representation of the dynamic thermal performance of buildings. These advanced building energy simulation tools also enable trade-offs between all building services including lighting systems and air-conditioning systems in addition to building envelope components. However, it is noteworthy that OTTV based algorithms are still used by many developing nations, particularly Asian countries in their building energy codes. The major reasons behind these developing countries still depending upon steady-state algorithms in their national building energy codes are listed below:

1. Technical constraints: many developing nations do not necessarily have enough professionals possessing the required technical capacity or resources across the geographical territory to implement advanced methods such as building energy simulations. Therefore, the use of simpler steady-state algorithms for code compliance is better suited and more feasible for ensuring effective implementation of these national building energy codes.
2. Historical factor: most of these developing nations had adopted steady-state algorithm approach for code compliance in early versions of their building energy codes, and since then have decided to retain it in the updated versions of building energy codes.
3. Cost: performing building energy simulations can be expensive and time-consuming, while it may not necessarily provide meaningful value-addition to comparatively smaller projects or the projects which are already at final stages of design or construction. The cost includes both the cost of simulation software and the professional fee of experts. Hence, implementing these advanced simulation methods can be prohibitive for projects with limited budgets and time.
4. Ease of compliance: many developing countries are still in the nascent stages of implementing building energy codes. Hence, the adoption of the steady-state algorithm approach is a more feasible first step toward enhancing energy efficiency of the building sector. The compliance using steady-state algorithm approach can be demonstrated using much simpler spreadsheets and is easier for implementing agency to verify as well.

5. Lack of awareness: the majority of primary stakeholders including real-estate developers in these developing countries are still not aware of the benefits of using more advanced building energy simulation methods. Until the integrated design processes for building projects are mainstreamed through enhanced awareness, the incorporation of building energy simulation methods would remain a challenge.

While ASHRAE along with other developed countries have transitioned away from using steady-state algorithm based approach in their building energy codes [18], many developing countries including India are still using it in their building energy codes [19].

## 3 STEADY-STATE BUILDING HEAT TRANSFER ALGORITHMS FOR INDIA

India is predominantly a cooling-dominated country [20]. Therefore, to restrict the heat transfer through building envelope, the ENS (Part-I) limits the RETV to a maximum of 15 W/m$^2$ for all climatic zones except cold. The ENS (Part-I) is the first national code that evaluated thermal performance of building envelope in terms of RETV. The major advantage of RETV is that it provides flexibility to the designer to trade-off between the efficiencies of envelope components (walls, fenestration, and shading) while ensuring overall envelope efficiency [9].

Devgan, et al. (2010) have proposed and verified a set of overall thermal transfer value (OTTV) coefficients for three Indian climatic zones [4]. The proposed algorithm and coefficients can be used to compute the OTTV value for day-time use air-conditioned office buildings located in selected climatic zones. The study found that OTTV corresponds effectively with annual space cooling and heating energy consumption.

A comparable approach has been followed in the "Building Envelope Trade-off Method" provided in ECBC that uses the Envelope Performance Factor (EPF) to quantify the thermal performance of the building envelope [21] [22]. A higher value of EPF would signify higher rates of heat transfer through the building envelope and imply lower levels of thermal efficiency [23]. However, unlike Eco-Niwas Samhita 2018 (Part-1) and other international building energy codes, ECBC doesn't provide a fixed value for EPF to restrict heat transfer through the building envelope. Rather, ECBC utilizes a comparative approach to demonstrate compliance with the code. To achieve compliance, the EPF of the proposed design calculated using the spatial design parameters and thermo-physical properties of actual envelope assemblies shall be equal to or less than the EPF of reference case calculated using the thermo-physical specifications mentioned in the prescriptive provisions for respective envelope component [22].

