Analysis of Worldwide Performance of Façade Systems

Matthias Werner[1], Rainer Pfluger[1], David Geisler-Moroder[2], Wolfgang Feist[1]
[1]University of Innsbruck, Innsbruck, Austria
[2]Bartenbach GmbH, Aldrans, Austria

Abstract

The façade mainly defines the heating, cooling and electric light demand. Depending on the insulation quality and the transparent parts with its specific system for glare, sun protection and/or daylight redirection the transmission losses and gains are defined. This paper analyses façade solutions and shading strategies in terms of minimal total final energy demand for worldwide-distributed locations with the help of a coupled lighting and thermal simulation. The study focuses on a very efficient building standard (passive house, heating and cooling supply by heat pumps, dimmable LED artificial light system), equator oriented facades and an office usage. A conventional shading system (external venetian blind) and a complex façade system (daylight redirection system) are evaluated. The optimized shading period for every location is presented and it can be shown that the optimal shading duration is highly depended on the latitude. The electric light demand has a significant influence on the total final energy demand and has therefore an impact on the façade design. Thus, the optimization with an integral approach of heating, cooling and artificial light determines much larger transparent areas than a thermal optimization. Savings of up to 30% of the total primary energy demand can be achieved. In addition, with the use of a daylight redirection system savings of up to 20% are possible.

Introduction

The façade has a major influence on the energy demand of a building. In order to reduce heating, cooling and artificial light demand, the façade transmission losses as well as the percentage of glazing have to be optimized (Feist 1994). The translucent part of the façade at the same time defines the level of solar gains and how much daylight is impinging at the internal spaces. Lack of daylight increases the demand for artificial lighting, which in turn increases the building's internal heat gains. In addition, both sun and glare protection reduce the solar gain and daylight input. These effects are highly depending on the local climate and influence the optimized façade design in terms of daylight input and energy demand.

At this matter, also a realizable shading period (start and end times) has to be defined for the different climate zones. Moveable shading systems are applied in order to reduce overheating in summer and allow useful solar gains in winter.

Previous facade studies for different climate zones usually do not consider the influence of the daylight depended electric light demand as internal gain and the glare protection to the solar gain (Banihashemi et al. 2015; Pekdemir and Muehleisen 2012). General worldwide design information with this integral approach, which considers the whole interactions mentioned above, do not exist yet.

Parametric Study

The goal of this paper is to generate design principles for the shading period and transparent areas of the building envelope in combination with different facade systems. For this purpose, the study focuses on new construction with a high building standard. Therefore, worldwide parametric studies are carried out with an external venetian blind and a daylight redirection facade system:

- The first parametric study determines the optimized **duration of shading period** in terms of a minimal total final energy demand. Therefore the start and end of the shading period in which a sun protection can be activated ($I_{vertical,global}$ > 200W/m²) is varied. The time frame [d] of shading period with a minimal final energy demand is determined and is used as input for the second study.

- In a second parametric study, the optimized **transparent façade area** for an external venetian blind (VB) and a daylight redirection system (DRS) is evaluated in terms of minimal heating, cooling and artificial light.

This study focuses on an efficient office building standard with a high envelope quality and a very efficient building technology. This allows design recommendation on facades related to new non-residential buildings. The following chapter describes the used simulation method as well as the applied boundary conditions.

Simulation Method

For the parametric studies, the validated façade simulation tool DALEC (http://www.dalec.net) is used (Werner et al. 2016). This façade evaluation method simulates the daylight input for two sensor points (MP1 and MP2, see Figure 1). The daylight simulation method is based on pre-calculated coefficients with the raytracing software RADIANCE, which allows fast calculations and high accuracy even for DRS. Based on this daylight input, the necessary electric light demand is defined for two luminaire groups and each time step. Furthermore, the luminances from viewpoints 1 and 2 are simulated to detect glare situations.

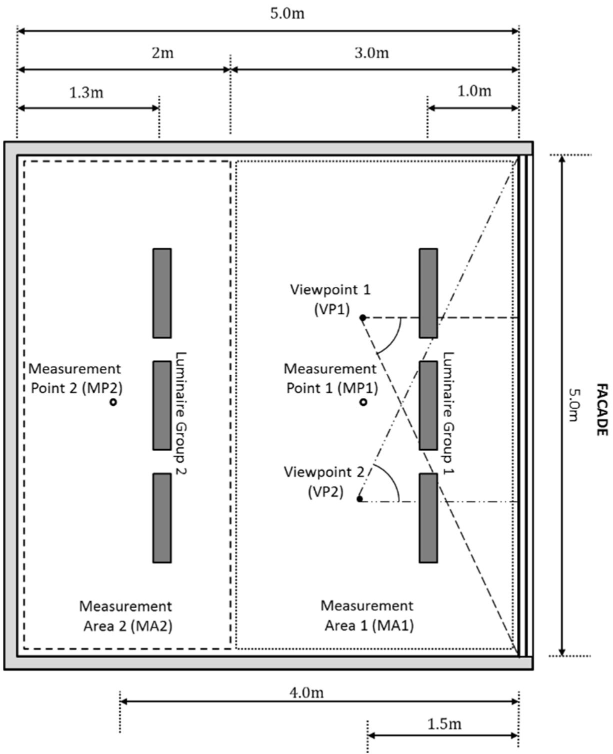

Figure 1: Room dimensions, measurement areas measurement points and viewpoints

Depending on the façade system and its sun protection control strategy (via threshold of vertical irradiance) and glare protection (via luminance detection at viewpoints 1 and 2), the solar gain is determined with angle-dependent SHGCs.

