Ranking the Thermal Calibre of Capacitive Building Envelopes Using Data Envelopment Analysis

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Abstract

Thermal response of building envelopes is driven by the thermal resistance, capacitance, and configuration of the envelope. However, thermal capacity has been majorly neglected in the performance assessments of envelopes.

This study presents a novel approach for efficiently ranking capacitive building envelopes using Data Envelopment Analysis (DEA). A thermodynamic Esp-r model of a residential building located in Ahmedabad, India, is developed. Thermal performance of 27 envelopes of varying thermal capacity are ranked using DEA for four major orientations.

It is observed that capacitive envelopes exhibit higher thermal calibre in south and east exposed scenarios compared to north and west scenarios.

Key Innovations

- A novel approach for efficiency-based ranking of capacitive building envelopes using data envelopment analysis is presented
- The concept of thermal calibre of capacitive building envelopes is defined

Practical Implications

The approach used in this study captures the dynamics in thermal performance efficiency of capacitive building envelopes. This study will comprehensively represent the overall thermal capacity and facilitate the optimum choice of envelope assemblies.

Introduction

Building envelopes regulate the heat transfer process between the outdoor environment and the indoor spaces. The thermal response of a building envelope is driven by the resistive and capacitive properties of the individual layers and their relative position in the overall envelope configuration. Materials with high thermal capacity are also referred to as high thermal mass materials and vice versa. Thermal mass modulates the periodicity of the building's heat transfer process. It is effective for locations where diurnal temperature variations are greater than 10°C, and alternate heat gain and loss occur at the envelope interface due to these daily temperature variations (Childs et al., 1997). The advantages of envelope thermal capacity have been discussed in previous studies by Balaras (1996), Childs (1997), and Yang and Li (2008).

Several researchers have attempted to capture the thermal capacity of building envelopes for robust and comprehensive thermal performance assessments. Kossecka and Kosny (2002, 2015) presented the dynamic benefit for massive systems (DBMS), which expressed the envelope thermal mass benefits as a function of material configuration and climate. The mass-enhanced R-value, specified in the building code of Australia, defines the ratio of the R-value determined for a massive construction at a constant energy load to the R-value for a specific location (Williamson, 2011). The thermal time constant (TTC) captures the dynamic behaviour of building envelopes representing the response rate for a step change in temperature (Reilly & Kinnane, 2017). Tsilingiris (2004) defined the forward thermal time constant (FTTC) and the reverse thermal time constant (RTTC) considering the heat flow from outside to inside and vice versa. It was based on the distribution of heat capacity with respect to the wall's plane of symmetry. Despite several such studies, there has not been a unified framework to represent thermal capacity benefits of building envelope and extend them to detailed building performance assessments.

It has been challenging to accurately represent thermal capacity as it is associated with dynamic thermal response. The thermal boundary conditions drive the envelope performance, which vary over time. Several studies have used parametric analysis to assess the effectiveness of thermal capacity in envelopes (Asan, 1998; Aste et al., 2009). However, these studies do not sufficiently account for the dynamic response of the capacitive materials. Thus, the representation of capacitive response along with the resistive response of the envelope is critical in the building's thermal performance assessments.

This study presents a novel approach for the efficiency-based ranking of capacitive building envelopes. Data envelopment analysis is used for ranking the thermal performance of envelopes over the entire year.

Method

Location

The location of the study is Ahmedabad, India (23.04° N, 72.46° E). It is classified as BSh (Hot semi-arid steppe) per the Koppen-Geiger climate classification. The diurnal temperature difference is high, and alternate heat gain and loss phenomena are observed at the envelope. A cluster analysis of the typical meteorological year (TMY) data of

Ahmedabad obtained from the Indian Society of Heating, Refrigerating and Air Conditioning Engineers (ISHRAE) database was performed.

