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Article

Determining the impact of horizontal and vertical fins of office facades on visual and thermal comfort

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ABSTRACT

A high degree of transparency is customary in modern building design, and horizontal or/ and vertical fins are often employed for shading the building envelope. This study proposes a method to limit horizontal and vertical fin ranges according to current visual and thermal comfort standards. The study was carried out considering a module office room, which is assumed to be located in an office building, and one long wall is transparent. The minimum and maximum fit ranges were determined for four glazing types and seven directions the transparent wall faces (a total of 112 cases). The criteria suggested in the standard EN 17037 have been considered for visual comfort. In the first stage of providing thermal comfort, solar control was implemented to limit the fin range, that is, the annual shading need and solar gain were identified depending on the direction. Afterward, the adaptive comfort method recommended for naturally ventilated spaces in the ASHRAE 55-2017 standard was applied to evaluate the comfort conditions of the fit ranges. The detailed analysis revealed that the optimum direction regarding thermal and visual comfort is south, and the fin type in this direction is horizontal. Vertical fins in the west, east, northwest, and northeast directions provide positive outcomes. The performance of the horizontal and vertical fins is close to each other in the southwest and southeast directions. The results for the module office room can be used to take principle decisions for fit design.

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INTRODUCTION

The design of a comfortable building consuming energy at a minimal level is a complex process involving a large number of interdependent variables. In a complex system consisting of criteria that often contradict each other, it is essential to make an integrated design. Determining the limitations that meet the minimum conditions of comfort criteria provides a great deal of convenience to the designer. Solar control, in other words, benefiting from the sun and/ or avoiding the sun depending on the conditions, is a passive design strategy that directly affects thermal and visual comfort. Solar radiation affects the illuminance generated by natural light, and therefore the energy to be consumed in electric lighting. In addition, depending on climatic and seasonal conditions, it also affects the heating and/or

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cooling load. The main parameters affecting the heating and cooling loads are the transparency ratio and shading property of the building envelope. In recent years, a high transparency ratio is quite common in modern building design. Transparent areas in the building envelope are the most sensitive element of the structure and create the greatest effect on the heat flow balance (Olgyay & Olgyay, 1957). Increasing the transparency ratio in the building envelope increases the daylight illuminance level and solar gain indoors, while it may also cause unwanted solar gains and glare. One of the most effective ways to reduce the solar load in transparent areas is to block direct incoming solar radiations before they reach the glazing (ASHRAE, 2013). However, in the design of shading elements, it is important to establish a balance between "benefiting from daylight and solar energy" and "unwanted solar gain and glare control". For this reason, building energy consumption can be reduced with an effective passive solar design approach which will be used at the early design stage and will benefit from solar energy and daylight while avoiding their negative effects (DeKay & Brown, 2013).

The most up-to-date standard for the assessment of visual comfort in interiors is "EN 17037: Daylight in Buildings". In the standard, the criteria for the assessment of daylight are listed as *"daylight provision, protection from glare, exposure to sunlight, and view out (i.e., visual connection with the external environment)"* (European Committee for Standardization, 2018, 2022). The studies carried out within the scope of this standard basically cover the assessment of sample spaces based on daylight criteria (Paule et al., 2018; Yılmaz, 2019). As a different approach, in his study, Schouws (2022) investigated how much influence the European standard in question had on the energy consumption of a typical office building and whether BREEAM and LEED requirements could still be met (Schouws, 2022). Rasmussen and Pedersen (2019), on the other hand, showed the difficulties that designers face when trying to simulate building performance by taking into account daylight, indoor climate, and landscape.

There are many standards for indoor thermal comfort such as ISO 7730, ASHRAE 55, EN 15251, and CIBSE (ASHRAE, 2013; CIBSE, 2006; EN 15251, 2007; ISO, 2005). In these standards predicted mean votes (PMV) thermal comfort model and adaptive comfort model are included. Based on the temperature of the indoor environment, air movement speed, average radiative temperature, relative humidity, activity level of people, and clothing insulation values, Fanger created the PMV model in which he transferred the satisfaction states of individuals to numerical data (Fanger, 1970). The PMV thermal comfort model, created with a limited number of users in an air-conditioned laboratory environment, was designed for use in buildings that do not have natural ventilation. Therefore, in buildings with different climate types or natural ventilation, it can determine the level of thermal comfort as colder or warmer than it is (Nicol, 2004; Rijal et al., 2017; Wu et al., 2017). On the other hand, the Adaptive Comfort model proposed by Dear and Brager was created by making 21000 measurements in 160 buildings, most of which are offices. In this model, indoor temperatures or acceptable temperature ranges are associated with outdoor meteorological or climatic parameters. This method defines acceptable thermal environments for areas that are naturally ventilated only by user control and do not have any mechanical cooling and heating systems operating (de Dear and Brager, 1998). Since there is no mechanical heating and cooling system, passive climate-based design approaches are more applicable (Nicol et al., 2012; Parkinson et al., 2020). Passive design approaches can be carried out using traditional design tools or climate-based computer programs. "Solar Path Diagrams" and "Shading Masks", which are among the traditional design tools, have created a framework in terms of passive design strategies, analysis, and calculations for shading elements in buildings and minimising overheating (Olgyay & Olgyay, 1957; Mazria, 1979). Thanks to the development of technology, climate-based software can combine climate data with traditional design tools and translate them into meaningful graphics.

In recent years, different design approaches have been developed, especially regarding shading and shaping fins for facade aesthetics (Kuhn, 2017). The most common method used for evaluating the fins made for shading purposes in terms of different criteria is the genetic algorithm. Genetic algorithms are the most advanced improvement method that works using mechanisms similar to evolutionary mechanisms observed in nature (Zitzler, 1999). Design alternatives are calculated based on different criteria and offer the most appropriate solution from a large number of options. The optimisation studies carried out in this direction have been usually limited to a single space (Manzan, 2014; Manzan & Padovan, 2015; Khoroshiltseva et al., 2016; Settino et al., 2020; Mangkuto et al., 2021; Luca et al., 2022; Noorzai et al., 2022). However, since the exposure to sunlight states of rooms facing in different directions are also different, the solution sets that meet the requirements for various criteria will also differ. Examining the literature, a study that takes into account all the criteria in the EN 17034 daylight standard along with thermal comfort was not found.

In this study, an approach was developed to determine the optimum fin range, providing visual and thermal comfort for offices facing in different directions. In this context, by taking into account also facade alignment, horizontal and vertical fins were considered separately in the rooms that receive light from one facade and two facades. The effect of obstacles outside the building was excluded from the scope of the study. In this article, the results obtained related to the rooms that receive light from only one facade are presented.

VISUAL AND THERMAL COMFORT CRITERIA

In the study, in terms of visual comfort criteria, it benefited from the European Standard "TS EN 17037". In the standard, the criteria for using daylight are specified as daylight provision, protection from glare, exposure to sunlight, and assessment for view out. The minimum, medium and high levels recommended in the standard for these four criteria are given in Table 1. It is important to meet the requirements for these criteria when determining the ranges of fins.

In this standard, the minimum requirement in terms of daylight illuminance is recommended as ≥ 300 lx. For spaces with vertical windows, it is expected that ≥ 300 lx illuminance will be provided at ≥50% of the reference plane of the room and that an illuminance of 100 lx will occur in 95% of the same plane. It is stated that these illuminances should be provided at ≥50% of daylight hours throughout the year. For the three levels of protection from glare, the recommended daylight glare probability (DGP) values are shown in Table 1. The criterion of exposure to sunlight is expressed by the number of hours the space receives direct sunlight on a cloudless reference day to be selected between February 1st and March 21st. The assessment of view out is performed based on the horizontal sight angle, the distance of external obstacles from the building, and the number of seen layers. The recommended values for these three magnitudes must be provided in at least 75% of the used area of the room.