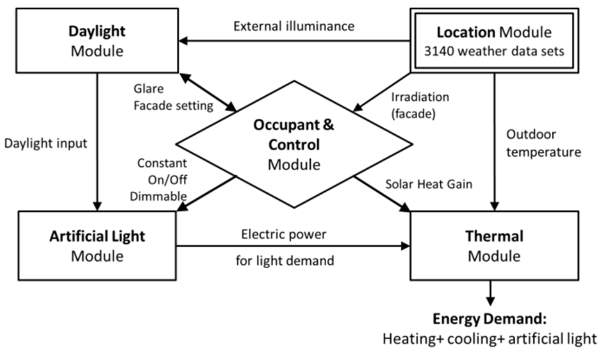

Figure 2: Schematic workflow of the integral façade simulation method

These internal and solar gains are inputs for a dynamic thermal building simulation (Austrian Standards Institute 2008), which calculates heating and cooling demands based on the local climate at hourly time steps. Figure 2 shows the schematic workflow of this simulation routine. A detailed description of the coupled daylight, electric light and thermal simulation is given in (Werner et al. 2016).

Boundary Conditions

Room:

The parametric study uses a reference office room setting (depth/wide/height = 5x5x3m) with two occupants located at viewpoint 1 and 2.

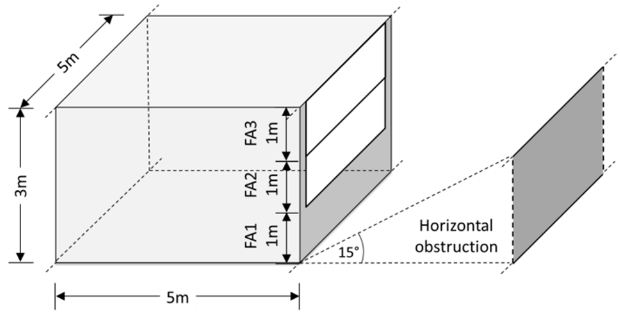

Figure 3: Geometry Room

The reference room is embedded in the second of three floors to consider also equivalent losses through ceiling and cellar and is always equator orientated (south at northern hemisphere, north at southern hemisphere). This setting is evaluated for 3140 locations (weather stations of IWEC2, TMY3 and CWEC datasets) distributed worldwide. These applied weather files provide all of the necessary data for this integral approach (external temperature, horizontal direct and diffuse irradiance as well as horizontal illuminance) with an hourly time step.

Façade:

Climate recommended very efficient passive house U-values for external wall, roof, cellar and window of (Schnieders et al. 2011) and thermal bridges (Feist 2003) are used to create a reasonable insulation for the different investigated locations and comparable boundary conditions. The mean U-values for the building envelope for the evaluated locations with an exemplary window area fraction of 50% of FA2 and FA3 are shown in Figure 4. This reduces heating and cooling loads significantly, guarantees best possible comfort and is open for any solution for the daylighting system.

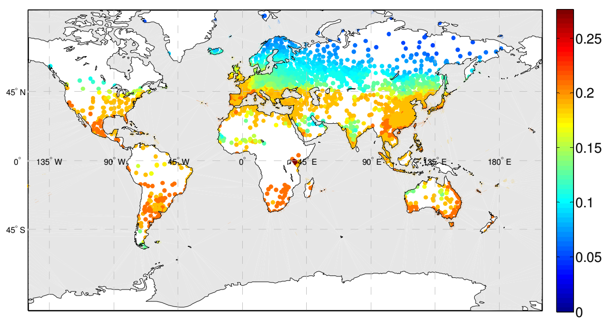

Figure 4: Mean envelope U-value for a transparent area fraction of 50% of FA2 and FA3 [W/(m²K)]

The internal walls are considered as adiabatic, which presents a perimeter zoning of equator-oriented facade. Furthermore, a night ventilation is implemented but only activated if it is realisable due to humidity reasons (Schnieders et al. 2011). The façade is divided into a bottom (FA1), middle (FA2) and upper part (FA3) (Figure 3). Due to the daylight contribution of FA1 being negligible, this section is always defined as an opaque parapet. For façade area 2 (FA2) and 3 (FA3), a transparent area combined with a system for a glare and sun protection is varied and evaluated.

The façade systems External Venetian Blind (EVB, see Figure 5) and daylight redirection system (DRS, see Figure 6 and Figure 7) are placed in front of a triple glazing (τ=72%). In addition, the DRS system is protected with another glazing against dirt and wind (Protection Glazing). The external venetian blind system is used for glare as well as sun protection. The DRS has a daylight redirection function in the upper part of the façade (FA3) as well as a venetian blind for glare and sun protection in the middle part of the facade (FA2).

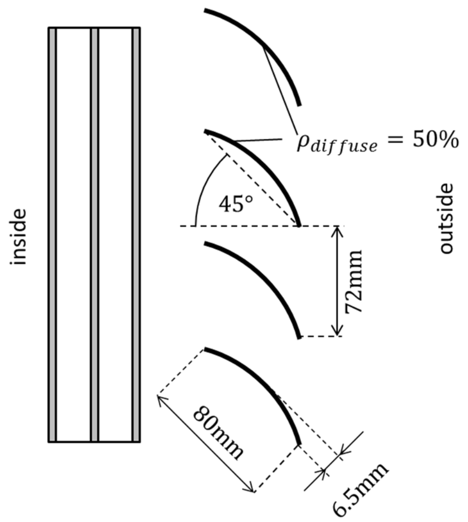

Figure 5: Triple glazing and external venetian blind

The system for glare protection is activated if the sun is located in the field of view. An overcast (2000 cd/m²) and clear sky (8000 cd/m²) is not identified in this study as a visual uncomfortable situation. Thus a threshold for glare protection for viewpoint 1 and 2 (VP1 and VP2, Figure 1) of 10.000cd/m² is chosen. The sun protection is used, if the vertical global irradiance is higher than 200W/m² (only within the solar shading period). This value detects sunny situations in cooling periods. In