The two-step clustering considering the daily maximum temperature (Ta_max), minimum temperature (Ta_min), and mean global horizontal irradiance (GHI_avg) yielded four seasonal clusters. The clustering is done to group the days in the year into similar ambient condition clusters to compare performance. The cluster-wise summary is presented in Table 1. Since the use of thermal mass in heating dominant conditions is not efficient, as suggested by (Reilly & Kinnane, 2017), cluster 4 is excluded from this study. Hence, the cooling dominant clusters 1, 2, and 3 are considered in the study.

Building Modelling

A thermodynamic model of a 9 m^2 room is developed in ESP-r. ESP-r uses the finite volume conservation method. The spatial configuration and geometry of the model, as shown in Figure 1, were defined in Esp-r along with the envelope thermophysical properties. A single exposed scenario was simulated for the four orientations. The rest surfaces were adiabatic.

A fluid flow network was defined to represent the airflow pattern based on incident ambient air velocities. The room contained a flow node connected to the outdoor node through the fenestration component. Infiltration was modelled at 0.5 ach. The window was modelled to open when the ambient temperature was above 28° C and remained closed otherwise. The simulations were carried out in hourly time steps. Weather data from the ISHRAE database were adopted for simulations.

The simulation model was validated using real-time data on indoor temperature and inside surface temperature of exposed walls of a residential apartment in Ahmedabad (Rajasekar et al., 2015). The east and north-exposed bedroom data is compared with the simulated east and north-exposed model. The simulated instantaneous surface temperature values agreed well with the measured values for the corresponding exposed room (R^2 =0.89).

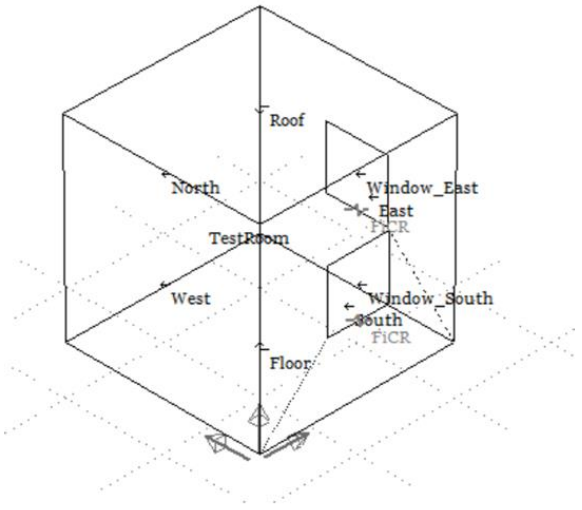

Figure 1: Esp-r model of the room for south orientation

Envelope Cases

Three capacitive building materials were selected from the existing materials used in the construction industry corresponding to high and medium thermal mass, as shown in Table 2. The 27 possible configurations of building envelope using the three materials in 3 layers of 100mm thickness each and their thermal properties are presented in table 3. The thermal transmittance of the 27 envelopes lies between 1.76 W/m^2K and 3.03 W/m^2K.

Table 2: Building material's thermophysical properties

Material	**Density** Kg/m3	**Thermal conductivity** W/mK	**Specific heat capacity** J/kgK
A	2410	1.74	880
B	1820	0.81	880
C	1646	0.73	880

Data Envelopment Analysis

Data envelopment analysis or DEA, is a non-parametric, non-statistical mathematical method that employs linear programming to measure the relative efficiency of decision-making units (DMUs). It measures the comparative performance of DMUs by evaluating a set of total inputs and total outputs and ranks the performance of the DMUs (Emrouznejad et al., 2016; Farantos, 2015). Efficiency is defined for each DMU as the ratio of weighted outputs to weighted inputs (Charnes, 1978). The main characteristic of DEA is its ability to provide a unified efficiency score. The efficiency lies between 0 (least efficient) and 1 (most efficient). In DEA, the reference set of efficient DMUs can be used to identify the best DMUs with which to compare non-efficient DMUs.