In the study, two different methods were used to ensure thermal comfort. The first method is to conduct a solar control in order to limit the horizontal and vertical fin ranges; that is, the first method focuses on determining and limiting the annual need for shading and solar gain of the rooms under consideration. The second method used to assess the comfort conditions of fin ranges is adaptive comfort, which is recommended for naturally ventilated spaces in the ASHRAE 55-2017 standard. This method, which defines acceptable thermal environments for user-controlled naturally ventilated areas, includes the following restrictions:

- Any mechanical cooling or heating system is not working.
- The metabolic rate is between 1.0 and 1.3.
- The clothing insulation values are at least 0.5 clo and at most 1.0 clo.
- The average outdoor temperature should be at least 10°C (50°F) and no more than 33.5°C (92.3°F).

METHOD

There are many factors that determine the thermal and visual comfort of the interiors. In this study, the factors affecting visual and thermal comfort were grouped into two groups: constant and variable. The number of variable factors was limited in order to obtain interpretable and meaningful results. The approach followed in the study was to determine which values related to variable factors would be considered and to perform optimisation by determining the fin ranges that meet the requirements for thermal and visual comfort criteria. The decisions taken and the examinations carried out within the scope of the steps listed below the approach are explained in the following sections:

- Assumptions related to constant factors
- Assumptions related to variable factors
- Determination of the calculation method
- Process of conducting calculations

Assumptions Related to Constant Factors

The space considered within the scope of the study was designed as a module room for 24 people as a result of the examination of sample office rooms and design sources (Neufert& Neufert, 2012) (Figure 1). The assumptions made for the constant factors are listed below.

Constant factors related to the room:

- Location: Istanbul-Turkey
- Number of employees in the office: 24
- Length, width and ceiling height of the room: 15.00 m, 7.50 m, 3.00 m

Table 1. Assessment of daylight in interiors

Criteria for the assessment of daylight		Level of recommendation		
		Minimum	Medium	High
Daylight provision	Target illuminance	≥300 lx	≥500 lx	≥750 lx
	Minimum target illuminance	≥100 lx	≥300 lx	≥500 lx
Protection from glare		0.40<DGP≤0.45	0.35<DGP≤0.40	DGP≤0.35
Exposure to sunlight		1.5 h	3 h	4 h
Assessment for view out	Horizontal sight angle	≥14°	≥28°	≥54°
	Outside distance of the view	≥6 m	≥20 m	≥50 m
	Number of layers to be seen	1 layer	2 layers	3 layers

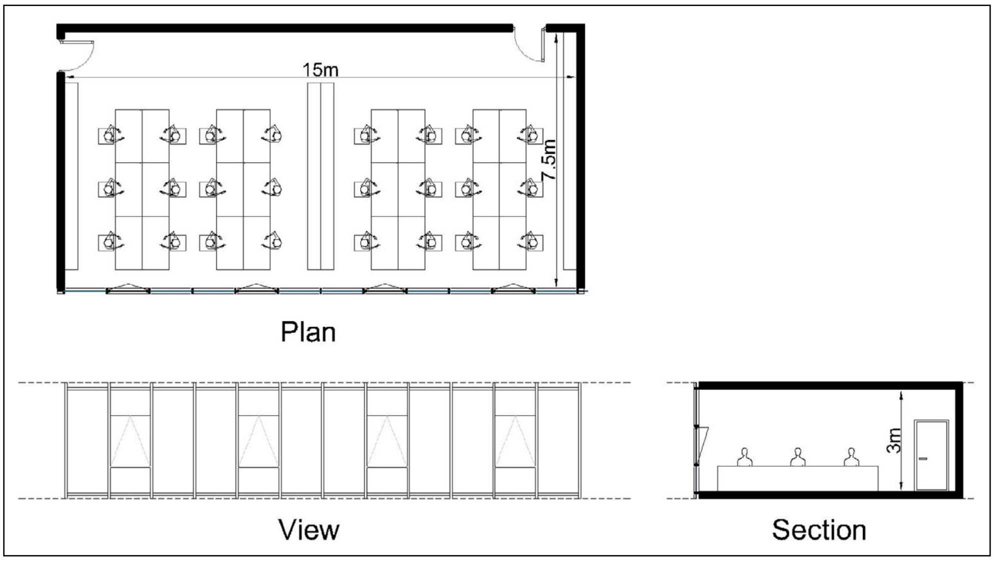


Figure 1. Module office room of 24 people.

- Window area: One long wall of the room
- Joinery dimensions and axle ranges in the window: 0.05 m × 0.15 m and 1.25 m
- Location of the joinery within the wall section: Outside the section
- Reflectance of wall, ceiling and floor of the room: 70%, 80%, 40%
- Days and times of the use of the room: five days a week, from 08:00 to 18:00
- The size, thickness and reflectance of the horizontal and vertical fins: 0.30 m, 0.025 m and 60%

Constant factors related to the light:

- Reference plane for illuminance calculations: Horizontal plane at a distance of 0.77 m from the floor and 0.50 m from the walls (table height: 0.75 m)
- Calculation points for horizontal viewing angle and glare: Eye-level at a distance of 1.20 m from the floor, at the middle level of the work table, and 10 cm from the table (Figures 2 and 4)
- Points considered related to exposure to sunlight: The closest point of the fins to the window glass (Figure 4)

Constant factors related to the heat:

- U value of the aluminium joinery: 3.3 W/m2K
- Number of people per area: 0.47 ppl/m2
- Metabolic rate: 1.0–1.3 met
- Occupants' clothing insulation: 0.5–1.0 clo
- Air speed: 0.2 m/s
- Natural ventilation settings: Minimum and maximum outdoor temperatures: 10°C and 33.5°C. Minimum and maximum indoor temperatures: 22°C and 24°C

Assumptions Related to the Variable Factors

In the study, the process was performed for four different types of window glazing and for the cases in which the window wall faces in seven different directions.

- The direction which the window wall is facing: South, east, west, southeast, southwest, northeast, northwest
- Glass type: 4 different glazing types (Table 2)

Determination of the Calculation Method

Various simulation programs were used to be able to provide optimisation between visual and thermal comfort criteria. The programs used and the path followed in the calculation are summarised below for light and heat.

Table 2. Types of glazing

#	Glazing type	Visible transmittance (%)	Solar heat gain coefficient	Thermal transmittance (W/m^{2}K)
1	4 mm Low-E + 16 mm + 4 mm	79	0.64	1.3
2	4 mm Low-E + 16 mm + 4 mm	71	0.51	1.3
3	6 mm Solar Low-E + 16 mm + 6 mm	69	0.42	1.3
4	6 mm Solar Low-E + 16 mm + 6 mm	58	0.37	1.3

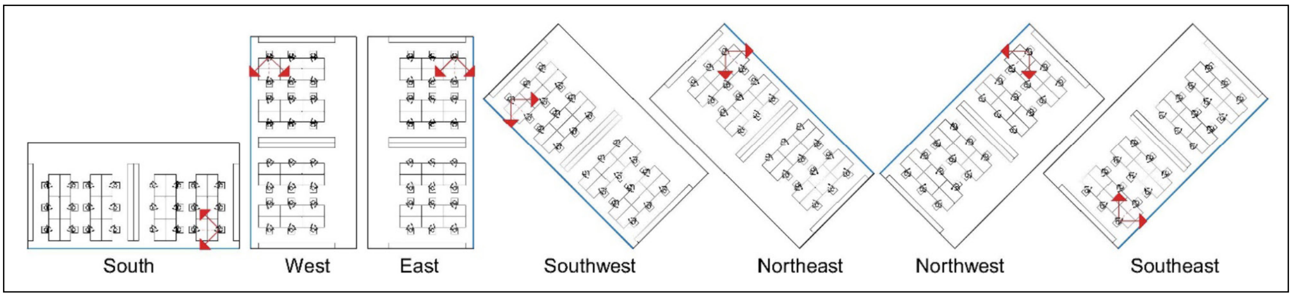


Figure 2. Change of camera position by directions in the glare calculation.