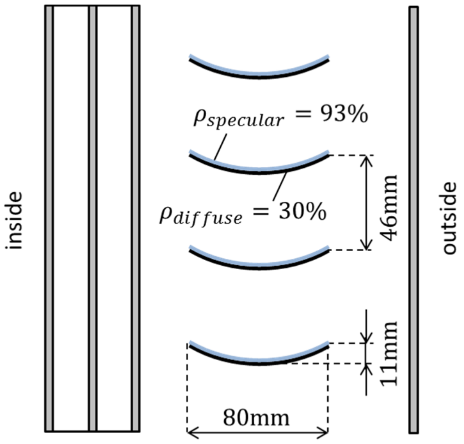

Figure 6: Triple glazing, daylight redirection system (0° blind position) and protection glazing

Table 1 the different shading situations of the systems EVB and DRS are summed up.

Table 1: Shading systems for sun and glare protection at the different façade parts

Façade area	**No sun or glare protection**	**Glare protection**	**Sun- & glare protection**
External venetian blind system (EVB)			
FA3:	-	ext. venetian blind fix 45° blind position	ext. venetian blind fix 45° blind position
FA2:	-	ext. venetian blind fix 45° blind position	ext. venetian blind fix 45° blind position
FA1:	parapet	parapet	parapet
Daylight redirection system (DRS)			
FA3:	daylight redirection 0° blind position	daylight redirection 0° blind position	daylight redirection retro (sun tracking)
FA2:	-	ext. venetian blind cut-off blind position	ext. venetian blind fixed 45° blind position
FA1:	parapet	parapet	parapet

Figure 7: Lamella of the daylight redirection system

The angle depended solar heat gain coefficients for the triple glazing and the shading system with different blind positions are shown in Figure 8 (data simulated with *WINDOW 7.4* (Robin Mitchell et al. 2008)*)*.

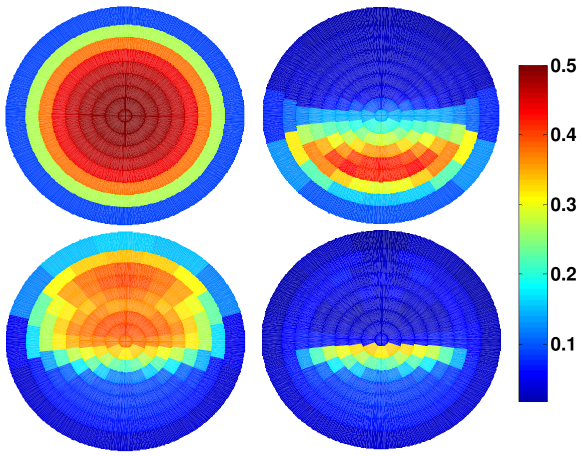

Figure 8: Angle depended solar heat gain coefficients (incident angle via Klems Patches); top left: triple glazing (TG), top right: TG + ext. venetian blind fixed 45° blind position; bottom left: TsG + daylight redirection with 0° blind position; bottom right: TG + daylight redirection with retroreflective position

<u>Electric Light System:</u>
A very efficient LED light system with two luminaire groups (see Figure 1) is considered with a daylight dimmable control strategy, which only adds the illuminance for MA1 and MA2 to the daylight input, which is necessary to achieve the required illuminance level. Table 2 sums up the properties of the parametric study.

Table 2: Boundary Conditions

<u>Parameter</u>	**<u>Value</u>**	**<u>Unit</u>**
Geometry		
Width/depth/height	5/5/3	m
Reflectance factor ceiling/wall/floor	80/50/30	%
Reduction factor (pollution)	0.9	
Horizontal obstruction	15	°
Façade orientation northern / southern hemisphere	south / north	
Facade		
Transmission glazing	0.72	
Window Area FA1/FA2/FA3	0/75/75	%
Facade Control & Occupant behaviour		
Occupancy time	8:00 - 18:00	
Glare protection activated if inner luminance of VP1 or VP2 above	10.000	cd/m²
Sun protection activated, if vertical global irradiation above	200	W/m²
Artificial Light		
Required illuminance MA1	500	lx
Required illuminance MA2	300	lx
Efficiency of luminaire	100	lm/W
Control	daylight dimmable	
power if switched 100% on	5.5	W/m²
Building Physics		
Effective thermal capacity	165 000	J/(m²K)
Infiltration	0.042	1/h
Heat recovery efficiency of the ventilation system	0.85	
Necessary air exchange rate of fresh air	0.5	1/h
Night ventilation	Yes / no in conformity with (Schnieders et al. 2011)	
Air exchange rate if night ventilation is activated	0.4	1/h
Internal temperature, when window ventilation is activated	25	°C
Internal temperature min (below heating)	20	°C
Internal temperature max (above cooling)	24	°C
Additional internal gains during occupation time	7	W/m²

<u>Final energy demand and selection of minimum value:</u>
A heat pump/cooling unit (SPF: heating = 3.0 and cooling = 3.5) provides the heating and cooling supply. The total final energy demand of electric light, heating and cooling

is then in total a current demand. In this study, two optimisations are analysed:

I) Minimum of heating and cooling: Usually during the design phase, no simulation of the artificial light demand depended on the daylight input is considered. Therefore, the first function determines the best variation regarded to a minimal final energy of heating and cooling.