To assess a building envelope's efficiency, its thermal calibre must be considered. Thermal calibre is defined as the ratio of the envelope performance (resistive and capacitive) on a particular day to its best performance in the year. DEA offers the advantage of comparing different envelopes on all days based on their relative performance. Thus, a building envelope is compared against its best daily performance and against the best performance of other envelopes. Therefore, the DEA efficiency score is the thermal calibre of the envelope on a given day, expressed in a ratio between 0 and 1.

The first step in a DEA study is identifying the decision-making units (DMUs) to be evaluated. In this study, the DMUs are the 27 building envelope cases. The next step is the selection of inputs and outputs for each DMU based on the criteria on which they are to be compared. The selection of inputs and outputs used to perform the data envelopment analysis is critical.

The selected inputs in this study are the thermal time constant and diurnal sol-air temperature gradient. TTC represents the envelope thermal properties, while the sol-air temperature gradient (i.e., the difference between the maximum and minimum sol-air temperatures) represents the boundary condition. The sol-air temperature considers the effect of solar radiation incidents on the surface and the outside air temperature.

To capture the thermal response of the building envelope total heat gains through the envelope and total heat storage are considered outputs for DEA. Total heat gain represents the amount of heat entering the indoor spaces, which should be minimized. Whereas total heat storage represents the thermal capacity of the envelope and is the amount of heat that the envelope holds and releases over a day. The total heat storage should be maximized. Both the selected DEA outputs are obtained from the dynamic simulations of envelope assemblies through the ESP-r model.

Weights are assigned to each input and output, and the efficiency of a DMU is expressed as a ratio of the sum of weighted outputs to the sum of weighted inputs. Thus, this ratio needs to be maximized for higher efficiency.

DEA is solved using the MAXDEA Ultra v. 8.7. The model used is a constant return to scale (CRS) model and is output oriented. The CRS model assumes that an increase in inputs leads to a proportionate increase in outputs. Output orientation implies that the outputs are maximized before the inputs are minimized in calculating the efficiency score.

A building envelope assembly would have a higher performance if the heat gain is low and heat storage is high for the cooling dominant period. In DEA, outputs are maximized, and inputs are minimized. However, the output heat gain and heat storage are contradictory since heat gain is to be minimized, and heat storage should be maximized. To solve models with this contradictory nature, the undesirable outputs model is used where the contradictory output (heat gain) is defined as an undesirable output and is minimized simultaneously as the desirable output (heat storage) is maximized (Jahanshahloo et al., 2005). The outputs are inseparable as total heat gain is affected by total heat storage and the two inputs.

DEA was performed for 27 building envelope cases for 280 cooling-dominated days. Thus, 7,560 DMUs (27 x 280) were considered for each of the four orientations.

In summary, a total of two inputs (TTC and Sol-air temperature gradient) and two outputs (Total heat gain and Total heat storage) are used for DEA in this study. There are 7,560 DMUs for each orientation exposure. Total heat gain is minimized, and total heat storage is maximized using CRS, output oriented, undesirable output-inseparable model.

Results and Discussion

Dynamics of capacitive heat transfer

High thermal mass envelope stores the heat from the outdoor environment and does not let it into the building due to its high storage capacity. The percentage utilization of the combined thermal resistance and storage by the envelope to the maximum combined thermal resistance and storage by the envelope is defined as the thermal calibre of the envelope. In this study, the thermal calibre of building envelopes is represented by the relative efficiency score of the envelope from DEA.

Figure 2 presents the thermal calibre (efficiency score) frequency distribution of 27 envelopes across all orientations for 280 days. For most of the studied period, the building envelope assemblies act in a thermal calibre range of 0.7 to 1.0.

Effect of position of thermal mass in capacitive envelopes

Figure 2 shows that the envelopes with the same thermal transmittance U-value have different efficiency distributions due to the inherent mass of the layers. Additionally, the position of thermal mass layers affects the performance of the envelopes. For instance, cases 3 to 5 have the same U-value of 2.53 W/m^{2}K; however, case 5 outperforms cases 3 and 4. Case 5 comprises a 200mm external layer of high-capacity material A, and the internal layer is medium thermal mass material B. However, when a high thermal mass layer is sandwiched between medium mass layers, such as in cases 7, 14, 22, and 26, it performs better than having 200mm medium mass layers externally or internally. However, if a medium mass material is sandwiched between two high mass layers, it performs poorly, as seen in case 11.

