Total economy of windows and facades in low energy office buildings

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Facade performance including windows, opaque elements and shadings has strong impact on heating, cooling and electric lighting energy as well as on daylight. For low-energy office buildings some general guidelines of façade design can be given regarding energy-efficiency, daylighting and cost effectiveness.

Keywords: Façade design, daylight, nZEB, nearly zero energy buildings, cost optimality, energy simulations.

In office buildings, often large windows have been used without special measures, resulting in high heating and cooling needs, high investment cost and often poor solar protection and glare. Evidently low and nearly zero energy buildings will need careful design to optimize the facade performance. It is important to assure daylight and views outside which both have proven evidence on occupant satisfaction and productivity. Several studies have shown that lowering window to wall ratio (WWR) improves energy performance, but on the other hand it also reduces daylighting.

In this study we derived cost optimal design principles for a cold climate regarding window sizes, solar protection, thermal insulation and daylight leading to optimized total energy performance of office buildings. Some analyses were also conducted for Central European climate. Special attention was paid to highly insulated glazing elements with U-values of 0.6 W/(m² K) and below and high visible light transmittance of about 0.5–0.7. Energy and daylight simulations for calculating heating, cooling and lighting energy were conducted for model office space representing typical open plan offices. Window to wall ratio, solar heat gain coefficient, visible transmittance, solar shading and external wall U-value was varied in order to analyze energy performance. Lower limit of window size was determined by the average daylight factor criterion of 2%, but cases with larger windows were also analyzed. Investment cost of windows and external walls was compared to generate simulation cases so that optimal insulation thicknesses would be used with each glazing variant. More thorough information about the study can be found in [1] and [2].

Simulation model

Energy simulations with the climate of Tallinn, Estonia using IDA ICE 4.5 were conducted on the basis of a generic open-plan office single floor model that was divided into 5 zones, from which 4 orientated to south, west, east and north respectively and in addition one in the middle of the building (**Figure 1**). The initial data of simulation model is shown in **Table 1**.

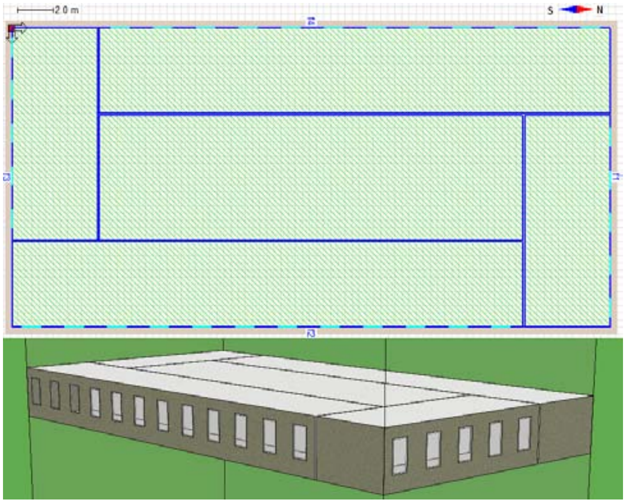


Figure 1. The plan and 3D view of the simulation model of IDA ICE. The longer zones consisted of 12 room modules of 2.4 m and shorter ones of 5 room modules, resulting in inner dimensions of the floor 33.6 x 16.8 m.

Daylight requirements

It is usually well known among building designers that large windows cause high energy bills, however it is uncertain up to which extent window area can be reduced. This uncertainty impedes negotiations between architects standing for the visual appearance of the building and engineers concerning for energy efficiency and indoor environment quality. Pr BS 8206-2 [3] states that average daylight factor should not be below 2% in office rooms. Daylight calculations were made assuming that average daylight factor 2% would be assured up to 4 meter distance from the external wall and that the office room consists of 2 modules resulting in room width 4.8 meters. The minimum window-to-wall ratios (WWR) depending on the visible transmittance have been shown in **Figure 2** and the window sizes in case of different glazing variants have been shown in **Table 2**. Window height was in all cases 1.8 m.

Table 1. Input data of office rooms and HVAC systems for energy calculations.