### 3.1 Energy Conservation Building Code (ECBC)

ECBC 2007 uses the following equation for calculating Envelope Performance Factor (EPF) [21]:

**Equation 3**

$$EPF = C_{roof} \times U_{roof} \times A_{roof} + C_{wall} \times U_{wall} \times A_{wall} + C_{windowU} \times U_{window} \times A_{window} + C_{windowSHGC} \times SHGC_{window} \times M_{window} \times A_{window} + C_{skylightU} \times U_{skylight} \times A_{skylight} + C_{skylightSHGC} \times SHGC_{skylight} \times A_{skylight}$$

Where,

| | |
|---|---|
| $A_n$ | is net area of respective envelope component |
| $U_n$ | is U-factor of respective envelope component |
| $SHGC_n$ | is SHGC of respective envelope component |
| $C_{roof}$ | varies between 5.46 and 11.93 depending upon building operation and climate zone |
| $C_{wall}$ | varies between 2.017 and 15.72 depending upon climate zone and mass |
| $C_{windowU}$ | varies between -11.95 and 1.55 depending upon building operation, climate zone and orientation (north & non-north) |
| $C_{windowSHGC}$ | varies between 9.13 and 86.57 depending upon building operation, climate zone and orientation (north & non-north) |
| $C_{skylightU}$ | varies between -295.81 and -93.44 depending upon building operation and climate zone |
| $C_{skylightSHGC}$ | varies between 283.18 and 923.01 depending upon building operation and climate zone |
| $M_{window}$ | is the multiplication factor for equivalent SHGC and varies depending upon latitude (≥15 N & <15 N), orientation, type and projection factor of shading device |

Similarly, ECBC 2017 with slight modifications uses the following equation for calculating Envelope Performance Factor [22]:

**Equation 4**

$$EPF = C_{roof} \times U_{roof} \times A_{roof} + C_{wall} \times U_{wall} \times A_{wall} + C_{windowU} \times U_{window} \times A_{window} + C_{windowSHGC} \times SHGC_{window} \times A_{window} \div SEF_{window}$$

Where,

| | |
|---|---|
| $A_n$ | is net area of respective envelope component |
| $U_n$ | is U-factor of respective envelope component |
| $SHGC_n$ | is SHGC of respective envelope component |

| | |
|---|---|
| $C_{roof}$ | varies between 32.3 and 80.7 depending upon building operation and climate zone |
| $C_{wall}$ | varies between 17.2 and 55.9 depending upon climate zone |
| $C_{windowU}$ | varies between 10.9 and 49.2 depending upon building operation, climate zone and orientation (north, south, east & west) |
| $C_{windowSHGC}$ | varies between 114.3 and 607.4 depending upon building operation, climate zone and orientation (north, south, east & west) |
| $SEF_{window}$ | is the shading equivalent factor for SHGC and varies depending upon latitude (≥15 N & <15 N), orientation, type and projection factor of shading device |

It is important to note that ECBC doesn't provide a threshold EPF value for achieving compliance, rather it utilizes a comparative approach. If the EPF of the proposed design is equal to or less than the EPF of the reference case developed using prescriptive provisions, the building envelope is considered to be code-compliant [22].

## 3.2 Eco-Niwas Samhita 2018 (Part-1)

The RETV compliance provision incorporated in Eco-Niwas Samhita 2018 (Part-1), in principle is much closer to the standard OTTV concept. The threshold value to demonstrate compliance with the code has been fixed at 15 W/m² [19]. Unlike ECBC 2017 which has provided EPF based compliance provision for all five climatic zones, ENS 2018 provides the steady-state RETV algorithm only for cooling-dominated climatic zones (Hot-Dry, Composite, Warm-Humid, and Temperate). The equation developed for calculating RETV is placed below:

**Equation 5**

$$RETV = a * (1 - WWR) * U_{opaque} * \omega$$
$$+ b * WWR * U_{non-opaque} * \omega$$
$$+ c * WWR * SHGC_{eq} * \omega$$

Where,

| | |
|---|---|
| $U_n$ | is U-factor of respective envelope component |
| $SHGC_n$ | is equivalent SHGC of respective envelope component |
| $a$ | varies between 3.38 and 6.06 depending upon climate zone |
| $b$ | varies between 0.37 and 1.85 depending upon climate zone |
| $c$ | varies between 63.69 and 68.99 depending upon climate zone |
| $\omega$ | is the orientation factor that varies between 114.3 and 607.4 depending upon latitude (≥23.5 N & <23.5 N) and orientation (north, south, east, west, north-east, north-west, south-east & south-west) |