$$q_{HC,j}^{i} = q_{HE,j}^{i}\frac{1}{3.0} + q_{CO,j}^{i}\frac{1}{3.5} \quad (1)$$

$$q_{HC,j}^{min} = \min\{q_{HC,j}^{1}, \dots, q_{HC,j}^{i}, \dots, q_{HC,j}^{n}\} \quad (2)$$

i: variation of the parametric study
j: location index
$q_{HC,j}^{i}$: annual total final energy demand of heating and cooling [kWh /(m²a)]
$q_{HE,j}^{i}$: annual heating demand [kWh/(m²a)]
$q_{CO,j}^{i}$: annual cooling demand [kWh /(m²a)]

II) Minimum of total final energy for heating, cooling and artificial light: The second optimisation routine identifies the best variation in terms of an integral approach of minimal total final energy of heating, cooling and artificial light.

$$q_{HCE,j}^{i} = q_{HE,j}^{i}\frac{1}{3.0} + q_{CO,j}^{i}\frac{1}{3.5} + q_{EL,j}^{i} \quad (3)$$

$$q_{HCE,j}^{min} = \min\{q_{HCE,j}^{1}, \dots, q_{HCE,j}^{i}, \dots, q_{HCE,j}^{n}\} \quad (4)$$

$q_{HCE,j}^{i}$: annual total final energy demand of heating cooling and electric light [kWh /(m²a)]
$q_{EL,j}^{i}$: annual electric light demand [kWh /(m²a)]

Discussion and result analysis

Solar shading period

The optimized duration of the shading period was evaluated with the façade system EVB. Figure 17 shows a world map with the investigated locations. The location points are coloured according to the results. The evaluation shows, that the shading period is highly depended on the latitude and minor depended on the altitude. At equator, throughout the whole year a shading system is necessary. With increasing latitude (southern/northern), the duration of the necessary shading period decreases. In Europe, a shading duration of 150-200 day is recommended. Furthermore, at coast region a slightly shorter period is noticed in comparison to upcountry. As remarked above dependence with the altitude is recognizable. E.g., locations in Himalaya have lower external temperatures due to their high elevation and therefore they present no or a very short shading period. Figure 18 shows the start date of the optimized shading period. The optimization routine II with the integral approach of heating, cooling and electric light and an evaluation with the system DRS determines nearly the same start and end points of the best shading period. This result seems to be very robust even for different climate data for the same locations and other façade systems and transparent area. These optimized shading periods are set as initial values for the next parametric study 'Transparent area'.

Transparent area

With the following parametric study, the optimized transparent area is determined in terms of minimal total final energy demand. First detailed analysis with the shading system EVB is given for the cities of *Table **3***. This allows to understand the building physics behaviour in the different climate zones and further the worldwide results.

Table 3: Detailed analysis of different cities in different climate zones

Climate Zone	City
Cold climate	Stockholm (Sweden)
Cool climate	Berlin (Germany)
Warm climate	Wellington (New Zealand)
Hot dry climate	Las Vegas (USA)
Tropical climate	Salvador (Brazil)

Stockholm (SWE):
Figure 9 shows the final energy demand for heating, cooling and artificial light demand for the location Stockholm according to the transparent area fraction of FA2 and FA3.

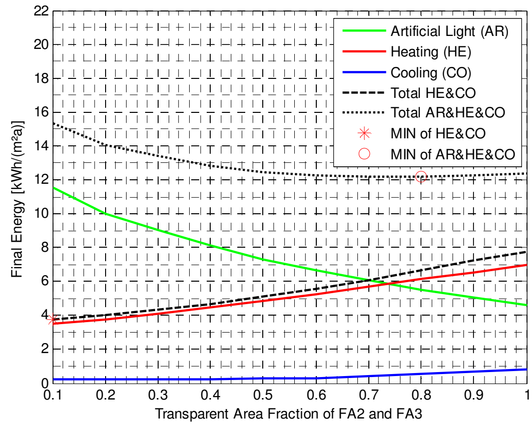

Figure 9: Final Energy of Heating, Cooling and Artificial Light [kWh/(m²a)] related to transparent window fraction of FA2 and FA3 (Stockholm)

Understandably, the larger the window area the less is the final energy demand for electric light.
Though more solar gain are available with increasing the transparent parts, the heating demand increases as well. Following aspects causes this behaviour. First, the solar gains in winter cannot be used totally because of the external shading is activated by glare protection. Second,

the artificial light and thus the internal gains decrease with larger window areas. Third, the mean U-value of the façade is getting worse with larger window areas (U-value for window is higher than that of the opaque wall). Thus, the transmission lost through the façade increases as well. These three main effects cause an increase of the heating demand with enlargement of the window area. The cooling demand is negligible. The electric light demand has the main influence to the final energy demand. Thus, the lowest total energy demand can be achieved with a transparent area fraction between 70%-100%.

Berlin (GER):
Figure 10 shows the energy curves for Berlin.

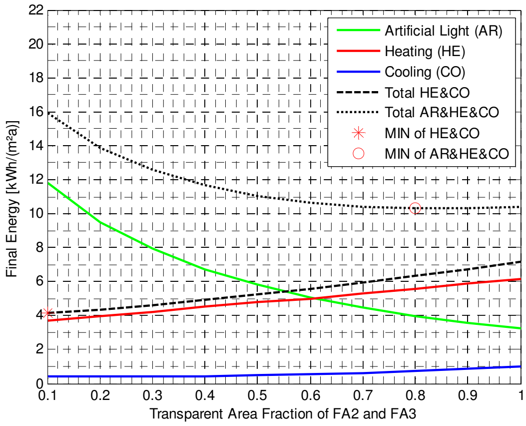

Figure 10: Final Energy of Heating, Cooling and Artificial Light [kWh/(m²a)] related to transparent window fraction of FA2 and FA3 (Berlin)

The energy behaviour in this case is comparable with the location Stockholm and can be explained with the same effects. The heating demand for large transparent areas is slightly smaller, which can be explained with the higher external temperatures in the winter compared to Stockholm. Thus, the transmission losses are slightly smaller as well. The total final energy optimum is also found in a wide range between 70% and 100% transparent fraction of FA2 and FA3.