Occupants, W/m²	5
Equipment, W/m²	12
Lighting, W/m²	5
Temperature set point for heating and cooling	+21 and+25°C
Air flow rate	1.5 l/(s·m²)
Illumination setpoint, lx	500
Total irradiance on facade above which solar shading is down, W/m²	200
Heating system (radiators) efficiency, -	0.97
Heat source (district heating) efficiency, -	1.0
Cooling system losses, % of cooling energy need	10
Mechanical cooling SEER, -	3.0
Ventilation SFP, kW/(m³/s)	1.3

Required glazing area can be calculated with the following formula:

$$A_W = \frac{D \times A \times (1 - R^2)}{T \times \theta \times m}$$

Where,
A_w – total glazed area of windows (**not** including window frames), m²
D – desired average daylight factor, 2%
A – total area of all interior surfaces (incl windows), 109.4 m²
R – mean surface reflectance, 0.5
T – scattered light transmittance of glazing (equals to 90% of visible transmittance τ), -
θ – sky angle, 80° (angle of visible sky from the center of window)
m – clearness of the glazing, 0.9

Optimal insulation thickness

External wall thermal resistance is mainly determined by the U-values of both windows and external wall and a good balance has to be found between investments for high performance glazing and insulation thickness. Combinations of several window types with minimum sizes and insulation thicknesses ranging from 150 to 390 mm were simulated. Combined with investment cost calculations, 20 year net present values were

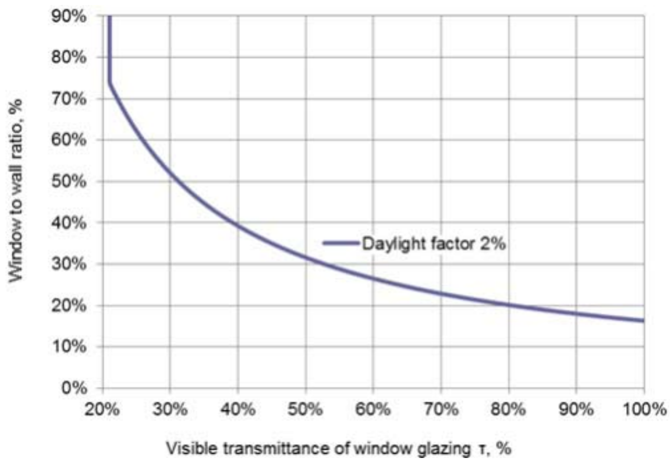


Figure 2. Minimum window-to-wall ratio (WWR) depending on visible transmittance of window glazing.

calculated and the results are shown in **Figure 3**. The insulation thickness which resulted in lowest NPV was 200 mm (U-value 0.16 W/(m²K)) for most cases, however compared to case with quadruple glazing and 200 mm insulation thickness both the investment cost and primary energy was lower for façade with triple windows and 300 mm insulation thickness. This made using 4 pane windows with 200 mm wall insulation insensible and 250 mm (U-value 0.13 W/(m²K)) was chosen for final analysis of 4 pane glazing. A similar situation appeared in case of 5 window panes, which required 390 mm of insulation thickness (U-value 0.09 W/(m²K)) to show lower primary energy than that of best 4 pane case. Cost analyses of glazing units showed that double glazing and simple triple glazing investment cost did not differ significantly from the best available triple glazing, which could be partly explained by high volumes of the latter one. Thus there is no point in using worse glazing than the best performing triple glazing.