## 3.3 Predetermined OTTV coefficients for Composite, Hot-Dry and Warm-Humid climates

Apart from the national building energy codes developed by the Bureau of Energy Efficiency, the study "Predetermined overall thermal transfer value coefficients for Composite, Hot-Dry and Warm-Humid climates" by Devgan et al. (2010) is the only extensive work that has attempted to develop an OTTV based steady-state algorithm for three Indian climatic zones [4]. The study establishes an OTTV algorithm along with coefficients for Composite, Hot-Dry and Warm-Humid climatic zones. Compared to other OTTV based heat transfer steady-state models the algorithm developed by Devgan et al. (2010) is more complex, as it uses a combination of linear and second-degree polynomial correlation for conduction heat transfers through walls and windows. The algorithm developed for calculating OTTV is placed below:

$$OTTV = [S_{SU} \times (U_w \times \alpha)^2 + L_{SU} \times (Uw \times \alpha)] \times [1 - WWR] \times ESM$$
$$+ [S_{GU} \times (U_f)^2 + L_{GU} \times U_f] \times [WWR] + SF \times SC \times WWR \times ESM$$

Where,

| | |
|---|---|
| $U_n$ | is U-factor of respective envelope component |
| $\alpha$ | is solar absorptance of wall surface |
| $L_{SU}$ | is solar transmittance coefficient that varies between 30.5 and 52.5 depending upon orientation and climate zone |
| $S_{SU}$ | is solar transmittance coefficient that varies between -4.45 and -5.75 depending upon climate zone |
| $L_{GU}$ | is solar transmittance coefficient that varies between 10.5 and 15.5 depending upon climate zone |
| $S_{GU}$ | is solar transmittance coefficient that varies between -0.69 and -1.04 depending upon climate zone |
| $SF$ | is solar factor that varies between 92 and 263 depending upon orientation and climate zone |
| $SC$ | is shading coefficient of window |
| $ESM$ | is external shading multiplier that varies depending upon projection factor, orientation, pitch angle of walls and climate zone |

### 3.4 Comparison of Steady-state algorithms

There isn't much information available in the public domain on the precise methods employed by the Bureau of Energy Efficiency while developing the algorithm and computing the coefficients. Discussions with Dr. N. K. Bansal, Chair of the ECBC 2007 committee, and Mr. Saurabh Diddi, Director, BEE provided valuable insights which have been documented in Table 2 and Table 3. The equations proposed for calculating respective performance indicators (EPF for ECBC, RETV for ENS and OTTV) for the mentioned algorithms have been discussed in this section.

**Table 2:** Comparison of Steady-state algorithms for India

| Particular | ECBC 2007 | ECBC 2017 | ENS 2018 | S. Devgan |
|---|---|---|---|---|
| Source | Energy Conservation Building Code 2007 [21] | Energy Conservation Building Code 2017 [22] | Eco-Niwas Samhita 2018 Part I: Building Envelope [19] | Predetermined overall thermal transfer value coefficients [4] |
| Performance Indicator | Envelope Performance Factor (EPF) | Envelope Performance Factor (EPF) | Residential Envelope Transmittance Value (RETV) | Overall Thermal Transfer Value (OTTV) |
| Compliance value | N.A. | N.A. | ≤ 15 W/m2 | N.A. |
| Climate zones | Hot-Dry;<br>Warm-Humid;<br>Composite;<br>Moderate; and<br>Cold | Hot-Dry;<br>Warm-Humid;<br>Composite;<br>Temperate; and<br>Cold | Hot-Dry;<br>Warm-Humid;<br>Composite; and<br>Temperate | Hot-Dry;<br>Warm-Humid; and<br>Composite |
| Operation schedule | Day-time<br>24-hour | Day-time<br>24-hour | N.A. | - |
| Envelope components | | | | |
| Roof area | yes | yes | no | no |
| Roof U-factor | yes | yes | no | no |
| Roof solar absorbance | no | no | no | no |
| Wall area | yes | yes | yes | yes |
| Wall U-factor | yes | yes | yes | yes |
| Wall solar absorbance | no | no | no | yes |
| Window area | yes | yes | yes | yes |
| Window U-factor | yes | yes | yes | yes |
| Window SHGC | yes | yes | yes | yes |
| Window shading | yes | yes | yes | yes |
| Skylight area | yes | no | no | no |
| Skylight U-factor | yes | no | no | no |
| Skylight SHGC | yes | no | no | no |
| WWR limit | no | 40% | no | no |
| Orientation factor | | | | |
| Wall | no | no | 8 orientations | 16 orientations |
| Window U-factor | 2 orientations | 4 orientations | 8 orientations | 1 orientation |
| Window SHGC | 2 orientations | 4 orientations | 8 orientations | 16 orientations |
| Shading | 4 orientations | 8 orientations | 8 orientations | 16 orientations |
| Window Shading | | | | |
| Overhang | yes | yes | yes | yes |
| Sidefin | yes | yes | yes | yes |
| Overhang + Sidefin | yes | yes | yes | no |