Simulation Programs Used for Light and the Assumptions

For the simulation analyses for daylight illuminance and glare analysis, Rhino 3D modeling tool, Grasshopper visual coding program, Honeybee, Ladybug plug-in programs, and Daysim and Radiance simulation engines were used. The assumptions within the scope of the study were processed into the program and the analysis of the fin ranges was performed. Climate data for Istanbul province was transferred from the EnergyPlus website by using the Ladybug plug-in program (https://energyplus.net/weather). Calculations of daylight illuminances were made at 10 cm interval points determined on the reference plane and the annual calculation results were analysed with daylight autonomy (DA) values. Daylight autonomy refers to the ratio of the time during which the targeted daylight illuminance is provided (or exceeded) at a certain point of the space to the duration of use of the space throughout the year in percentage terms (Illuminating Engineering Society, 2013).

In the EN 17037 standard, the daylight glare probability thresholds are allowed to exceed the referenced space by 5% of the annual period of use. Therefore, when performing glare analyses, it was taken into account that the degree of targeted daylight glare probability (DGP) could be exceeded by 130 hours per year (2600×0.05=130). The position of the person who would be most exposed to glare in the module office room was investigated, and the DGP was calculated for the person who would be most affected by the glare. The directions in which the person could turn his head to avoid glare depending on the conditions were accepted as ±45° with the direction of view. The change of the camera position based on the directions is shown in Figure 2.

To calculate the time for exposure to sunlight, the minimum altitude angle (γs, min) for the city of Istanbul and the day of March 21 was first investigated, and it was determined as 18.80° (EN 17037, 2018; Darula and Malikova, 2017). Then, using the SunCalc simulation program, the hours when the γs, min angle is in question for March 21 were determined as 8.51 and 17.33 (https://www.suncalc.org/). In more specific terms, the exposure to sunlight occurs between 8:51 and 17.33 hours on March 21. Taking the minimum altitude angle as a reference, horizontal and vertical fin ranges providing minimal, medium, and high degrees of sunlight exposure for seven different directions were determined.

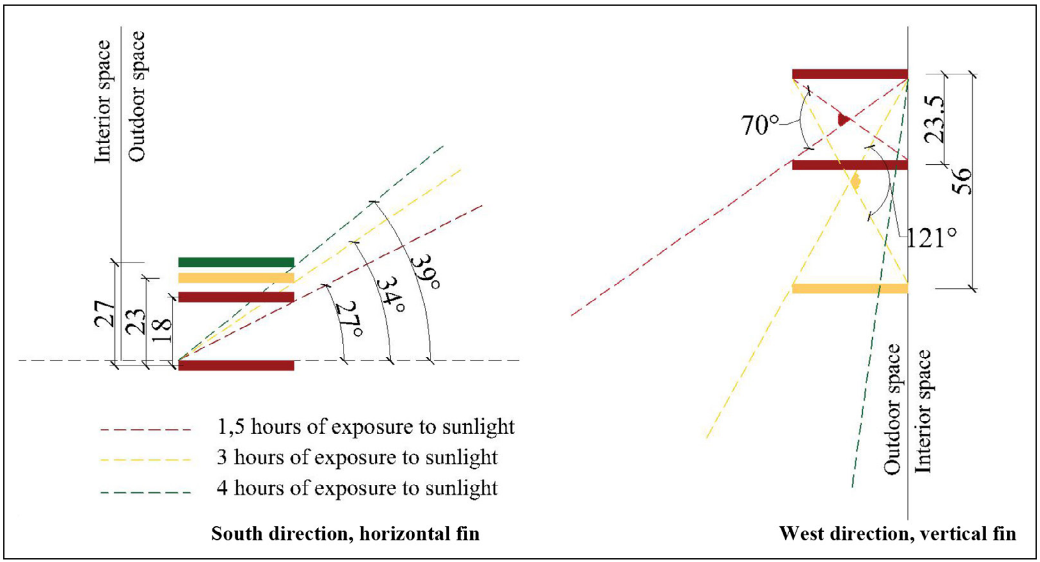


Figure 3. Horizontal and vertical fin ranges providing minimum, medium, and high level sunlight exposure.

These determined values were used in the optimisation related to visual and thermal comfort criteria. Horizontal fin ranges that provide minimal, medium, and high levels of sunlight exposure are shown as an example for the southern facade and vertical fin ranges are shown as an example for the western facade in Figure 3. In the southern direction, the horizontal fin ranges, which provide minimum (1.5 hours), medium (3 hours), and high (4.5 hours) exposures to sunlight, are 18 cm, 23 cm, and 27 cm, respectively. In the western direction, on the other hand, the vertical fin ranges, which provide minimal and medium sunlight exposures, are 23.5 cm and 56 cm, respectively; however, a high level of sunlight exposure can only be achieved without a fin.

Since obstacles outside the building were excluded from the scope of the study, only a horizontal viewing angle study was performed for the “view out” criterion. For each of the 24 users of the space, ranges that provided the minimum, medium and maximum level of horizontal viewing angle in the use of vertical fin were studied. Since the horizontal fins did not restrict the horizontal viewing angle, they were not considered. The observer’s visual field was assumed to be a maximum of 124° horizontally (Panero & Zelnik, 1979). It was assumed that in rooms that receive light from a single facade where the line of sight was parallel to the window wall, the person will turn his head 90° towards the window to establish a visual connection with the external environment. Tangent rays were drawn from each observer’s position to the vertical fins, and the horizontal viewing angle was determined by summing all the fin range angles located within the observer’s visual field of 124° (±62°). The vertical fin ranges, which provided the minimum, medium, and high horizontal viewing angles at all observer points, were 12.5 cm, 23.44 cm, and 68.18 cm, respectively (Figure 4). These measures were used as data in determining the optimisation of visual and thermal comfort criteria.

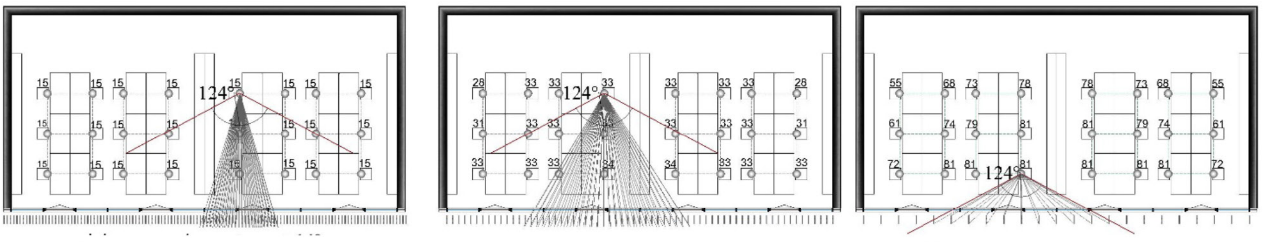
Simulation Programs Used for Heat and Assumptions

For thermal comfort simulation studies, the Rhino 3D modeling tool, Grasshopper visual coding program, Honeybee, and Ladybug plug-in programs were used. The limitations of the adaptive comfort method and the assumptions determined for the office room were processed in the program and the analysis of the fin ranges was carried out. The climate data for the province of Istanbul were transferred from the EnergyPlus website by using the Ladybug plug-in program (https://energyplus.net/weather). By assuming that the module room is located in an office building, it was assumed that there was no heat exchange from the wall, floor, and ceiling components. These surfaces were defined as Adiabatic to the program. In accordance with the adaptive comfort approach, it was assumed that there was no heating, cooling, and mechanical ventilation system in the room.

In terms of solar control, in other words, for shading and solar gain, the Sun Shading Chart in the Climate Consultant program was used (https://www.sbse.org/resources/climate-consultant). In the program where Istanbul climate data was used and the adaptive comfort model was selected, the comfortable temperature range was expressed as 20°C-24°C. Based on this, the hours when it is >24°C throughout the year were evaluated as shading needs, and the hours when it is <20°C were evaluated as solar gain needs. In this context, the need for annual shading and utilisation of solar energy for each direction was obtained in hours. It is stated that when the dry thermometer temperature rises above 24°C degrees, thermal stress begins in the person (Matzarakis et al., 1999). By collecting the data in the winter-spring and summer-fall charts, which show the annual comfort conditions, the proportion of shading and solar gain for the direction and fin range was determined (Figures 5 and 6).