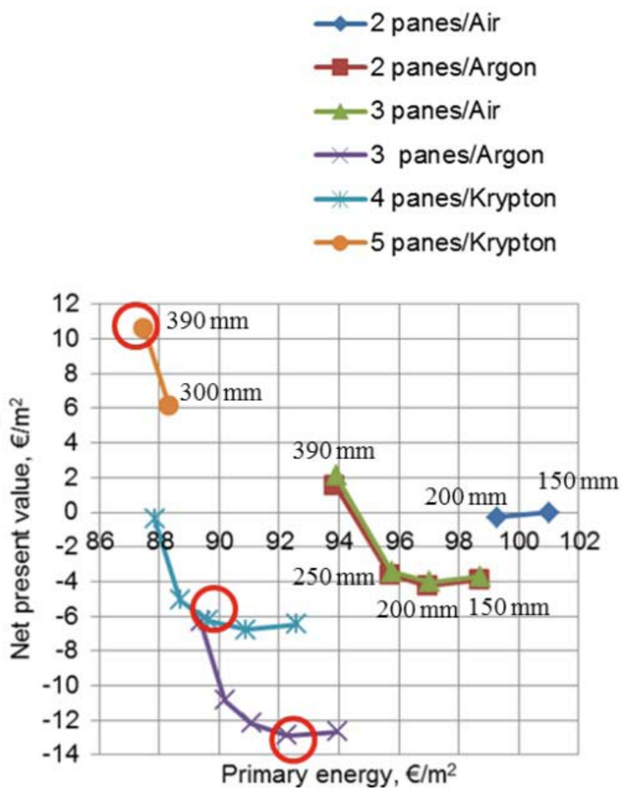


Figure 3. Net present values of 20 years and primary energy as a function of window type and insulation thickness. The points of each curve represent the insulation thicknesses 150, 200, 250, 300 and 390 mm from left to right if not otherwise specified. The most sensible insulation thicknesses at different insulation levels have been marked with red circles, while 3-panes/200 mm show the cost optimal.

Optimal fenestration solution

Results in **Figure 3** were calculated with minimum WWRs shown in **Table 2**. These results were refined so that the financially most feasible window sizes for each glazing type and orientation were determined as shown

Table 2. The properties and minimum window sizes of a selection of highly transparent glazing variants.

No of panes /Gas between panes	Glazing					
	U-value, W/(m² K)	No of low-E layers	Solar factor g, -	Visible transmittance τvis, -	WWR, %	Window width, m
2/Air	1.4	1	0.61	0.78	21.6	0.95
2/Argon	1.1	1	0.61	0.78	21.6	0.95
3/Air	1.1	1	0.52	0.71	23.9	1.05
3/Argon	0.54	2	0.49	0.70	23.9	1.05
4/Krypton	0.32	3	0.36	0.63	26.1	1.15
5/Krypton	0.21	4	0.24	0.56	29.5	1.30

in **Figure 4**. Generally window to wall ratio of 37.5% was most feasible solution for triple and quadruple windows mainly due to reduced lighting needs, however in case of triple glazing the WWR 23.9% resulted in best energy performance and only slightly higher NPV. Increasing quintuple windows proved too expensive and minimum sizes proved to be financially most feasible despite the fact that WWR 60% resulted in lowest primary energy use. In addition, the effect of external shading revealed too small to be financially reasonable. The description and key performance indicators of the mentioned cases are shown in **Table 3.**

Even though triple clear glazing windows with a WWR of 37.5% were found to be cost optimal, it was actually recommended to use triple glazing with a WWR of 23.9%. This was because smaller windows resulted in significantly smaller cooling loads (50 vs. 70 W/m²), which in turn results in better indoor climate and smaller investment on the cooling system.

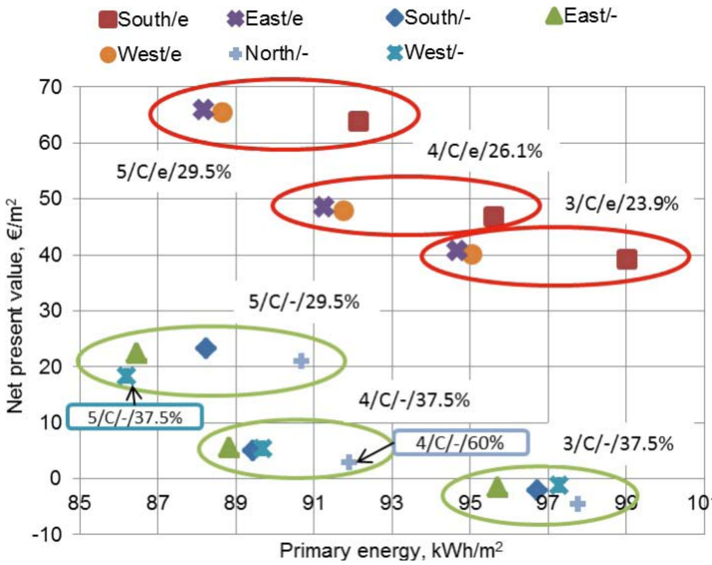


Figure 4. Net present value and primary energy for the facades. Code - 4/C/e/26.1% means quadruple (4) highly transparent (C) window with external shading (e) and WWR 26.1%. Cases with external shading (marked with red circles) appeared to be at significantly higher cost level.