The methodologies employed for developing the steady-state thermal performance algorithm and the simulations performed for computing the coefficients are mentioned in Table 3. Unfortunately, extremely limited information is available in the public domain regarding the methodology utilized for developing building envelope trade-off method for demonstrating compliance with ECBC 2007 [21].

**Table 3:** Comparison of energy modelling and analysis for developing algorithms

| Particular | ECBC 2007[1] | ECBC 2017[2] | ENS 2018[3] | S. Devgan |
|---|---|---|---|---|
| Source | [21] | [22], [24] | [19], [25] | [4] |
| Software | - | eQUEST 3.64 | EnergyPlus | eQUEST v.3.6 |
| Number of cases simulated[4] | - | ~3,870 | 27,360 | ~573 |
| Representative cities | | | | |
| Hot-Dry | Ahmedabad | Ahmedabad | Ahmedabad | Ahmedabad |
| Warm-Humid | Kolkata | Kolkata | Mumbai, Chennai, Kolkata | Chennai |
| Composite | New Delhi | New Delhi | New Delhi, Nagpur | New Delhi |
| Moderate | Bengaluru | Bengaluru | Bengaluru | N.A. |
| Cold | Shillong | Srinagar | N.A. | N.A. |
| Geometry | | | | |
| Layout | - | Rectangular layout having 3 above grade floors of 6,000 m² having 1:1.8 aspect ratio | 2 layout options (point block & doubly loaded corridor) | Octagonal layout having 15 above grade floors with total area of 38,715 m² |
| WWR | - | 41% | 10%, 15%, 20%, 25%, 30%, 35% | 40% |
| Construction assembly | | | | |
| Roof options | - | 37 | N.A. | N.A. |
| Wall options | - | ~300 | 5 | 98 |
| Window options | - | 85 | 4 | 93 |
| Building systems | | | | |
| HVAC thermostat setpoint | - | CL: 24°C<br>HT: 20°C | IMAC mixed mode, 90% acceptability band | CL: 23°C<br>HT: 21°C |
| HAVC system type | | Packaged system with COP 3.2 | Ideal load air system | Auto sized |
| Operation schedule | Day-time<br>24-hour | Day-time<br>24-hour | 24-hour | Day-time (08:00–20:00 h) |
| Occupant density | - | As per NBC 2005 | 2 occupants per bedroom; 4 occupants per living room | 18 m²/person |
| Lighting system | - | 10.8 W/m² | 5 W/m² | 20 W/m² |
| Equipment power | - | 25% of the total electric demand | 50W in living room | 2 W/m² |
| Method for computing coefficients | | | | |
| Roof | - | Simple regression (linear) | N.A. | N.A. |
| Wall | - | Simple regression (linear) | Multiple regression (linear) | Simple regression (2nd degree polynomial) |
| Window conductance | - | Simple regression (linear) | Multiple regression (linear) | Simple regression (linear) |

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[1] Limited information available in public domain regarding the methodology utilized for computing EPF coefficients. Discussions with Dr. N. K. Bansal, Chair of the ECBC 2007 committee provided the mentioned insights.

[2] The author was member of the Working Group on Building Envelope and contributed to the development process.

[3] The author was member of the technical committee and contributed to the development process.