In capacitive envelopes, high thermal mass external layers perform better as they can absorb the heat entering the building at the envelope interface. If, however, the outer layer is made up of low thermal mass, then once the external layer's heat capacity is saturated, the excess heat will enter the interior spaces of the building.

Thus, the external layer is critical and vital in a capacitive envelope. This is different from a combined thermal mass and insulation envelope; the external layer (insulation) that restricts the heat from entering the envelope is preferred, while the interior thermal mass helps regulate the indoor temperature, as presented by Kossecka and Kosny (2002, 2015).

When the middle layer is of medium thermal mass, and the other layers are of high thermal mass, it implies that the intermediate layer will get saturated first and actively facilitate the heat transfer between the other two layers. The external and internal layers will attempt to reach thermal equilibrium and hence, negate the benefits of the thermal mass construction. Thus, a middle layer of lower thermal mass should be avoided compared to the outer and inner thermal mass layers. The opposite is true for the middle layer to be of higher thermal mass compared to the outer and inner layers of lower thermal mass. It is due to the middle layer's ability to withstand an additional heat load and store it instead of letting it inside. Thus, a higher thermal mass middle layer benefits a capacitive envelope.

Cases 12 and 26 perform significantly better than the other envelopes. It is important to note that both cases have a high U-value (2.44 W/m^{2}K and 2.11 W/m^{2}K, respectively) along with at least one high mass layer. Case 12 has a dominantly high external thermal mass, while case 26 has a high thermal mass middle layer.

Additionally, the thermal transmittance and inherent thermal capacity are critical to assessing the thermal performance of building envelopes. Thus this dual criterion-based assessment is important in understanding the behaviour of thermal mass envelopes.

Evaluation of thermal calibre of capacitive envelopes

Figure 3 presents the pixel chart demonstrating the thermal calibre across the year for three envelopes having the same U-value – cases 23, 24, and 26. Each pixel represents a day of the year, with the columns representing the month and the rows representing the day. The efficiency is depicted by the colour of each pixel using the legend. The variation between the efficiency is visible across the different orientations for the three envelopes. Case 26 is the most efficient, followed by cases 24 and 23, respectively. Thermal calibre distribution is observed in different periods in different orientations. For instance, in the south orientation, high thermal calibre is seen between April to June and from mid-September to November. Case 26 has a higher efficiency score across these months than the other two cases. Similarly, in the East orientation, higher thermal calibre is seen from February till mid-May and from mid-September until November.

Effect of orientation

The envelopes have higher efficiencies in the south and east orientations than in the north and west orientations. Figure 3 shows that the thermal calibre is highest in the east, followed by the south, west, and north orientations.

Ranking of capacitive building envelope assemblies

Table 4 presents the ranking of the studied envelopes across the different orientations based on their thermal calibre. From the table, we can determine the best envelope for the different orientations for the studied residential unit in Ahmedabad. It is observed that envelopes 12 and 26 have the best performance. While a building designer will adopt a simple U-value based material selection as prescribed in the National building code (2016), the ranking shows that the envelope with the highest U-value, i.e., case 1, isn’t the best performer. Thus the hypothesis that the ‘higher the thermal mass, the better the envelope performance’ is not correct, the inherent thermal mass of the envelope layer performs dynamically and is represented in the methodology of this study. Hence, careful consideration and selection of envelope layers are important in the early design stage of a building.

Simulation-DEA Methodology

The Simulation-DEA methodology employed for this study allows building designers to compare and rank envelopes for efficient thermal capacitive performance. Depending on the capacitive envelopes and inputs and outputs selection, this method can be used to determine the efficient thermal mass of capacitive building materials for building applications in diverse climates such that their thermal calibre is close to 1. This paper has presented this methodology for the efficient thermal capacitive performance of a residential building in a hot and dry region.