Wellington (NZL)
At Wellington the heating demand can be reduced with increasing the transparent area. Because of the warm climate, a higher U-value for the wall can be used. The external temperatures in the winter cause less transmission losses compared to Berlin or Stockholm. Therefore, the solar gains are higher than the losses in winter. The cooling demand is also negligible. The electric light demands also decrease significantly with an enlargement of the window area.

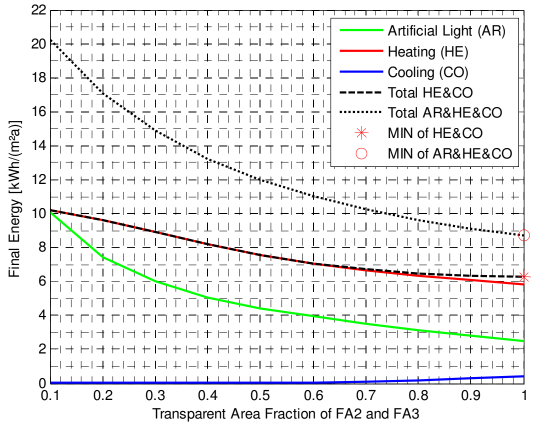

Figure 11: Final Energy of Heating, Cooling and Artificial Light [kWh/(m²a)] related to transparent window fraction of FA2 and FA3 (Wellington)

Las Vegas (USA):
The energetic behaviour of location Las Vegas is comparable with the location Wellington. However, there is a cooling demand with large window areas. However, night ventilation is activated and decreasing internal gains caused by electric light, the cooling demand increases with larger transparent areas because of the higher solar gains.

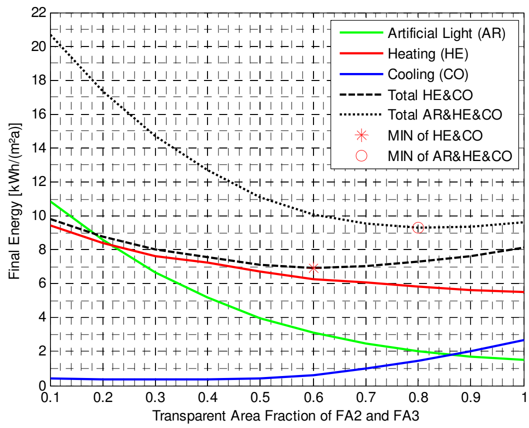

Figure 12: Final Energy of Heating, Cooling and Artificial Light [kWh/(m²a)] related to transparent window fraction of FA2 and FA3 (Las Vegas)

Salvador da Bahia (BRA):
At Salvador da Bahia no heating is necessary. Due to the high additional dehumidification demand night ventilation is not applicable. This results in a high cooling demand. The decrease of the internal gains (electric light) with larger window areas is compensated with the solar gains, which are strongly reduced because of a year-round shading period. Therefore, the cooling demand is just slightly increasing. Thus, the minimum of the total final energy demand can be found with taking in account the electric light and cooling and is also located in a range

between 70% and 100% window fraction of FA2 and FA3.

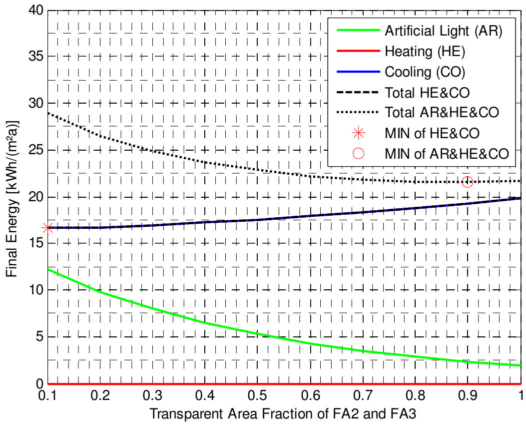

Figure 13: Final Energy of Heating, Cooling and Artificial Light [kWh/(m²a)] related to transparent window fraction of FA2 and FA3 (Salvador da Bahia)

The analysis of the transparent area fraction of FA2 and FA3 is carried out for the worldwide locations and the variation is determined with the lowest final energy demand for optimization routine I and II. It has to remarked, that an optimum could be found also in situations, where the variations produce negligible deviations (see Figure 13 minimum of heating and cooling). Thus, the optimum is in some cases not always significant.

Optimisation case I – heating and cooling:
Figure 19 (appendix) shows the best transparent area fraction for optimisation case I (minimal heating and cooling demand, $q_{HC,j}^{min}$). In a range of latitude of 90° - 45° a window area less than 20% of FA2 and FA3 is recommend. As remarked at the detailed analysis of city Stockholm, the high transmission losses through the window predominate the solar gains that could be achieved with larger transparent areas. Additional glare protection avoids useful solar gains in the winter. In the latitude range 45° - 30° window area fractions up to 50% of FA2 and FA3 are recommended. For locations in a region of latitude 0° - 30° the optimisation routine identifies small windows area because of high solar gains, which are responsible for a high cooling demand.