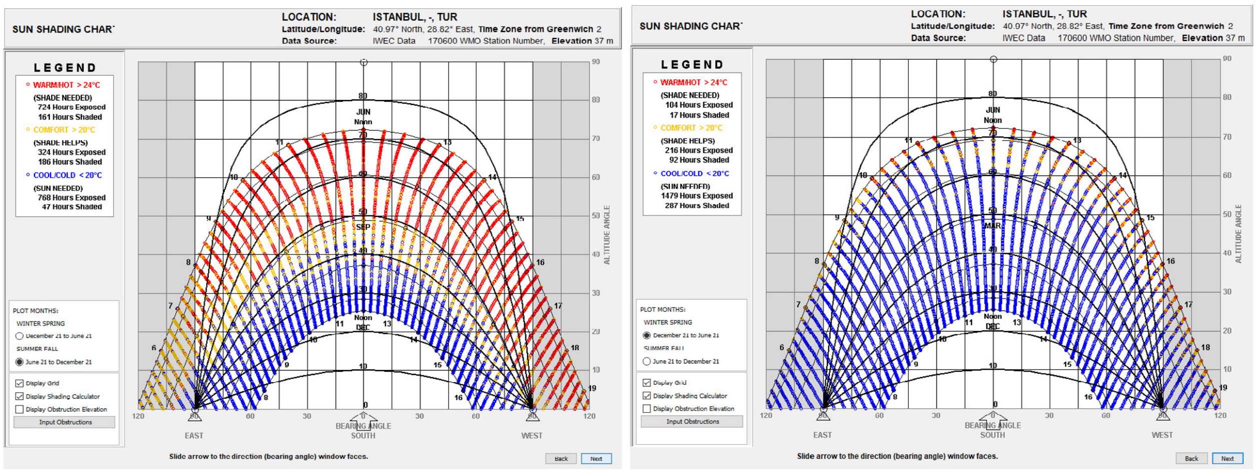
In order to determine and limit the annual shading needs and solar gains of the discussed rooms, a number of assumptions had to be made. The following assumptions, which vary by the sunlight exposure that depends on the direction and fin type, constituted data in terms of determining the optimal fin range.

- *The minimum horizontal fin range* is the range that provides maximum shading and allows maximum solar gain based on the sunlight exposure conditions of the building facade.
- *The minimum vertical fin range* is the range that allows solar gain at least at a rate of 50% (25% in the northwest and northeast directions).



Fin range: 12.5 cm Fin range: 23.44 cm Fin range: 68.18 cm

Figure 4. Vertical fin ranges providing minimum, medium and high level horizontal viewing angle.



SUN SHADING CHART

LOCATION: ISTANBUL, -, TUR
Latitude/Longitude: 40.97° North, 28.82° East, Time Zone from Greenwich 2
Data Source: IWEC Data 170600 WMO Station Number, Elevation 37 m

LEGEND
WARM/HOT > 24°C
(SHADE NEEDED)
724 Hours Exposed
161 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
324 Hours Exposed
186 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
768 Hours Exposed
47 Hours Shaded

PLOT MONTHS:
WINTER SPRING
○ December 21 to June 21
SUMMER FALL
● June 21 to December 21
☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

SUN SHADING CHART

LOCATION: ISTANBUL, -, TUR
Latitude/Longitude: 40.97° North, 28.82° East, Time Zone from Greenwich 2
Data Source: IWEC Data 170600 WMO Station Number, Elevation 37 m

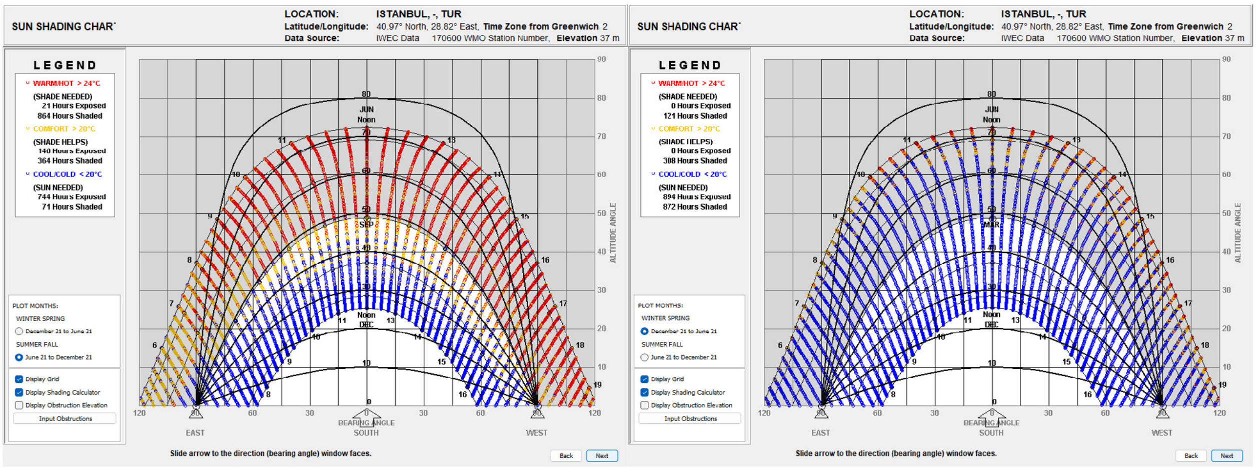
LEGEND
WARM/HOT > 24°C
(SHADE NEEDED)
104 Hours Exposed
17 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
216 Hours Exposed
92 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
1479 Hours Exposed
287 Hours Shaded

PLOT MONTHS:
WINTER SPRING
● December 21 to June 21
SUMMER FALL
○ June 21 to December 21
☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

Winter-Spring

Summer-Fall

Figure 5. An example of solar control analysis with Sun Shading Chart: The situation of sunlight exposure without fin on the south facade.



SUN SHADING CHART

LOCATION: ISTANBUL, -, TUR
Latitude/Longitude: 40.97° North, 28.82° East, Time Zone from Greenwich 2
Data Source: IWEC Data 170600 WMO Station Number, Elevation 37 m

LEGEND
WARM/HOT > 24°C
(SHADE NEEDED)
21 Hours Exposed
864 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
140 Hours Exposed
364 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
744 Hours Exposed
71 Hours Shaded

PLOT MONTHS:
WINTER SPRING
○ December 21 to June 21
SUMMER FALL
● June 21 to December 21
☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

SUN SHADING CHART

LOCATION: ISTANBUL, -, TUR
Latitude/Longitude: 40.97° North, 28.82° East, Time Zone from Greenwich 2
Data Source: IWEC Data 170600 WMO Station Number, Elevation 37 m

LEGEND
WARM/HOT > 24°C
(SHADE NEEDED)
0 Hours Exposed
121 Hours Shaded
COMFORT > 20°C
(SHADE HELPS)
0 Hours Exposed
308 Hours Shaded
COOL/COLD < 20°C
(SUN NEEDED)
894 Hours Exposed
872 Hours Shaded

PLOT MONTHS:
WINTER SPRING
● December 21 to June 21
SUMMER FALL
○ June 21 to December 21
☑ Display Grid
☑ Display Shading Calculator
☐ Display Obstruction Elevation

Winter-Spring

Summer-Fall

Figure 6. An example of solar control analysis with Sun Shading Chart: The situation of sunlight exposure on the southern facade as a result of the addition of horizontal fins with 37.5 cm ranges.

- *The maximum horizontal/vertical fin range* is the range that provides minimum shading and maximum solar gain depending on sunlight exposure conditions of the building facade and solar control performances of fin types.