Conclusion

Thermal storage or capacity has been a neglected factor for assessing building envelope performance. The building envelope’s performance is dynamic in nature. It is influenced by the layer configuration, material properties, and envelope orientation. This paper presented a framework to rank envelopes based on the thermal calibre of the envelope. Thermal calibre gives due respect to thermal resistance and thermal storage in the dynamic performance assessment.

Based on the findings, the efficiency of a building envelope varies for different orientations. The performance of a building envelope is not a constant value but a dynamic value that shifts throughout the year. This study was performed in seasonal clusters to highlight the importance of the daily boundary conditions. Thus, particular clusters can be selected based on a location’s seasonal criticality and used for assessing capacitive performance. The study is helpful in selecting efficient materials and designing appropriate building envelopes.

Nomenclature

DEA: Data Envelopment Analysis

DBMS: Dynamic Benefit for Massive Systems

R-value: Thermal Resistance

TTC: Thermal Time Constant

FTTC: Forward Thermal Time Constant

RTTC: Reverse Thermal Time Constant

BSh: Hot semi-Arid Steppe climate

TMY: Typical Meteorological Year

ISHRAE: Indian Society of Heating, Refrigerating and Air Conditioning Engineers

DMU: Decision Making Unit

CRS: Constant Return to Scale

U-value: Thermal Transmittance

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Table 1: Summary of clusters

Cluster No.	**Parameter**	**Cluster mean**	**Cluster std. Dev.**	**Cluster max**	**Cluster min**	**Cluster size**
1	Ta_max	39.7	1.9	44.2	35.2	94
	Ta_min	27.1	2.1	30.7	22.0	
	GHI_avg	541.6	42.8	1224.0	461.6	
2	Ta_max	34.6	1.8	38.8	29.4	84
	Ta_min	19.2	2.0	24.2	13.7	
	GHI_avg	483.9	49.8	605.1	393.8	
3	Ta_max	33.1	2.5	38.3	26.4	102
	Ta_min	25.7	1.4	28.6	20.4	
	GHI_avg	401.2	50.2	490.8	276.5	
4	Ta_max	28.4	2.3	33.1	21.4	85
	Ta_min	14.4	2.3	21.0	8.9	
	GHI_avg	397.2	46.6	492.7	236.6	

Ta_max: Daily maximum temperature, Ta_min: Daily minimum temperature, GHI_avg: Mean global horizontal irradiance

Table 3: Building envelope configurations and calculated properties

Case No.	**Layer 1 External** 100mm	**Layer 2 Middle** 100mm	**Layer 3 Internal** 100mm	**Thermal Time Constant** hr	**U-Value** W/m^2K
1	A	A	A	24.14	3.03
2	B	B	B	31.41	1.90
3	B	A	A	32.22	2.53
4	A	B	A	27.51	2.53
5	A	A	B	22.80	2.53
6	B	B	A	34.64	2.17
7	B	A	B	29.93	2.17
8	A	B	B	25.22	2.17
9	C	C	C	30.88	1.76

10	C	A	A	33.63	2.44
11	A	C	A	27.87	2.44
12	A	A	C	22.11	2.44
13	A	C	C	24.36	2.05
14	C	A	C	30.12	2.05
15	C	C	A	35.88	2.05
16	B	C	C	29.98	1.80
17	C	B	C	31.11	1.80
18	C	C	B	32.25	1.80
19	B	B	C	30.16	1.85
20	B	C	B	31.29	1.85
21	C	B	B	32.42	1.85
22	C	A	B	31.15	2.11
23	C	B	A	35.85	2.11
24	A	B	C	24.25	2.11
25	A	C	B	25.39	2.11
26	B	A	C	28.96	2.11
27	B	C	A	34.72	2.11

A is high thermal mass material, B and C are medium thermal mass materials with thermophysical properties, as in Table 2