Optimisation case II – heating, cooling and artificial light:
Figure 20 (appendix) shows the variation of transparent façade area with the lowest final energy demand in terms of heating, cooling and artificial light demand ($q_{HCE,j}^{min}$). Compared to optimization routine I the general trend notes much larger window areas for each location. The need of the electric light demand causes higher transparent areas. The electric demand for the artificial light is valuable compared to the supply of heating and cooling with the help of efficient heat pumps in a passive house office. The huge difference between a purely thermally and an integrally optimized façade design shows the need of coupled thermal and lighting simulation and evaluation, especially in the early design phase. Figure 14, Figure 15 and Figure 16 show the current demand for heating, cooling and electric light for the optimized transparent area fraction of the facade.

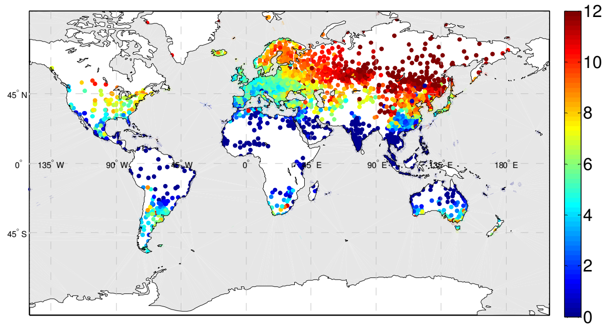

Figure 14: Current Heating Demand $\boldsymbol{q_{HE}}$ for the variation with optimized transparent area [kWh/m²a]

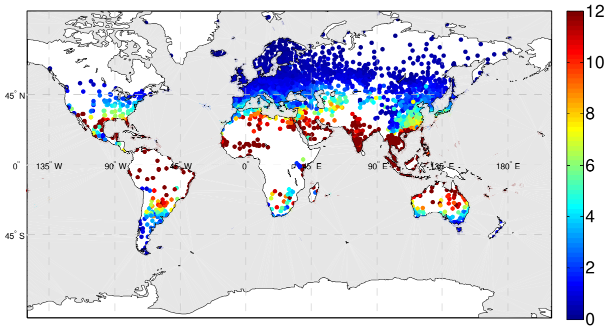

Figure 15: Current Cooling Demand $\boldsymbol{q_{CO}}$ for the variation with optimized transparent area [kWh/m²a]

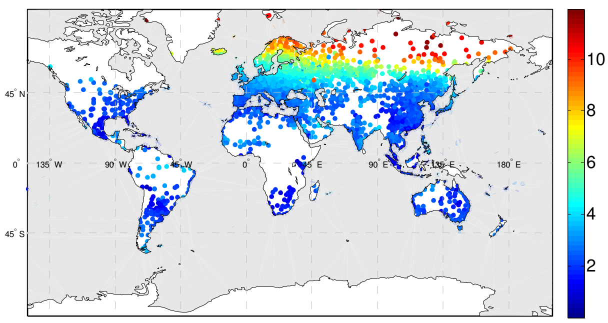

Figure 16: Current Electric Light Demand $\boldsymbol{q_{EL}}$ for the variation with optimized transparent area [kWh/m²a]

Comparison of façade system EVB and DRS

Figure 21 (appendix) shows the percentage deviation $q_{dev,j}$ of the energetic optimized transparent areas variations of system EVB and DRS. A negative value means, that the system EVB achieves a lower final energy demand while positive values show a better energetic performance of the façade system DRS. The deviation is calculated with following equation:

$$\boldsymbol{q_{dev,j}} = \frac{q_{HCE,j}^{min,DRS} - q_{HCE,j}^{min,EVB}}{q_{HCE,j}^{min,DRS}} \qquad (5)$$

The main trend is, that with façade system DRS lower final energy demands are reached. Especially in Southern Europe savings up to 20% are possible compared to the conventional system EVB. Also at South Australia and South America savings up to 30%, in middle and north Europe savings of 5-10% can be reached with the system DRS. At equator (with latitude of +/- 20°) both systems show nearly the same performance. The savings are mainly caused by a higher solar gain utilization in winter though glare protection is activated, which reduce the heating demand. Furthermore, the artificial light demand can be slightly decreased.

Conclusion

An integral thermal and day- and electric light simulation was carried out at worldwide locations to find the best shading period and transparent area in terms of minimal final energy demand. Climate adapted passive house U-values and a very efficient building technology were used to ensure a reasonable building quality. A conventional façade system (external venetian blind) and complex façade system (external venetian blind + daylight redirection) are considered, which provide glare and sun protection if required. The influence of different transparent areas combined with these façade systems to the heating, cooling and electric light demand was evaluated. The following conclusions can be drawn:

At the equator an all-year shading period is necessary. With increasing latitude (northern and southern) the shading period decreases. In Central Europe a shading period of 170 days is recommended. Locations with a high altitude need shorter shading periods, caused by the lower external temperatures. The shown result can be used to preset facade control strategy systems.

With increasing transparent area of the middle and upper part of the façade, the electric light demand is decreasing – up to some 70% significantly, then slowly. In cold climate zones the heating demand cannot be reduced with larger window areas because the external glare protection strongly reduces usable solar gains. The transmission losses increase due to the worse U-value of the rising window area. Though a very efficient electric light solution was considered, the electric light demand has strong influence to the façade design.

The integral optimization of heating, cooling and electric light determines in nearly all locations more transparent area than the optimization, which was carried out for just heating and cooling. Savings up to 20% in term of total final energy can be achieved with this optimized façade design.

A daylight redirection systems (DRS) in the upper part of the facade allows under this integral consideration additional savings of up to 30% in terms of total final energy demand. At equator, the applied conventional and daylight redirection system show nearly the same performance.