[4] Calculated by author based on documented methodology.

| Particular | ECBC 2007[1] | ECBC 2017[2] | ENS 2018[3] | S. Devgan |
|---|---|---|---|---|
| Window SHGC | - | Simple regression (linear) | Multiple regression (linear) | Simple regression (linear) |
| Shading factor | - | Simple regression (3rd degree polynomial) | N.A. | Manual calculation considering summer months |
| Simulation period | - | Annual | For Hot-Dry, Composite & Temperate: Mar - Oct; and for Warm-Humid: Feb-Nov | Annual |
| Dependant variable | - | Annual Energy Consumption in terms of EPI ($kWh/m^2.yr$) | Sensible cooling load for summer period | Component level “net summer gain minus winter losses” |

### 3.5 Limitations of Steady-state Heat Transfer algorithms

The lack of reliable information on the methodology used for the computation of EPF coefficients provided in ECBC 2007 makes it difficult to comment on their accuracy and validity in different scenarios. It is noteworthy that even the tables listing these coefficients mention that these values are under review [21, pp. D.2-D.3]. However, the major concern regarding the provided coefficients is the presence of negative values for conduction heat transfer coefficients through windows and skylights. This is most likely a result of the incorrect application of net heat transfer through individual envelope components as the dependent variable. ECBC 2007 also provides separate coefficients for mass wall and curtain walls without defining the mass or density threshold for these categories. Another notable inaccuracy of ECBC 2007 is that it provides orientation-specific coefficients based on climate zones, which is a result of intermixing climate classification based on temperature and humidity (NBC) and latitude-dependent solar radiation distribution across different orientations. However, for computing shading multipliers for effective SHGC of fenestrations with shading devices ECBC 2007 uses 15 N latitude to classify India into two separate geographic regions.

The ECBC 2017, employs a component approach for computing EPF coefficients based on prototype models developed for different building typologies. The code limits the application of ‘Building Envelope Trade-off method’ to buildings having WWR up to 40 percent but doesn’t provide the basis for this limit. It can be assumed that the parametric runs performed for computing these coefficients used models with WWR ≤40 percent. The energy simulation and parametric runs were performed using eQuest v.3.64 [24]. Similar to ECBC 2007, the EPF coefficients have been provided for two groups of building operations- daytime and 24-hour occupancies. The skylight has not been included in the trade-off analysis, due to its limited occurrence observed in data collected for developing prototype models. Similar to ECBC 2007, the orientation-specific coefficients provided in ECBC 2017 are once again a result of the intermixing of climate classification based on temperature and humidity (NBC) and latitude-dependent solar radiation distribution across different orientations. The 15 N latitude has been used for classifying India into two separate geographical regions for computing shading equivalent factors [22].

The Eco-Niwas Samhita 2018 (Part-1) provides coefficients to calculate the Residential Envelope Transmittance Value (RETV) of buildings located in four climate zones (except for cold zone) of India. It has merged the Hot-Dry and Composite zones due to similar weather conditions during the observed cooling period between March and October [25]. The coefficients for RETV were computed through simulation models created using DesignBuilder with EnergyPlus solver. The methodology is based on the average of multiple representative cities, which means that the computed coefficients are an average of the selected representative cities. However, it is important to note that unlike ECBC the roof of the building is not included in the RETV algorithm. Two separate prototype layouts were used for performing the parametric simulations and the orientation factor was calculated by considering the amount of solar radiation incident on eight façades of an octagonal building during the simulated cooling period [25]. Ideally, the amount of solar radiation transmitted through the eight façades of the octagonal building should be referred to instead of the amount incident. Fortunately, the ECBC’s inaccuracy of intermixing climate zones with orientation specific coefficients has not been replicated in ENS 2018. The orientation factor is independent of the climate zone, but the same orientation factors are applied for both conductive and radiative heat gain components which can’t be the accurate representation based on building physics principles. Both the orientation factor and shading multiplier have been computed based on the 23.5° N latitude for classifying India into two separate geographic regions [19]. It is also important to note that since the simulation for developing the RETV algorithm was carried out only for the respective cooling periods, the envelope specifications selected based on this algorithm may not necessarily be optimized for the building's annual operation.