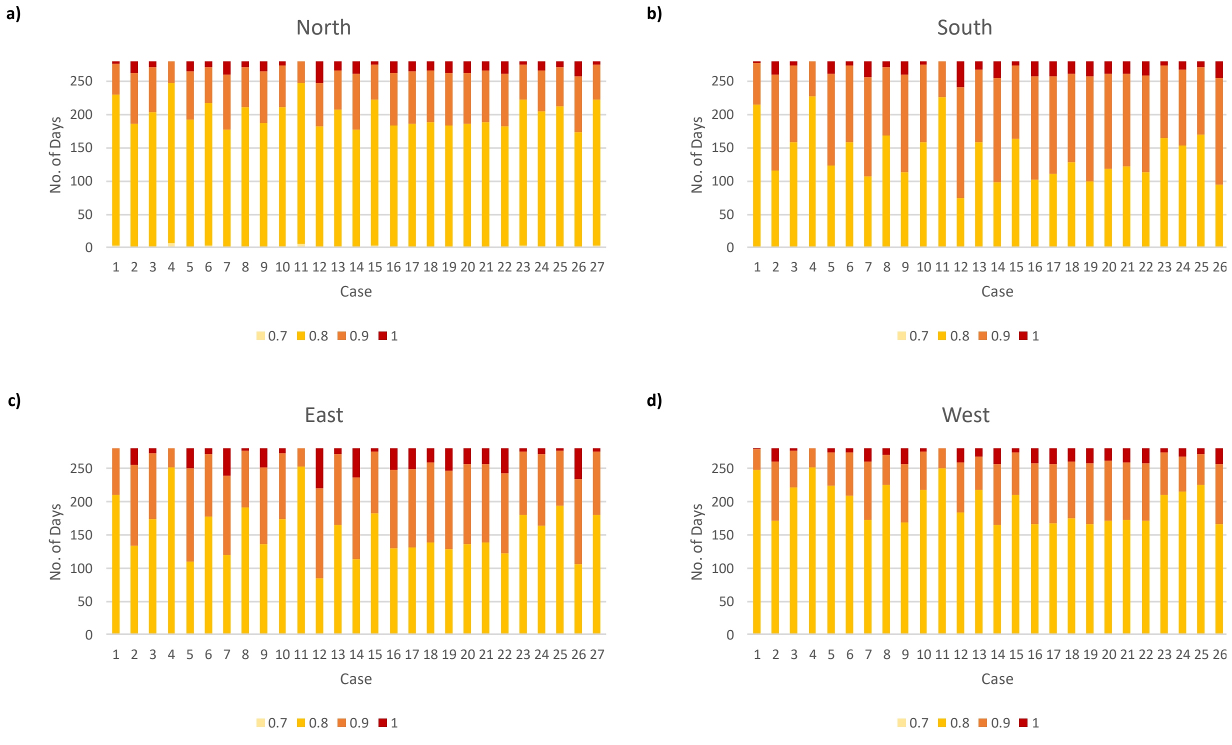

Figure 2: Thermal Calibre frequency distribution for a) North, b) South, c) East, and d) West orientation for a total of 280 cooling-dominant days from clusters 1 to 3

