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Cost optimal and nearly zero energy building solutions for office buildings

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ABSTRACT

European Union (EU) has established directives and guidelines that soon require building industry to comply with nearly zero energy building (nZEB) targets in their daily work. This will necessitate new design solutions based on new knowledge. At a high performance level, it is a multifaceted problem, while solutions must be both energy and cost efficient. Most studies have focused on energy efficiency issues and neglected to analyze the cost optimality of technical solutions. This paper considers possible office building fenestration design solutions which take into account both energy efficiency and cost optimality. The analysis also looks at alternative measures to achieve the nZEB level. It was observed that for the cold Estonian climate, triple glazed argon filled windows with a small window to wall ratio and walls with 200 mm thick insulation are energy efficient and cost optimal within 20 years. Achieving nZEB required the use of photovoltaic panels for generating electricity. Existing nZEB solutions are not cost optimal, but this should change in the near future. In conclusion, the paper proposes design guidelines for high performance office building facades.

1. Introduction

According to different studies, buildings consume up to 40% of energy consumed nationally and produce 36% of the EU's CO_2 emissions. A 20% reduction in both CO_2 emissions and energy consumption by 2020 has been made a priority of EU Member States [1].

EPBD-recast 2010 states that Member States cannot apply rules that exclude the consideration of cost optimality [2]. When buildings are designed, alternatives must be considered, including fenestration design, energy sources and building systems. In this context, cost optimality means energy efficient solutions with a minimal life-cycle cost. There are a great number of studies focused on building systems, energy sources and fenestration design but fewer which also consider cost optimality.

Kurnitski et al. [3] studied cost optimal solutions for residential and office buildings. In the case of office buildings, they concluded that a construction concept with a specific heat loss of 0.33 W/(K m^2) and district heating at around 140 kWh/(m^2 a) is the cost optimal solution. This specific heat loss coefficient, which includes transmission and infiltration losses through the building envelope per heated net floor area, shows a reasonably good insulation level of the envelope. The authors included labor costs, material costs, overheads and value added tax (VAT) in the energy performance related construction costs. They did not, however, take into account maintenance, replacement and disposal costs, as these had a minimal impact on net present value (NPV), and this also allowed them to keep the calculations transparent.

Other examples include Hamdy et al. [4], who developed a multi-stage methodology to design nZEB. The objective of the study was to develop an optimization method for single-family houses in Finland. The optimal solution depends on the selected heating/cooling systems and escalation of energy costs together with energy-saving measures (ESM) and renewable energy sources. They introduce an efficient, transparent, and time-saving simulation-based optimization method for such explorations. The method is applied to find the cost-optimal and nZEB energy performance levels for a single-family house in Finland. These studies cannot be applied to office buildings, as residential buildings serve a different function and have different performance characteristics.

Analyses taking into account the new EU directives have also been published. Many of these consider how to achieve energy efficient solutions but not cost efficiency. For example, Chidiaca et al. [5] considered the most effective energy retrofit measures (ERM) for renovating office buildings. ERM solutions range from physical changes to a building to changes in operational practices including

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advanced controls and efficient lighting. They concluded that conventional methods are adequate for saving energy, but they did not consider costs in their analysis.

Kim et al. [6] tried to develop a data mining approach for designing energy efficient buildings in the early design stages by using building information models (BIM). Decisions must be made regarding the following aspects: the overall geometry of a building; the optimal orientation of a building; selection of building elements that affect the building performance and selection of building services. The authors provide a methodology for comparing outcomes on the basis of energy efficiency without regard to the investment costs of different optimal solutions.

Poirazis et al. [7] studied the impact of different levels of glazing on energy efficiency. They concluded that more glazing means more energy consumption, due to the increasing levels of cooling required but added that energy costs could be reduced through careful design. The authors proposed that double skin facades could provide a solution for highly glazed buildings, but they did not pursue this idea further in their study. While Poirazis et al. [7] did not consider life-cycle costs and investment costs, it could not be concluded which solutions would be optimal in terms not only of energy but also of cost.