The study titled "Predetermined overall thermal transfer value coefficients for Composite, Hot-Dry and Warm-Humid climates" by S. Devgan et al. (2010) was also an attempt at addressing the limitations and errors of ECBC 2007. It developed OTTV based algorithm for three climate zones- Hot-Dry, Warm-Humid and Composite. The development of the prototype building model for the simulation and parametric runs is based on a limited dataset of four air-conditioned office buildings located in Delhi NCR. Therefore, the developed prototype building model may not be representative of other regions of India. The study used eQuest v.3.6 for building energy simulations, and was limited to a single 16-story office building having an octagonal plan for parametric runs. The study performed calculations for the exterior shading multiplier for windows and then proceeds to apply it to shaded walls as well. Considering the different nature of heat transmission (conductive for opaque assemblies and radiative in the case of non-opaque assemblies) the application of the same exterior shading multipliers is bound to generate inaccurate results. Additionally, the orientation factors and shading multipliers were computed for 8 orientations (N, S, E, W, NE, NW, SE & SW) by performing parametric runs, and the coefficients for in-between 8 orientations (NNE, ENE, ESE, SSE, SSW, WSW, WNW & NNW) was derived via interpolation. The study considered 98 types of exterior wall constructions and 93 types of glass constructions were evaluated for each climate type. Regression analysis was performed to develop a new OTTV equation and computation of coefficients for the three climate zones. The ECBC's erroneous method of developing orientation-specific coefficients based on climate zones has been followed in this study as well. This is a result of flawed intermixing of climate classification based on temperature and humidity and latitude-dependent solar radiation distribution across different orientations. The developed OTTV algorithm was validated by calculating OTTV for the four reference case study buildings, and the results exhibited a good linear correlation with the annual air-conditioning energy use in the three climates.

The latitude of the city where the project is located plays a significant role in determining the amount of solar radiation that is incident on the façade of the building facing different orientations. For example, the buildings that are located closer to the equator will receive uniform solar radiation on the north and south façades of the building, whereas buildings located farther from the equator shall receive significantly higher solar radiation on the façade oriented towards the equator. Therefore, the shading devices shall be optimized based on the orientation of the building façade and considering the variations in solar path with changes in the latitude of project location. However, the above-developed algorithms (except RETV of ENS 2018) have applied NBC climate classification for computing orientation specific factors instead of latitude based geographical classification.

The OTTV approach is based on steady-state heat transfer calculations, that does not accurately represent the dynamic thermal behaviour of buildings. This can lead to oversimplification of building envelope performance and does not account for the impact of variations in internal loads and operation schedules on building energy consumption. Despite the intrinsic limitations of the OTTV approach it is a useful tool for evaluating the thermal performance of building envelopes at an early design stage, where the application of advanced building energy simulation tools may not be viable. However, the OTTV approach requires accurate coefficients for the building envelope components, which are specific to the climate zones of India. The lack of accurate coefficients for the building envelope components for the cooling-dominated climate zones of India is a major limitation of the OTTV approach. This research shall build upon the previous works and attempt to address the gaps while developing a building physics based steady-state algorithm to quantify the overall thermal performance of the building envelope for cooling-dominated Indian climates.

## 4 CONCLUSION

The design of the building envelope significantly impacts the thermal performance and overall energy efficiency of the building. Building envelope optimization has become a critical aspect of the design process, with the aim of reducing energy consumption, greenhouse gas emissions, and ensuring thermal comfort for the occupants. The optimization of the building envelope can be achieved through a combination of passive and active measures. The optimization of passive measures involves appropriate selection of parameters such as building orientation, shading, glazing, and insulation. The selection of the appropriate measures and their implementation requires a comprehensive understanding of building physics, climate classification, and thermal comfort standards. The building envelope optimization process also involves the integration of building energy codes and standards, which provide a framework for the design of thermally comfortable energy-efficient buildings. The implementation of building energy codes and standards in India is still in the nascent stage. However, with the increasing demand for energy-efficient buildings, there is a growing need for building envelope optimization and the adoption of performance-based codes and standards.

This paper identified Overall Thermal Transmittance Value (OTTV) as an effective tool not only for building envelope optimization, but also to demonstrate compliance with building energy codes. The development of an OTTV based algorithm for the thermal performance optimization of building envelopes in India can be a significant step towards mainstreaming climate-responsive design of commercial buildings. This paper reviewed different algorithms used to quantify thermal performance, its use in national building energy codes.

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