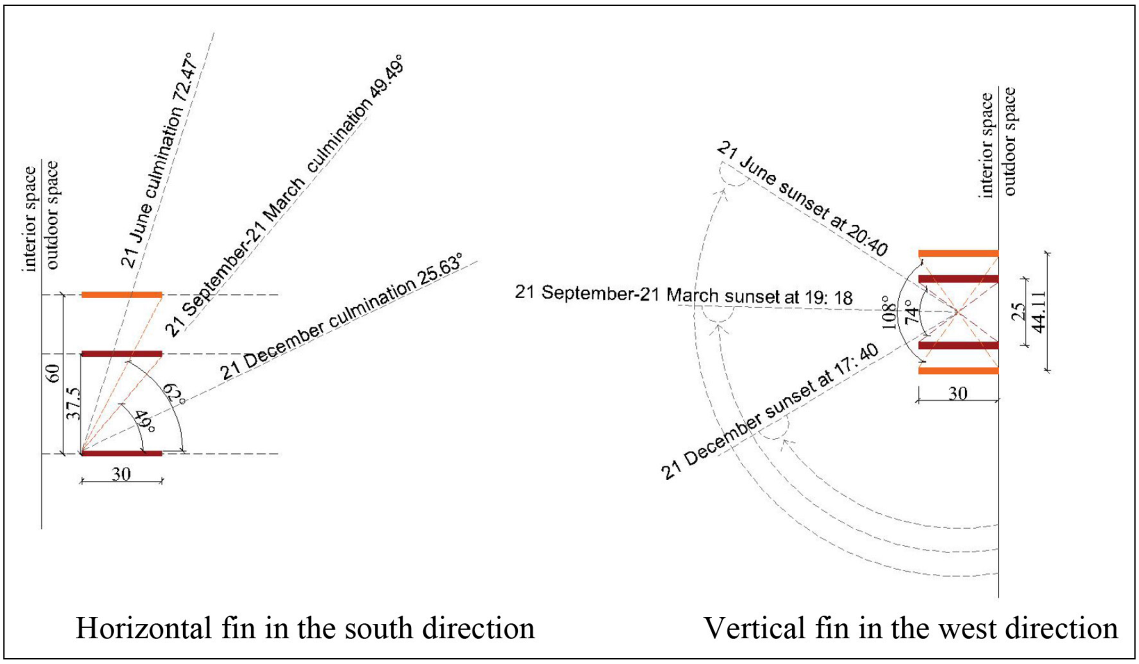
Process of Conducting Calculations

Calculations related to visual and thermal comfort criteria were performed by following the steps given below, respectively. It was based on dividing the fin ranges by the ceiling height and the width of the facade as integers.

1. The fin ranges were first determined for the G1 glazing, which has the highest light transmittance and solar heat gain coefficient.
2. Fin ranges that provided the minimum level of daylight criteria for horizontal and vertical fins were identified. Since horizontal fins did not restrict the horizontal viewing angle, this criterion was considered only for vertical fins. Since the minimum level of sunlight exposure criterion could not be achieved in the northeast and northwest directions, it was taken into account that the minimum level of the other three daylight criteria should be achieved in these directions.
3. The appropriateness of the fin ranges, determined in accordance with daylight criteria, in terms of solar control was investigated. In this context, it was ensured that the solar gain rates of minimum horizontal and vertical fin ranges were as parallel to each other as possible based on the directions. For

the minimum fin ranges, the solar gain was targeted to be 25% in the northeast and northwest directions and 50% in the other directions. In the determination of the minimum horizontal fin range, ensuring ≥300 lx daylight in the east, west, northeast, and northwest directions where the facade has less sunlight exposure and providing solar control (solar gain and shading) in the south, southeast, and southwest were effective. In the solar control studies, the appropriateness of fin ranges was checked by taking advantage of the sun's horizontal and vertical orbits that change by the seasons. The largest altitude angle of the sun for the horizontal fin in the southern direction and the direction of the sunlight at sunset for the vertical fin in the western direction are shown as examples in Figure 7. The fin ranges determined in the second step had to be revised according to the solar control studies. Which level the revised fin ranges provide for each of the daylight criteria was recalculated.

4. A decrease in the number of fins, that is, an increase in the fin range, increases the need for mechanical cooling in hot weather conditions, and therefore energy consumption. For this reason, it was aimed to provide minimum shading and maximum solar gain in determining the maximum horizontal and vertical fin ranges. For this purpose, shading and solar gain rates were investigated by systematically changing the fin numbers. For the maximum fin ranges, the fact that solar gain rates showed similarity by the directions was taken into account. It was calculated which level the determined fin ranges provide for each of the daylight criteria. It was checked whether the minimum level of protection from glare was achieved or not. It was planned to revise the fin ranges to achieve the minimum level for this criterion in the case that the minimum degree could not be achieved. However, there was no need to revise the fin range in terms of glare in spaces that received light from a single facade.
5. By referencing the minimum and maximum fin ranges determined for G1 glazing without solar control features, the minimum and maximum fin ranges were calculated for the other three glazing types. The



Horizontal fin in the south direction

Vertical fin in the west direction

Figure 7. The minimum and maximum fin ranges determined for the horizontal fin in the south direction and vertical fin in the west direction.

Table 3. Determination of fin ranges for glazing type G2: South direction

Glazing type	Horizontal range (cm)		Vertical range (cm)	
	Minimum	Maximum	Minimum	Maximum
G1	37.5 (h/8)	60 (h/5)	37.5 (a/40)	50 (a/30)
G2	37.5×1.25=46.88	60×1.25=75	37.50×1.25=46.88	50×1.25=62.5
	300/46.88=6.4≅6	300/75=4	1500/46.88=32	1500/62.5=24
	300/6=50; h/6	300/4=75; h/4	1500/32=46.88; a/32	1500/24=62.5; a/24

Table 4. Shading and solar utilisation rates of the minimum and maximum fin ranges for G1 glazing

	Annual shade need and sun need (hour)		Minimum and maximum ranges of horizontal fin						Minimum and maximum ranges of vertical fin					
			Min	Annual Shading and Solar Gain (%)		Max	Annual Shading and Solar Gain (%)		Min	Annual Shading and Solar Gain (%)		Max	Annual Shading and Solar Gain (%)	
Direction	Shade need	Sun need	h/n	S	SG	h/n	S	SG	a/n	S	SG	a/n	S	SG
South	828	2247	h/8	97	73	h/5	76	85	a/46	62	52	a/30	51	71
East	334	1278	h/6	47	80	h/4	30	94	a/62	37	53	a/36	20	71
West	572	1092	h/6	30	79	h/4	18	93	a/60	25	50	a/34	12	69
Southeast	552	1962	h/8	76	70	h/5	47	84	a/66	53	50	a/30	22	71
Southwest	778	1788	h/8	56	68	h/5	34	86	a/70	62	50	a/34	25	69
Northeast	228	800	h/5	64	74	h/4	38	80	a/46	85	27	a/24	46	51
Northwest	454	624	h/5	40	73	h/4	24	78	a/40	55	25	a/20	27	50

S: Shading, SG: Solar gain, h/n: Room height/number of fins, a/n: Facade width/number of fins.