Following general design recommendations for facades apply only for office buildings with a passive house standard and the mentioned boundary conditions: For a latitude range between

1) 30°N – 30°S the transparent part should be about 50% of FA2 and FA3 (33% of total façade area). It is a reasonable compromise between reducing solar gains and improving daylight input.
2) 30°N – 70°N and 30°S – 70°S the transparent part of the façade should be greater than 70% of FA2 and FA3 (50 % of total façade area) in order to reduce the artificial light demand.
3) 70°N – 90°N and 70°S – 90°S the transparent part should be smaller than 30% of FA2 and FA3 (20 % of total façade area). The high transmission lost predominate the useful solar gains and the daylight usage.
4) 30°N – 70°N and 30°S – 70°S Daylight redirection systems show a better energetic performance compared to conventional shading systems

This optimized façade design with its mentioned savings can only be determined with the help of a coupled thermal and lighting simulation routine and should be carried out in the early design phase already.

The presented results are valid for equator oriented reference rooms embedded in a thermally high efficient building. The findings are not tested for other building standards and HVAC systems. Thus, further analysis needs to be done to evaluate the influence of different oriented buildings (West, East and North), other buildings quality standards and further façade systems (e.g. internal glare protection for better use of solar gains in winter). In addition the renewable primary energy supply (Grove-Smith and Feist 2015) assess the heating and artificial light demand higher than the cooling demand and could influence also the façade design. This should also be analyzed for different climate zones.

Acknowledgement

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Appendix

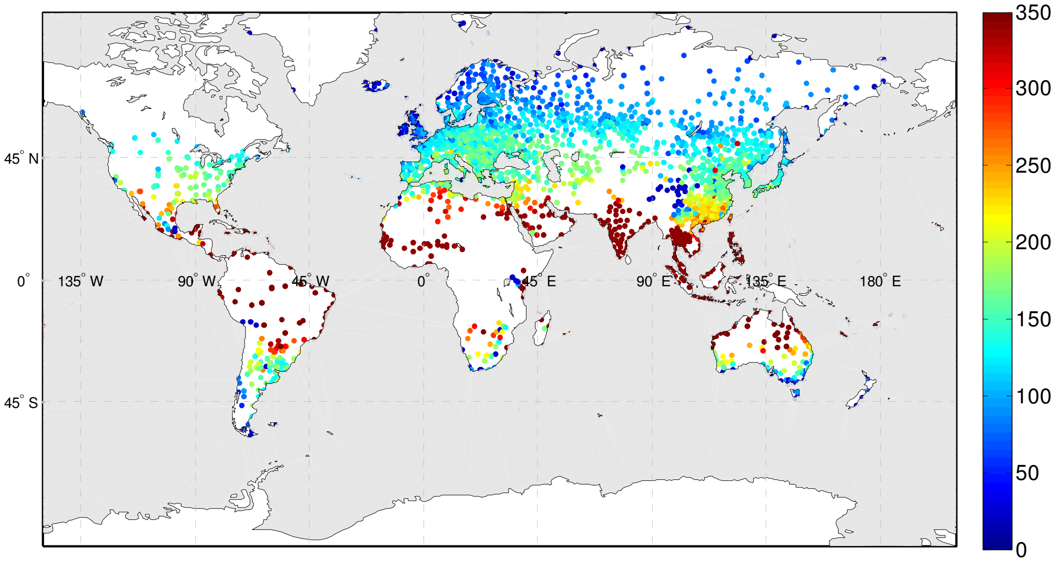

Figure 17: Optimized duration of shading period in terms of total final energy demand [d]

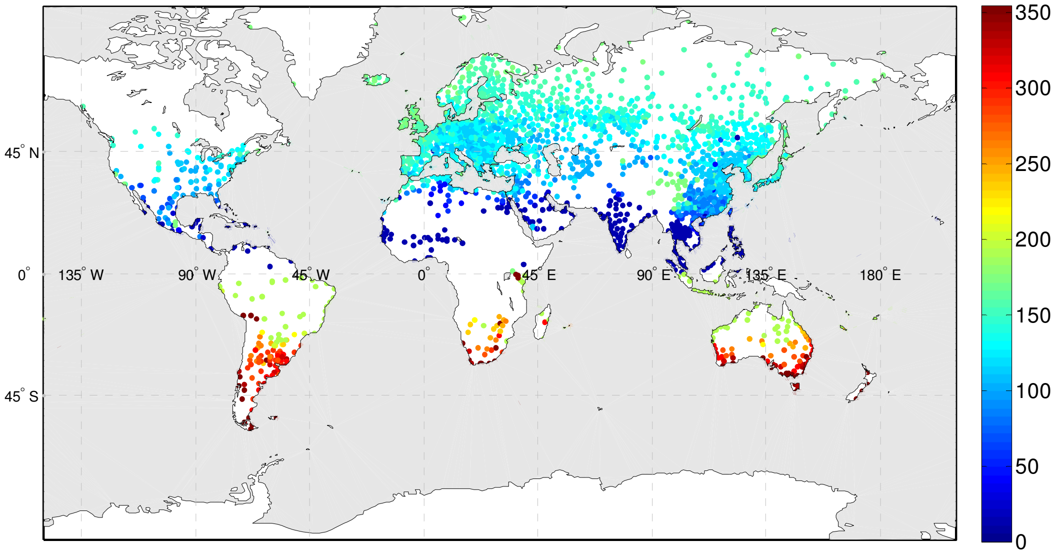

Figure 18: Start of optimized shading period [d]

