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Facade design principles for nearly zero energy buildings in a cold climate

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ABSTRACT

Cost optimal and as energy efficient as possible façade solutions, including window properties, external wall insulation, window-to-wall ratio and external shading were determined with energy and daylight simulations in the cold climate of Estonia. Heating dominated in the energy balance and therefore windows with higher number of panes and low emissivity coatings improved energy performance. The window sizes resulting in best energy performance for double and triple glazing were as small as daylight requirements allow, 22–24% respectively. For quadruple and hypothetical quintuple glazing the optimal window-to-wall ratios were larger, about 40% and 60% respectively, because of daylight utilization and good solar factor naturally provided by so many panes. The cost optimal façade solution was highly transparent triple low emissivity glazing with window-to-wall ratios of about 25% and external wall insulation thickness of 200 mm ($U = 0.16$). Dynamic external shading gave positive effect on energy performance only in case of large window sizes whereas due to high investment cost it was not financially feasible. Limited number of simulations with Central European climate showed that triple glazing with double low emissivity coating and window-to-wall ratio of about 40%, i.e. slightly larger and with external shading compared to Estonian cost optimal one, clearly outperformed conventional design.

1. Introduction

In order to achieve nearly zero energy building (nZEB) requirements by 2021 in a cold climate energy efficient façades are one important factor in the design of such buildings. Facade performance including windows, opaque elements and shadings has strong impact on heating, cooling and electric lighting energy needs as well as on daylight.

So far, 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. Double and triple pane windows are currently most commonly used, however one can choose between highly transparent windows, which do not offer good solar protection and may cause high cooling costs, or ones with good solar protection qualities, but lower visible transmittance, which result in high heating cost due to larger windows required by daylight standards. Evidently low and nearly zero energy buildings will need more 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 complex analyzes have been made about façade design influence on buildings' energy consumption. Poirazis et al. [1] conducted office building energy simulations studying window-to-wall ratios (WWR) between 30% and 100%, different glazing, shading and orientation options. It was concluded that office buildings with lower WWR consume less energy. Similar analyzes were made by Motuziene and Joudis [2] about office building in Lithuania. The results showed that optimal WWR was 20–40%, however it was noted that there will be problems fulfilling daylighting requirements. Susorova et al. [3] simulated office buildings in 7 different climates and concluded that in cold climates increasing WWR increases office buildings' total energy consumption. Using energy simulations of an institutional building Tzempelikos et al. [4] came to conclusions that substantial energy savings can be achieved using an optimum combination of glazings, shading devices and controllable electric lighting systems. Johnson et al. [5] optimized daylighting use and studied the sensitivity of orientation, window area, glazing properties, window management strategy, lighting installed power and control strategy. The results showed that saving can be significant with automatically controlled lighting, however total energy consumption must be kept in mind as analyzed parameters influenced the energy use of HVAC greatly.

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Boyano et al. [6] studied the effect of building envelope thermal resistance and also lighting system efficiency on office building energy efficiency and concluded that lighting plays significant role in energy use. The importance of taking into account the interaction between lighting and HVAC system was also stressed by Franzetti et al. [7]. All of the authors mentioned previously, have done thorough investigation of office building façade, however windows with U-values below 1.0 W/(m^2 K) have been rarely studied. One of the few studies, that has investigated office building energy use with glazing of extremely low U-values was conducted by Grynning et al. [8]. The results showed that lower U-values of windows result also in lower energy consumption and the optimum solar heat gain coefficient (SHGC) is 0.4. It was also concluded that cooling energy dominates the energy need, however cases with WWR of 55% were simulated and therefore it is still unclear whether these results also apply in case of different WWRs.

As previous studies have shown that lowering WWR increases energy efficiency, but on the other hand it also reduces daylighting efficiency. Therefore it is important to set lower limits to window sizes. Estonian Standard EVS 894:2008 “Daylight in dwellings and offices” [9] states that average daylight factor should not be below 2% in office rooms. Voll and Seinre [10] have used same guidelines in their description of a method for optimizing fenestration design for daylighting to reduce heating and cooling loads in offices. In addition to that maximum WWR values were derivated so that heating and cooling loads of office rooms would not exceed limit values.