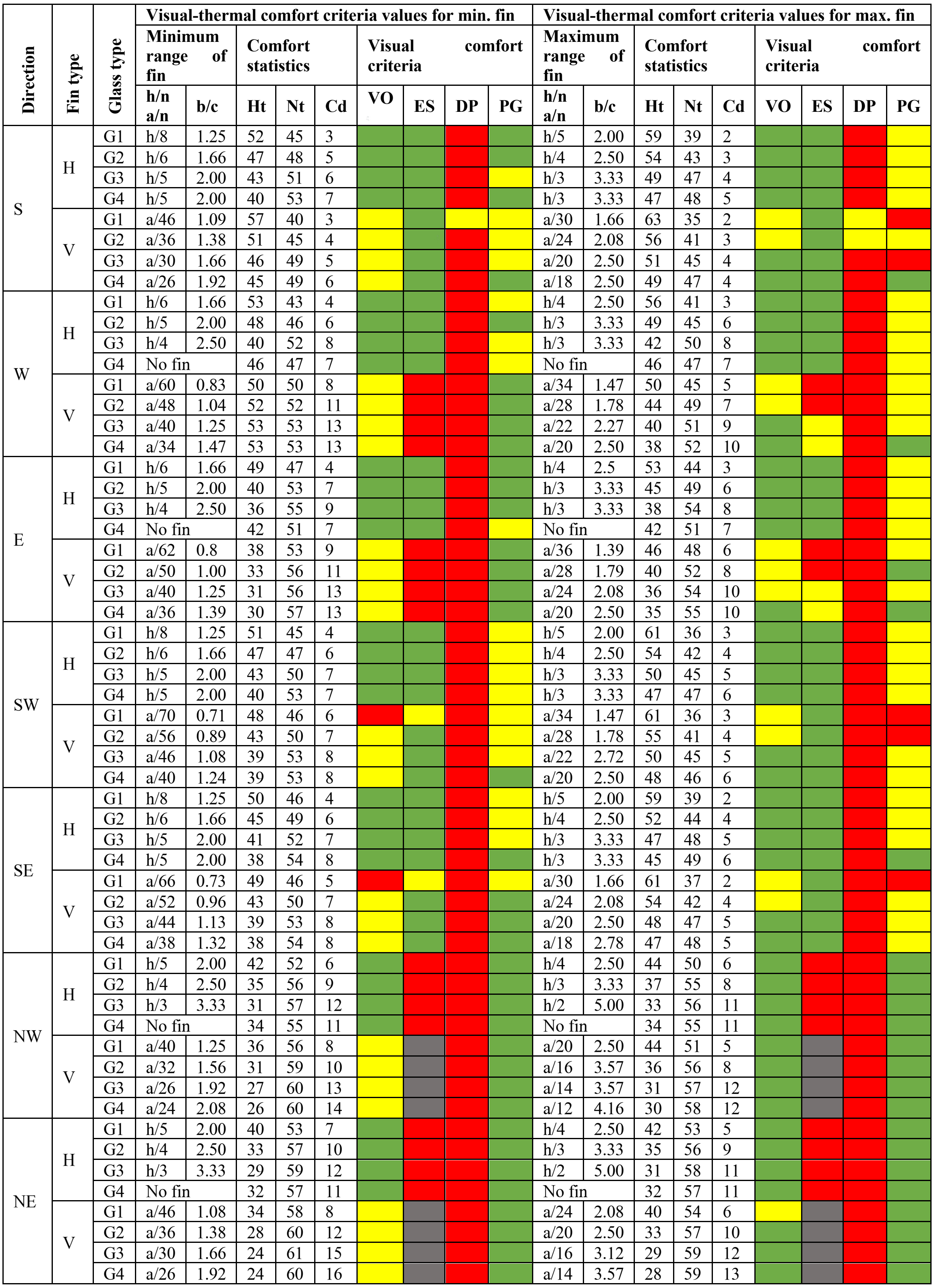
minimum and maximum fin ranges for G2, G3 and G4 glazing types were determined by increasing the fin range of G1 in a way that they would be inversely proportional to the shading coefficient of G1 glazing. For this, the number of fins, in which the ceiling height can be divided as an integer, was also taken into account, as was considered with the G1 glazing. That is, in the case when the fin number turns out to be a decimal number, it is rounded to the nearest integer. For example, the ratio of the shading coefficient between G1 and G1 glazing is 1.25 (0.64/0.51). The horizontal and vertical fin ranges determined for the G2 glazing in the southern direction are presented in Table 3 as an example. In the table, the expressions in parentheses indicate the number of fins. For example, (h/8) means that there are 8 horizontal fins in a room with a ceiling height (h) of 300 cm, and (a/40) means that there are 40 vertical fins in a room with a width (a) of 1500 cm. By the described calculation, it was checked whether the ranges determined for all windows meet the minimum degree for daylight illuminance and the other daylight criteria. It was verified that the optimum ranges defined for glazing G1, G2, G3, and G4 met the minimum (or medium/high) value of all daylight criteria.

6. The comfortable time percentages related to thermal comfort were calculated for the minimum and maximum fin ranges determined for all glazing types.

CALCULATION RESULTS

The shading and solar gain ratios for the minimum and maximum horizontal/vertical fin numbers and ranges determined in relation to the seven directions faced by the long wall of the office room are given in Table 4. The table shows the hours when there is a need for the annual shading and solar gain for G1 glazing, as well as the annual shading and solar gain ratios (%) calculated depending on these hours. For example, as shown in Figure 5, the annual need for shading in the southern direction is 828 hours, and the need for solar gain is 2247 hours. When the fins with a range of 37.5 cm are designated to the south, the need for shading decreases to 21 hours, and the need for solar gain decreases to 1638 hours (Figure 6). In this case, the shading and the solar gain rates become 97% (807/828=0.97) and 73% (1638/2247), respectively. The parallelism in solar gain rates between directions is clearly visible, except for the use of vertical fins in the northeast and northwest directions. This is due to the fact that in the simulations of the two directions mentioned, solar gain is allowed by 25%, different from the other directions (50%).

The number of horizontal (H) and vertical (V) fins, the thermal and visual comfort criteria of the minimum and maximum ranges between the fins, and the changes depending on the glazing type (G1, G2, G3, G4) and directions are presented in Figure 8. In the table, thermal comfort statistics are considered under the headings Hot (Ht), Neutral (Nt), and Cold (Cd). The levels that the criteria of the view out (VO), exposure to sunlight (ES), daylight provision (DP), and protection from glare (PG) provide in terms of visual comfort are expressed in colours (red: minimum, yellow: medium, green: high). The criterion for which even the minimum degree could not be achieved is indicated in grey. For each case considered, the table shows the ratio of the ceiling height to the number of horizontal fins (h/n), the ratio of the facade width to the number of vertical fins (a/n), and the ratio of the distance between the fins to the size of the fin (b/c).