Facade performance in Central Europe

We ran some simulations with the climate of Paris to find out to what extent the results might apply for the temperate climate of Central Europe. Cost optimal and the most energy efficient cases in Estonian climate were run without changes. For these cases U= 1.1 W/(m² K) was used for windows, and the less insulated external wall (150 mm) with U-value of 0.20 W/(m² K) was used. The results showed that the cooling energy started to dominate and also proportion of lighting energy increased. Due to larger cooling energy use the effect of external shading was positive in all the cases. However, similarly to Tallinn's results, smaller sizes of double and triple windows resulted in better energy performance. The situation could be different with higher internal gains, but this study used modern appliances and lighting suitable for nZEB buildings. Triple glazing showed significantly better results in primary energy than double glazing as can be seen in **Figure 5**. However, the performance of the case with Estonian most energy efficient façade was not achieved. This indicates that also in Central European climate, there is a need for façade components with improved thermal insulation. Indeed the solutions feasible in a cold climate could not pay back because of lower heating need.

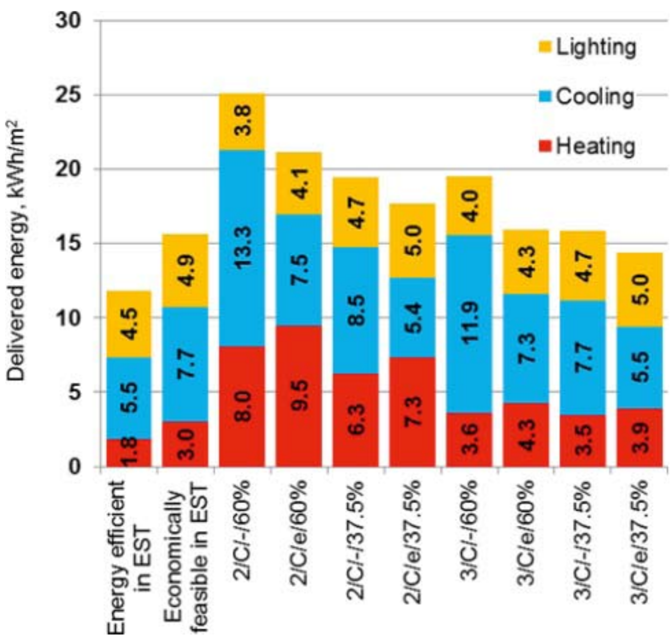
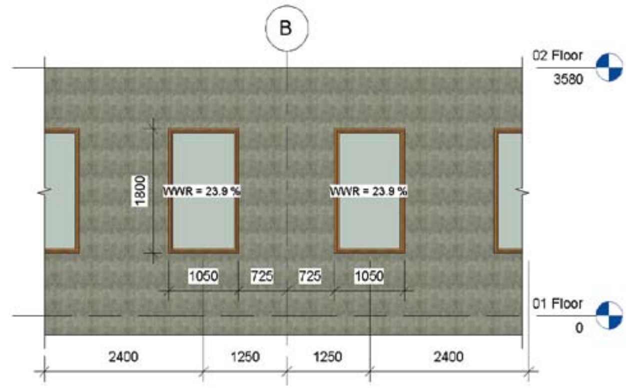
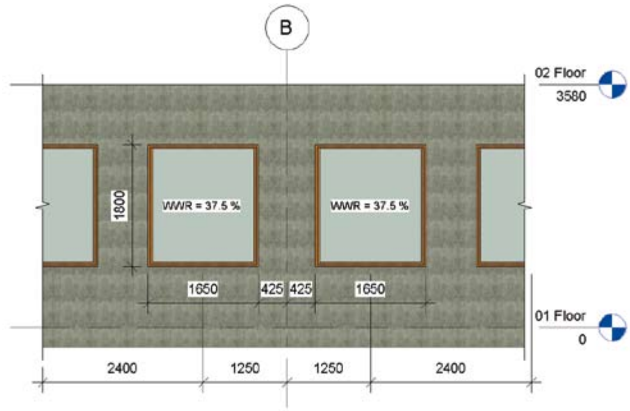
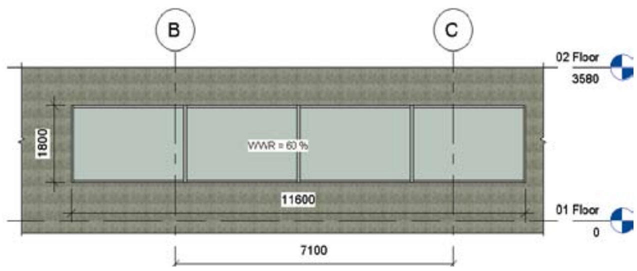


Figure 5. Delivered energy in Paris. In two first cases the cost effective and most energy efficient façade solutions in Estonian climate are used. Code: - 3/C/e/37.5% means triple (3) highly transparent (C) window with external shading (e) and WWR 37.5%.