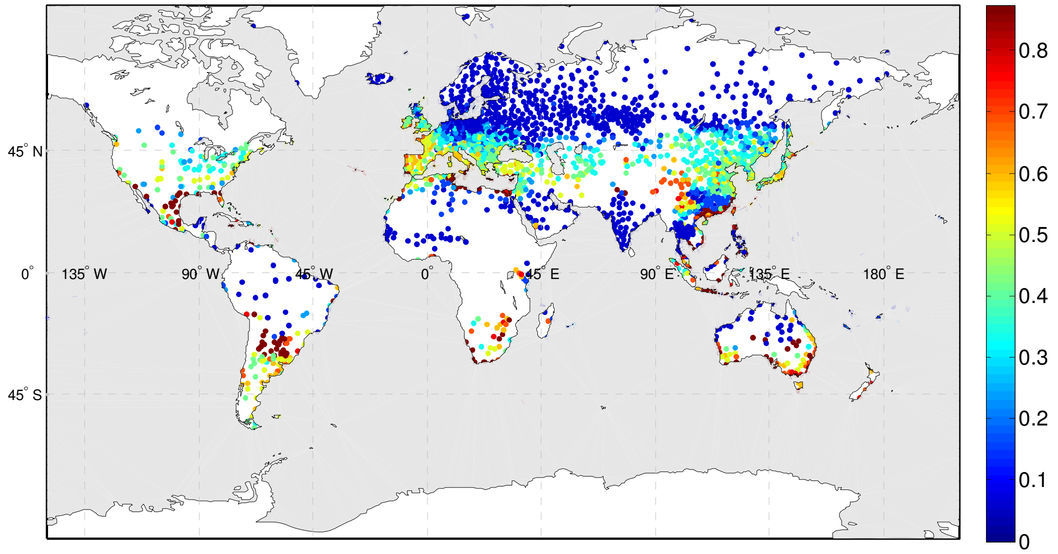

Figure 19: Optimized window area fraction of FA2 and FA3 in terms of heating and cooling demand

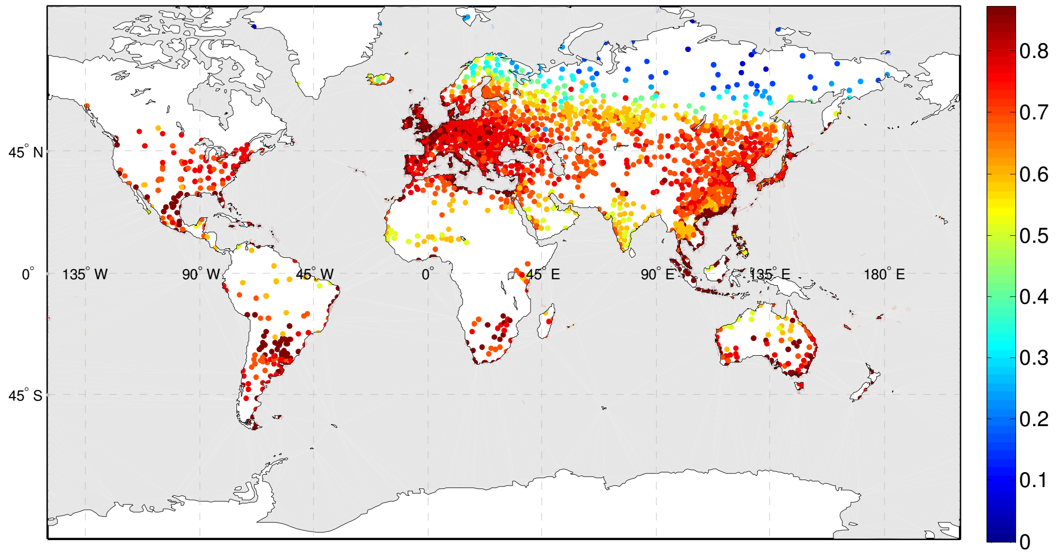

Figure 20: Optimized window area fraction of FA2 and FA3 in terms of heating, cooling and artificial light demand

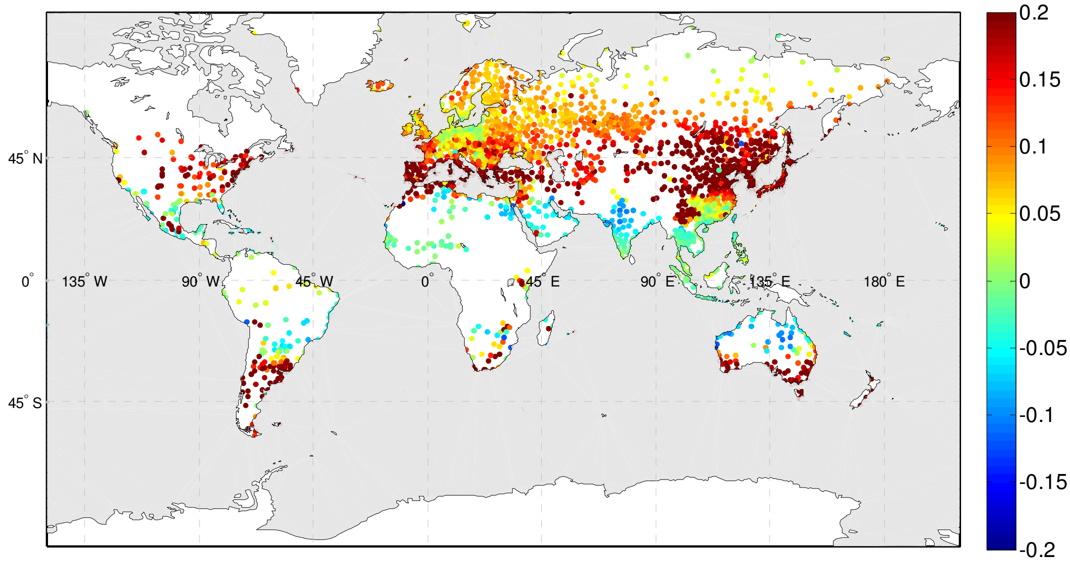

Figure 21: Relative final energy deviation of EVB against DRS