Direction	Fin type	Glass type	Visual-thermal comfort criteria values for min. fin									Visual-thermal comfort criteria values for max. fin								
			Minimum range of fin		Comfort statistics			Visual comfort criteria				Maximum range of fin		Comfort statistics			Visual comfort criteria			
			h/n a/n	b/c	Ht	Nt	Cd	VO	ES	DP	PG	h/n a/n	b/c	Ht	Nt	Cd	VO	ES	DP	PG
S	H	G1	h/8	1.25	52	45	3	🟩	🟩	🟥	🟩	h/5	2.00	59	39	2	🟩	🟩	🟥	🟨
		G2	h/6	1.66	47	48	5	🟩	🟩	🟥	🟩	h/4	2.50	54	43	3	🟩	🟩	🟥	🟨
		G3	h/5	2.00	43	51	6	🟩	🟩	🟥	🟨	h/3	3.33	49	47	4	🟩	🟩	🟥	🟨
		G4	h/5	2.00	40	53	7	🟩	🟩	🟥	🟩	h/3	3.33	47	48	5	🟩	🟩	🟥	🟨
	V	G1	a/46	1.09	57	40	3	🟨	🟩	🟨	🟨	a/30	1.66	63	35	2	🟨	🟩	🟨	🟥
		G2	a/36	1.38	51	45	4	🟨	🟩	🟥	🟨	a/24	2.08	56	41	3	🟨	🟩	🟨	🟨
		G3	a/30	1.66	46	49	5	🟨	🟩	🟥	🟨	a/20	2.50	51	45	4	🟩	🟩	🟥	🟥
		G4	a/26	1.92	45	49	6	🟨	🟩	🟥	🟩	a/18	2.50	49	47	4	🟩	🟩	🟥	🟩
W	H	G1	h/6	1.66	53	43	4	🟩	🟩	🟥	🟨	h/4	2.50	56	41	3	🟩	🟩	🟥	🟨
		G2	h/5	2.00	48	46	6	🟩	🟩	🟥	🟩	h/3	3.33	49	45	6	🟩	🟩	🟥	🟨
		G3	h/4	2.50	40	52	8	🟩	🟩	🟥	🟨	h/3	3.33	42	50	8	🟩	🟩	🟥	🟨
		G4	No fin		46	47	7	🟩	🟩	🟥	🟨	No fin		46	47	7	🟩	🟩	🟥	🟨
	V	G1	a/60	0.83	50	50	8	🟨	🟥	🟥	🟩	a/34	1.47	50	45	5	🟨	🟥	🟥	🟨
		G2	a/48	1.04	52	52	11	🟨	🟥	🟥	🟩	a/28	1.78	44	49	7	🟨	🟥	🟥	🟨
		G3	a/40	1.25	53	53	13	🟨	🟥	🟥	🟩	a/22	2.27	40	51	9	🟩	🟨	🟥	🟨
		G4	a/34	1.47	53	53	13	🟨	🟥	🟥	🟩	a/20	2.50	38	52	10	🟩	🟨	🟥	🟩
E	H	G1	h/6	1.66	49	47	4	🟩	🟩	🟥	🟩	h/4	2.5	53	44	3	🟩	🟩	🟥	🟨
		G2	h/5	2.00	40	53	7	🟩	🟩	🟥	🟩	h/3	3.33	45	49	6	🟩	🟩	🟥	🟨
		G3	h/4	2.50	36	55	9	🟩	🟩	🟥	🟩	h/3	3.33	38	54	8	🟩	🟩	🟥	🟨
		G4	No fin		42	51	7	🟩	🟩	🟥	🟨	No fin		42	51	7	🟩	🟩	🟥	🟨
	V	G1	a/62	0.8	38	53	9	🟨	🟥	🟥	🟩	a/36	1.39	46	48	6	🟨	🟥	🟥	🟨
		G2	a/50	1.00	33	56	11	🟨	🟥	🟥	🟩	a/28	1.79	40	52	8	🟨	🟥	🟥	🟩
		G3	a/40	1.25	31	56	13	🟨	🟥	🟥	🟩	a/24	2.08	36	54	10	🟨	🟨	🟥	🟨
		G4	a/36	1.39	30	57	13	🟨	🟥	🟥	🟩	a/20	2.50	35	55	10	🟩	🟨	🟥	🟩
SW	H	G1	h/8	1.25	51	45	4	🟩	🟩	🟥	🟨	h/5	2.00	61	36	3	🟩	🟩	🟥	🟨
		G2	h/6	1.66	47	47	6	🟩	🟩	🟥	🟨	h/4	2.50	54	42	4	🟩	🟩	🟥	🟨
		G3	h/5	2.00	43	50	7	🟩	🟩	🟥	🟨	h/3	3.33	50	45	5	🟩	🟩	🟥	🟨
		G4	h/5	2.00	40	53	7	🟩	🟩	🟥	🟨	h/3	3.33	47	47	6	🟩	🟩	🟥	🟨
	V	G1	a/70	0.71	48	46	6	🟥	🟨	🟥	🟨	a/34	1.47	61	36	3	🟨	🟩	🟥	🟥
		G2	a/56	0.89	43	50	7	🟨	🟩	🟥	🟨	a/28	1.78	55	41	4	🟨	🟩	🟥	🟥
		G3	a/46	1.08	39	53	8	🟨	🟩	🟥	🟨	a/22	2.72	50	45	5	🟩	🟩	🟥	🟨
		G4	a/40	1.24	39	53	8	🟨	🟩	🟥	🟩	a/20	2.50	48	46	6	🟩	🟩	🟥	🟨
SE	H	G1	h/8	1.25	50	46	4	🟩	🟩	🟥	🟨	h/5	2.00	59	39	2	🟩	🟩	🟥	🟨
		G2	h/6	1.66	45	49	6	🟩	🟩	🟥	🟨	h/4	2.50	52	44	4	🟩	🟩	🟥	🟨
		G3	h/5	2.00	41	52	7	🟩	🟩	🟥	🟨	h/3	3.33	47	48	5	🟩	🟩	🟥	🟨
		G4	h/5	2.00	38	54	8	🟩	🟩	🟥	🟩	h/3	3.33	45	49	6	🟩	🟩	🟥	🟩
	V	G1	a/66	0.73	49	46	5	🟥	🟨	🟥	🟨	a/30	1.66	61	37	2	🟨	🟩	🟥	🟥
		G2	a/52	0.96	43	50	7	🟨	🟩	🟥	🟩	a/24	2.08	54	42	4	🟨	🟩	🟥	🟨
		G3	a/44	1.13	39	53	8	🟨	🟩	🟥	🟩	a/20	2.50	48	47	5	🟩	🟩	🟥	🟨
		G4	a/38	1.32	38	54	8	🟨	🟩	🟥	🟩	a/18	2.78	47	48	5	🟩	🟩	🟥	🟨
NW	H	G1	h/5	2.00	42	52	6	🟩	🟥	🟥	🟩	h/4	2.50	44	50	6	🟩	🟥	🟥	🟩
		G2	h/4	2.50	35	56	9	🟩	🟥	🟥	🟩	h/3	3.33	37	55	8	🟩	🟥	🟥	🟩
		G3	h/3	3.33	31	57	12	🟩	🟥	🟥	🟩	h/2	5.00	33	56	11	🟩	🟥	🟥	🟩
		G4	No fin		34	55	11	🟩	🟥	🟥	🟩	No fin		34	55	11	🟩	🟥	🟥	🟩
	V	G1	a/40	1.25	36	56	8	🟨	⬛	🟥	🟩	a/20	2.50	44	51	5	🟩	⬛	🟥	🟩
		G2	a/32	1.56	31	59	10	🟨	⬛	🟥	🟩	a/16	3.57	36	56	8	🟩	⬛	🟥	🟩
		G3	a/26	1.92	27	60	13	🟨	⬛	🟥	🟩	a/14	3.57	31	57	12	🟩	⬛	🟥	🟩
		G4	a/24	2.08	26	60	14	🟨	⬛	🟥	🟩	a/12	4.16	30	58	12	🟩	⬛	🟥	🟩
NE	H	G1	h/5	2.00	40	53	7	🟩	🟥	🟥	🟩	h/4	2.50	42	53	5	🟩	🟥	🟥	🟩
		G2	h/4	2.50	33	57	10	🟩	🟥	🟥	🟩	h/3	3.33	35	56	9	🟩	🟥	🟥	🟩
		G3	h/3	3.33	29	59	12	🟩	🟥	🟥	🟩	h/2	5.00	31	58	11	🟩	🟥	🟥	🟩
		G4	No fin		32	57	11	🟩	🟥	🟥	🟩	No fin		32	57	11	🟩	🟥	🟥	🟩
	V	G1	a/46	1.08	34	58	8	🟨	⬛	🟥	🟩	a/24	2.08	40	54	6	🟨	⬛	🟥	🟩
		G2	a/36	1.38	28	60	12	🟨	⬛	🟥	🟩	a/20	2.50	33	57	10	🟩	⬛	🟥	🟩
		G3	a/30	1.66	24	61	15	🟨	⬛	🟥	🟩	a/16	3.12	29	59	12	🟩	⬛	🟥	🟩
		G4	a/26	1.92	24	60	16	🟨	⬛	🟥	🟩	a/14	3.57	28	59	13	🟩	⬛	🟥	🟩

H: horizontal, V: vertical, Ht: hot, Nt: neutral, Cd: cold, VO: view out, ES: exposure to sunlight, DP: daylight provision, PG: protection from glare, h/n: room height/number of fins, a/n: facade width/number of fins, b/c: distance between fins/fin size.

Level of visual comfort criteria: 🟥 Minimum 🟨 Medium 🟩 High ⬛ Unavailable

Figure 8. Change of the comfort criteria of horizontal and vertical fin ranges depending on glazing types and directions.

ASSESSMENT OF THE RESULTS

The study results summarised in Figure 8 can be assessed as follows:

- The sunlight exposure of the building facade is the main determinant of the fin ranges. In directions with high sunlight exposure rates (south, southwest, and southeast), the horizontal and vertical fin ranges (b) are narrower compared to the directions with lower sunlight exposure rates (west, east, northwest, and northeast).
- When the minimum and maximum horizontal/vertical fin ranges determined for all directions were examined, it was found that the vertical fin ranges were generally narrower.
- Due to the low transmittance of G4 glazing in the west, east, northwest, and northeast directions, the minimum degree of daylight illuminance is provided only in the non-fin state. Accordingly, for the case where the G4 glazing type was applied without a fin, other daylight criteria and comfortable time percentages were calculated.
- Vertical fins provide more positive results in terms of ensuring the illuminance, while horizontal fins provide more positive results in terms of protection from glare.
- Vertical fins prevent solar gain more compared to horizontal fins. In parallel, the criterion of exposure to sunlight related to visual comfort provided higher degrees in horizontal fins.
- As the shading coefficient of glazing types decreases (i.e., the shading property increases),
    - o the neutral time percentages become higher despite the fact that distance between the fins increases,
    - o the difference between the neutral time percentages of the minimum and maximum fin ranges decreases.
- Horizontal fins in the southern direction are more successful than vertical fins in terms of shading and solar gain. In parallel, their neutral time percentages are also higher than that of vertical fins. Horizontal fins also gave more positive results than vertical fins in terms of protection from glare, exposure to sunlight, and view out.
- The solar control performances in the east and west directions are lower compared to the other directions. In these directions, as the shading coefficient of glazing types decreases, the difference between the neutral time percentages of horizontal and vertical fins also decreases. The vertical fins in the east and west direction have quite narrow ranges. In these directions, the glare protection performances of vertical fins are higher than horizontal fins.
- The solar control performance in the southwest and southeast directions is lower compared to the south direction. The thermal comfort and visual comfort performances of the horizontal/vertical fins in these directions are parallel.
- Since the neutral time percentages are higher for vertical fins in the northwest and northeast directions, it can be said that they give a more positive result in terms of shading than horizontal fins. However, in these directions, even the minimum level of exposure to sunlight, cannot be ensured. In parallel with this, vertical fins also greatly prevent solar gain.
- While the directions that provide the highest neutral comfortable time percentage are northwest and northeast, the directions that provide the highest warm time percentage are south, southeast, and southwest.
- Since the horizontal viewing angle is not restricted in horizontal fins, a high degree is provided in all fin ranges.
- Higher degrees of the exposure to sunlight criterion are provided in the south, southwest, and southeast directions. In addition, in these directions, horizontal fins are more advantageous in terms of exposure to sunlight.
- The medium level of daylight illuminance was provided at the minimum and maximum vertical fin range, which was determined for the glazings G1 in the southern direction. In addition, the medium level of daylight illuminance was provided at the maximum vertical fin range, which was determined for the glazings G2 in the southern direction. In all other directions and fin ranges, the minimum degree was able to be achieved in the illuminance.
- In the north-western and north-eastern directions, high degrees were provided in terms of protection from glare in all ranges designated for horizontal/vertical fins.

DISCUSSION

This study proposes a method for limiting horizontal and vertical fin ranges based on the current visual and thermal comfort standards. Appropriate fin ranges were determined by using climate-based data and analysing visual and thermal comfort criteria. The study was conducted in a module office room, which was assumed to locate in an office building. It is obvious that in rooms with different sizes and different transparency ratios considered in the study, the results may differ. Though with the method proposed in this study, thermal and visual comfort conditions can be determined for each office room, or the office room that can provide targeted comfort conditions can be designed. The study determined the minimum and maximum fin ranges for spaces in different directions. The optimum range can be considered to be close to the middle of the minimum and maximum fin ranges.

Fin types and exposure to sunlight according to the directions significantly affect the performance of thermal and visual comfort criteria. For example, vertical fins affect the illuminance less compared to horizontal fins. This finding is in parallel with other studies (Lee et al., 2017). In addition, the shading performances of fin types show differences depending on the exposure to sunlight which is in accordance with the literature (Kirimtat et al., 2016; Yusoff et al., 2022). The finding that the horizontal fins in the southern direction are the most efficient fins in terms of shading and sun gaining confirms the relevant literature (Olgyay & Olgyay, 1957; Mangkuto et al., 2021). In this direction, the glazing type with high shading properties and the horizontal fin provided a high neutral time percentage and low cold time percentage. Horizontal fins in the southern direction are also positive in terms of visual comfort. Due to the movement of the sun, the potential of the southern building facade to be exposed to sunlight and provide the required illuminance is higher than in other directions. Furthermore, the finding that horizontal fins significantly prevent glare in this direction confirms the study by De Luca (De Luca et al., 2022). Therefore, in terms of thermal and visual comfort, the optimal direction is south and the type of fin is horizontal. The finding that vertical fins outperform horizontal fins in the east and west directions parallels O'Brien's work (O'Brian et al., 2013). The performance of solar control in the east and west directions is lower compared to other directions. In some studies, unlike horizontal and vertical fins, diagonal (i.e. angled) and adaptive shading elements have performed better in these two directions (Freewan, 2014; Mangkuto et al., 2021). Unlike the literature, in this current study, the neutral time percentages in horizontal and vertical fins approached each other much, especially with the increase in the shading properties of glasses in the eastern and western directions. This research showed that vertical fins also give positive results in northwest and northeast directions, consistent with Lee's study (Lee et al., 2017). In this present study, the neutral time percentage of vertical fins in these directions was higher compared to horizontal fins. Horizontal and vertical fins in the south-western and south-eastern directions gave close results to each other. Therefore, it can be said that horizontal+vertical fins show high performance in this direction (Kim et al., 2015).

The daylight and solar energy transmittance of glazing types directly affect thermal and visual comfort. Glazing types of lower shading coefficient (G3 and G4) showed more positive results in terms of thermal comfort which is in accordance with the literature (Ascione et al., 2020). The same glass types were also more effective in protecting from glare. However, G1 and G2 glasses gave more positive results in terms of daylight illuminance which confirms the literature (Rasmussen & Pedersen, 2019).

In modern building design, horizontal and vertical fins contribute to facade aesthetics as well as solar control. In terms of facade integrity, fins with the same range are usually designed in all directions. In this study, it was tried to seek an answer to the question *"Is there an optimal fin range for rooms facing different directions"*. For this reason, the common fin ranges for the rooms facing the cardinal and ordinal (*intercardinal*) directions were determined. For example, for the G1 glazing, the horizontal fin ranges common in the cardinal directions (*south, west, and east*) were 50 cm (h/5) and 60 cm (h/6). The common vertical fin range for G1 glazing was between 37.5 cm (a/40) and 41.66 cm (a/36) in these directions. On the other hand, in the ordinal directions (*southwest, southeast, northwest, and northeast*), the common horizontal fin range for G1 glazing was 60 cm (h/5). In these directions, the common vertical fin ranges for the same glazing (G1) were between 37.5 cm (a/40) and 44.12 cm (a/34). However, the ranges that were common to the cardinal/ordinal directions did not offer the optimal solution for all directions. Indeed, the horizontal fin range of 60 cm, which was common for ordinal directions, was the minimum range determined for the northwest and northeast directions. Similarly, the horizontal fin range of 60 cm was the maximum range determined for the southeast and southwest directions. The thermal and visual comfort effects of the common (60 cm) horizontal fin range in 4 different directions were also different. Therefore, considering the sunlight exposure relative to the directions is important in terms of holistic facade design and energy consumption. Beyond the horizontal/vertical fin, kinetic facade, biomimicry, and parametric facade designs suitable for the sunlight exposure of spaces are also being made today (Mahmoud & Elghazi, 2016).

CONCLUSION

Large glass surfaces are often used in modern office structures. The increase in the transparency ratio in the building envelope leads to the glare problem and causes excessive heat gain or heat loss depending on the season. This phenomenon makes it mandatory to carry out solar control with shading elements. The size, shape, number, and location of these elements also affect the architectural shaping of the building. In this context, as well as providing a comfortable physical environment for office workers, it is also important that the building acquire the character of a contemporary work of art. The formation of the physical environment depends on the control of elements such as heat, light, and sound. In this study, by taking into account only heat and light among these elements, a method was developed that can be used in the design of horizontal/vertical shading elements that provide thermal and visual comfort conditions. It should also be noted that for a complete indoor environment, the requirements for auditory comfort should also be taken into account.

The method proposed in the study is aimed at limiting horizontal or vertical fin ranges. The minimum and maximum fin ranges that could meet the minimum conditions of all visual and thermal comfort criteria were determined on a sample of a module office room. The effects of minimum and maximum fin ranges on comfort criteria were revealed, and thereby, designers were allowed to choose depending on their priorities. The results of this study in which the change of fin ranges by directions was also examined can also be used to make basic design decisions. The calculation of the initial construction and maintenance costs of the fins was excluded from the scope of this study. In future studies, by analysing the initial construction and maintenance costs of horizontal and vertical fins, their appropriateness depending on the directions can also be investigated from an economic point of view. In addition, the study can be improved by investigating the effect of shading and solar gain rates of fins on total energy consumption.

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