Conclusions

Daylight factor calculation is good method for setting the lower boundary to window sizes while analyzing different facade cases. The optimal solution for an office building façade in a cold climate revealed to

Table 3. Summary of fenestration design solutions for a low energy building.

Solution case	Technical details	Key performance indicators
Low Energy Building, ≤130 kWh/m²		
A. Recommended solution within cost optimal range that provides better indoor climate: triple glazing and 200 mm thick insulation 	**Windows:** • Triple glazing • WWR: 23.9% • U value: 0,54 W/(m²·K) • Gap filling: 90% argon • Solar factor g: 0.49 • Visible transmittance τ_{vis}: 0.70 • Cost per unit: 122 €/m² **Wall:** • Insulation thickness: 200 mm • U value: 0,20 W/(m²·K) Cost per unit: 122.00 €/m²	Investment: 95.7 €/m² Primary energy: 109,9 kWh/m² Total energy cost per year: 8.50 €/m² NPV: 295.70 €/m²
B. Next sensible solution: quadruple glazing and 250 mm thick insulation (north facing façade: see the figure for solution C) 	**Windows:** • Quadruple glazing • WWR: 37.5% and North 60% • U value: 0,32 W/(m²·K) • Gap filling: 90% krypton • Solar factor g: 0.36 • Visible transmittance τ_{vis}: 0.63 • Cost per unit: 176.88 €/m² and North 144.68 €/m² **Wall:** • Insulation thickness: 250 mm • U value: 0,13 W/(m²·K) • Cost per unit: 227.9 €/m²	Investment: 107.80 €/m² Primary energy: 109.1 kWh/m² Total energy cost per year: 8.19 €/m² NPV: 300.50 €/m²
C. The most energy efficient solution: quintuple glazing and 390 mm thick insulation. All orientations have windows with a size of 11600x1800 mm (figure below) 	**Windows:** • Quadruple glazing • WWR: 60% (11.6 m) • U value: 0,21 W/(m²·K) • Gap filling: 90% krypton • Solar factor g: 0.24 • Visible transmittance τ_{vis}: 0.56 • Cost per unit: 230.95 €/m² **Wall:** • Insulation thickness: 390 mm • U value: 0,093 W/(m²·K) • Cost per unit: 363.4 €/m²	Investment: 160.50 €/m² Primary energy: 103,4 kWh/m² Total energy cost per year: 8.03 €/m² NPV: 349.40 €/m²

be triple windows as small as daylight requirements allow (WWR=23.9%) and wall insulation thickness 200 mm. If better energy performance is required, quadruple windows with window to wall ratio approximately 40% and 250 mm insulation thickness is an option. The use of external shading was not justified as windows with reasonable size provided enough solar protection.

Limited number of simulations with Central European climate showed that similar solutions to Estonian cost optimal clearly outperform conventional design with double glazing, although cooling energy dominated instead of heating energy and also external shading was an effective means of reducing primary energy. Triple glazing with slightly larger size (WWR=37.5%) resulted in best energy performance and larger windows showed worse results. ■

Tallinn University of Technology (TUT) chair of heating and ventilation, prof Hedrik Voll, educates architects and engineers for daylighting and direct solar radiation with scale models and heliodon direct solar radiation table.

"We have discovered that building design through daylight seems to be the conversation topic that is of interest to both sides – architect and engineer. For architects, daylight is a very important element in designing. For engineers, daylight is nothing more than kW and kWh, which ultimately determines a large share of a building's energy efficiency. If the said approach is used in parallel for training both architects and HVAC engineers, we will find common ground and thus be able to negotiate the maze of designing and engineering low or near zero energy buildings."

References

[1] Thalfeldt M., Pikas E., Kurnitski J., Voll H. ***Façade design principles for nearly zero energy buildings in a cold climate.*** In «Energy and buildings», Vol. 67, pp. 309-321, December 2013.

[2] Pikas E., Thalfeldt M., Kurnitski J. ***Cost optimal and nearly zero energy building solutions for office buildings.*** To be published in «Energy and buildings», http://dx.doi.org/10.1016/j.enbuild.2014.01.039.

[3] Pr BS 8206-2 Lighting for buildings – Part 2: Code of practice for daylighting.