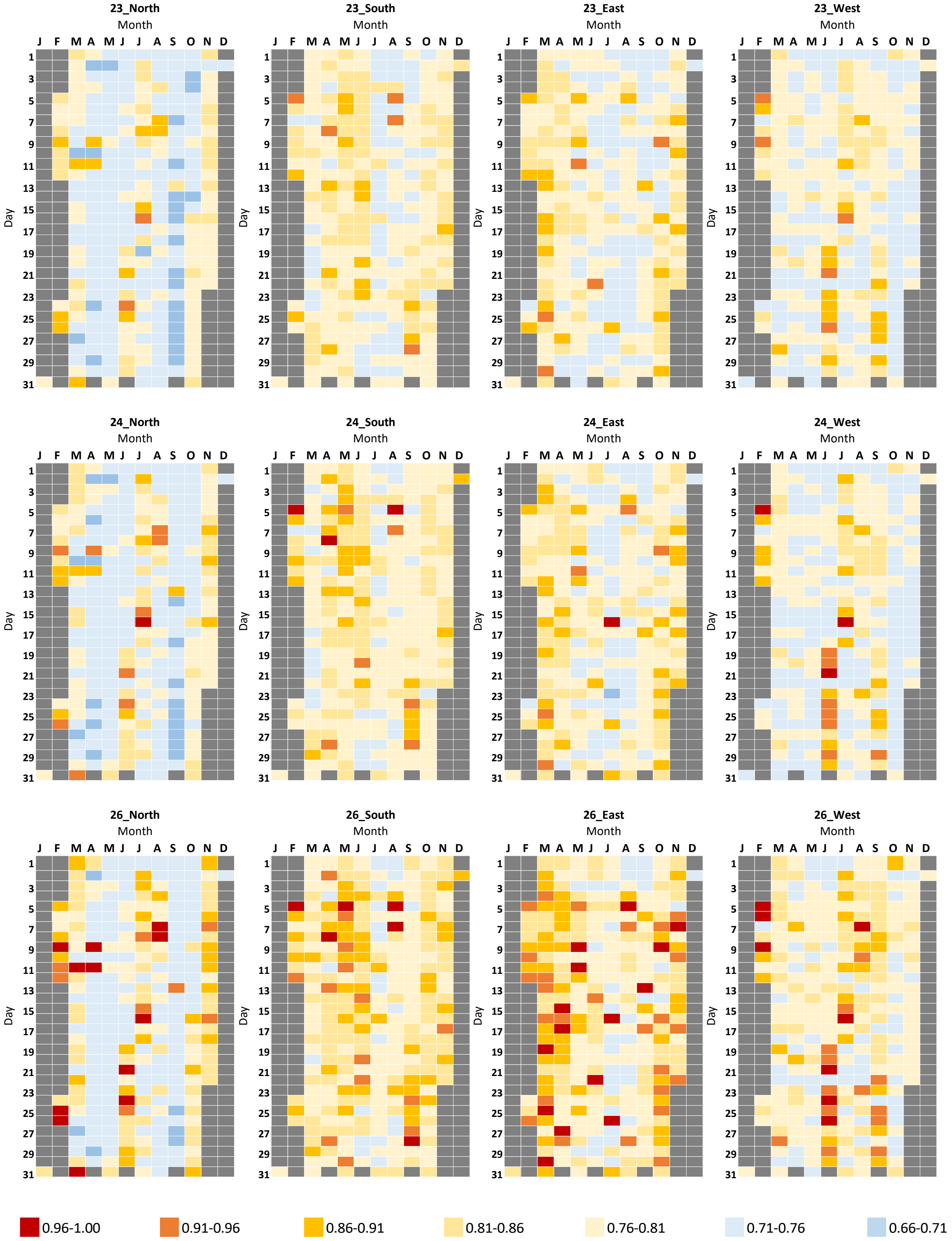

Figure 3: Yearly Thermal Calibre Pixel chart for all orientations for a) Case 23, b) Case 24, and c) Case 26
Each pixel represents a day of the year, with the columns representing the month and the rows representing the day.

Table 4: Ranking of envelope configurations across orientations

Case No.	**North**	**South**	**East**	**West**
1	25	25	25	25
2	8	10	11	8
3	17	17	17	23
4	26	27	26	27
5	14	13	5	23
6	21	18	19	14
7	3	6	4	10
8	18	23	23	21
9	11	9	10	6
10	20	19	18	20
11	26	26	27	26
12	1	1	1	13
13	16	16	16	19
14	4	3	3	1
15	22	20	22	16
16	6	5	8	3
17	10	7	9	3
18	12	14	14	12
19	6	4	7	3
20	8	11	12	10
21	13	12	13	8
22	5	8	6	7
23	22	21	20	16
24	15	15	15	14
25	19	24	24	22
26	2	2	2	2
27	22	21	20	16