A very common way of assessing feasibility of investments is calculating payback period of different cases, however it may not reveal the best option. Directive 2010/31/EU, EPBD [11] stipulates that EU members must ensure that energy performance requirements of buildings are set on cost optimal level. This means that primary energy requirements are set at level, where life cycle cost is minimal. The development of national requirements has been described by Kurnitski et al. [12], who presented calculation results for residential buildings using lowest NPV of building costs as the criteria for cost optimality. Life cycle cost analysis was proposed as a part of “Integrated Energy-Efficient Building Design Process” by Kanagaraj and Mahalingam [13]. It was found that considerable energy savings could be achieved using the process. Life-cycle cost analysis was also used by Kneifel [14] in his simulation-based case study of several building types including also office buildings.

The purpose of the study is to give guidelines of office buildings façade design from the perspective of energy-efficiency and daylighting to architects, engineers, real-estate developers etc. In this study we derived 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. Special attention was paid to highly insulated glazing elements with U-values of 0.6 W/(m^2 K) and below to 0.21 and high visible light transmittance of about 0.5–0.7. Energy and daylight simulations 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. Payback times and net present values (NPV) of studied cases were calculated to assess cost effectiveness.

The investment cost and NPV calculations have been thoroughly described in a companion paper by Pikas et al. [15]. The economic results necessary to determine optimal façade design solutions have been taken from the companion paper.

2. Methods

Key factors of a façade mostly influencing the energy performance of a building, such as window type, wall insulation, window-to-wall ratio (WWR) and shading devices, were optimized in the case of a generic office floor model for the lowest life cycle cost and alternatively for the best achievable energy performance. Step by step approach was used to start with double and triple pane glazing units and WWR determined by the daylight factor criterion. In total, four steps were used to determine the most energy efficient and cost optimal solutions for each orientation. These included:

(1) Selection between highly transparent vs. solar protection windows;
(2) Determination of the optimal size of windows (WWR) with fixed initial U-values of opaque elements of external walls;
(3) Determination of optimal external wall insulation thickness;
(4) Assessment of cost optimal and most energy efficient solutions for each façade.

2.1. Generic office floor model

Energy simulations were conducted on the basis of a generic open-plan office single floor model that was divided into 5 zones – 4 orientated to south, west, east and north respectively and in addition one in the middle of the building (Fig. 1). 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 m × 16.8 m. In all cases the heating was district heating with radiators (ideal heaters in the model), and air conditioning with room conditioning units (ideal coolers in the model) and mechanical supply and exhaust ventilation with heat recovery was used. The working hours were from 7:00 to 18:00 on weekdays and the usage factor of heat gains during working hours was 55%. Ventilation worked from 6:00 to 19:00 on weekdays. The lighting was with dimmable lamps and daylight control with setpoint of 500 lx in workplaces. The position of workplaces used for the control is shown in Fig. 1. Either external or internal blinds were automatically drawn, when total irradiance on the façade exceeded 200 W/m^2 to avoid glare.

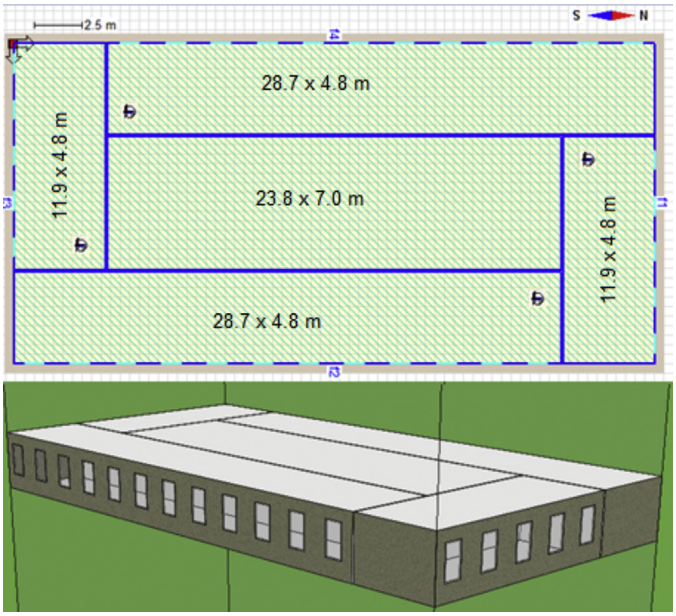

Fig. 1. The generic model of single floor of an office building constructed with 2.4 m room module–plan and 3D view. The locations of workplaces used for control of lighting are marked in the plan.