Susorova et al. [8] studied the importance of fenestration design (window to wall ratio, window orientation, and width to depth ratio) and concluded that optimal design can decrease building energy consumption in office buildings and achieve energy savings in all climate zones. Better energy savings would be achieved in hot climates. Optimal fenestration design would be least effective in cold climates. The results of this analysis show that conventional energy efficiency technologies such as thermal insulation, low-emissivity windows, window overhangs, and day lighting controls can be used to decrease energy use in new commercial buildings by 20–30% on average and up to over 40% for some building types and locations. In addition, they concluded that the time horizon for the payback period also impacts energy efficient solutions, and for investors it is also important to know future operation and maintenance costs of the facility.

Kanagaraj and Mahalingam [9] proposed an integrated design methodology to help designers iteratively consider alternative solutions on a macro and micro scale by incorporating stakeholder preferences. It was found that considerable energy savings could be achieved using the process. Kneifel [10] performed life-cycle analyses on simulation based cases including office buildings.

Conventional energy saving measures like high-quality windows, solar shading and the installation of additional insulation are simple and straightforward solutions for achieving better performing buildings. But the problem is that it has become common to design either fully or highly glazed office buildings without any serious consideration of energy consumption. The result is high heating and cooling needs, high investment costs and often poor solar protection and glare. Optimizing the performance of the envelope, while incorporating natural lighting and views to the outside, could be seen as one key method of achieving nZEB by 2021. Designers also need to think about what kind of local energy production methods are reasonable to lower the demand for delivered energy.

The present study focuses on an economic analysis of optimal façade solutions based on energy simulation results presented in a joint-research paper [11]. Thalfeldt et al. [11] looked at the optimal design solutions for an envelope leading to optimized total energy performance of office buildings in a cold climate. Energy and daylight simulations were conducted for the typical floor of an office building by paying special attention to insulated walls and windows with improved *U*-values. Required investment costs and NPV were calculated for a period of 20 years (non-residential buildings) by considering current construction and energy costs, cost escalation and inflation. Cost optimal performance level means the energy performance in terms of primary energy leading to minimal life cycle cost. Finding a cost optimal solution for the required energy class is a complex task that requires the study of a variety of potential fenestration solutions [11]. What is optimal now would probably not be an optimal solution in the next five to ten years. The purpose of the present study is to determine which façade solutions are cost optimal in the current economic environment and the additional cost of achieving a nZEB performance level in accordance with the Estonian nZEB requirement. A range of energy efficient design solutions with and without photovoltaic (PV) panels are compared with an indication of the sensitivity of solutions to interest rates and energy escalation. PV panels are included in the facade analyses because they are required to achieve an nZEB performance level [4]. Within this article abbreviation of nZEB for nearly zero energy building is used according to the REHVA terms and definitions [12].

2. Methods

2.1. Overall research design

In the present study, a step-wise approach was used to derive the energy and cost optimal solutions. This helped to reduce the vast amount of possible combinations. Each step led to a consecutive one in the selection of simulation cases. The basis for the simulation was an open-plan generic single office floor model divided into 5 zones, as shown in Fig. 1. All HVAC solutions were considered constants in this study: district heating with radiators, an air-cooled chiller and balanced heat recovery ventilation with chilled beams. The office was operated five days in a week from 7:00 to 18:00. Day lighting control systems were used to optimize electricity consumption together with motorized shading in the second stage of this study. For more detailed information, see the paper [11]. Models were simulated using IDA-ICE 4.5 and a test reference year for Estonia [11].

Window sizes and insulation thicknesses were considered variables. Window sizes were calculated in the joint-research paper. For the calculation, the sill height and window height were constants, and window width was a variable, to satisfy the requirement of the daylight factor, which was set to 2%. In all, six different glazing types were selected for the first round of simulations with the aim of selecting optimal insulation thicknesses. In the following step, each facade was considered separately using the results of the first step to identify energy and cost efficient solutions. This became the basis for the third step, the determination of optimal PV panel size using NPV as a key performance indicator. The research methodology is summarized in Fig. 2.

In total, if do not consider the input and the output of research methodology, three steps were used to determine cost optimal and nZEB levels, including:

1. Determination of optimal external wall insulation thickness.
2. Assessment of cost optimal and most energy efficient solutions for each façade.
3. Calculation of optimal PV panel size to achieve nZEB level.

2.2. Building energy performance related initial investment costs and energy cost calculations

Investment cost calculations for windows were based on offers from three Estonian manufacturers. The manufacturers were provided with a list of window types required for this study. Only windows with clear low emissivity glazing were used. A low emissivity coating was used in the gaps between the panes. The best offer was selected as a basis for the calculations, as shown in