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Total Economy of Energy-Efficient Office Building Facades in a Cold Climate

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Declaration: Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for a doctoral or any equivalent academic degree elsewhere.

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Külmas kliimas asuvate energiatõhusate büroohoonete fassaadi energia- ja majandusanalüüs

MARTIN THALFELDT

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ABSTRACT

The main purpose of this study was to create a holistic understanding about total economy of office building facades including heating, cooling, electric lighting, daylight and operational cost to support knowledge-based façade design of low and nearly zero energy buildings. We created a generic office floor model, compared various window types and sizes, external wall insulation thicknesses, calculated the investment costs and performed economic analysis to develop cost-effective façade solutions in a cold climate. Minimum window sizes were chosen so that average daylight factor would not be below 2%. The criterion for cost-effectiveness was lowest 20 year net present value. In addition we investigated control algorithms of dynamic external venetian blinds and studied the effect of window model, interest rates, inflation, energy and construction prices on the outcome of office building facades analyses.

Currently, triple pane highly transparent windows with double low-e layer were the financially feasible solution and cost-effective external wall mineral wool insulation thickness was 150 mm. The optimal window-to-wall ratio of highly transparent triple windows was 25-40% and north orientation tolerated slightly larger glazed areas without any significant energy penalties. Higher energy efficiency could be reached with clear 4 and 5 pane windows with U-value between 0.3-0.2 $W/(m^2 \cdot K)$. Such windows have relatively good solar protection qualities and larger glazed areas decreased electric lighting and heating energy need in some cases, which compensated increased cooling energy, thus larger glazed areas could be used.

Automated external venetian blinds were an effective method of decreasing cooling loads by 40-70%, however an advanced control algorithm was needed to minimize the total delivered energy. We developed such an algorithm, which in principle had to reduce the risk of glare during working hours and keep room temperature below cooling setpoint when no one was present. Primary energy savings up to 6 kWh/m^2 were achieved with the algorithm.

Finally, we identified that economic variables and construction costs had the largest influence on the cost-effective façade solutions as single variables, however the combination of all variables had the largest impact on the outcome of façade analysis. Therefore energy efficiency specialists should keep themselves up to date about the prices of different façade-related solutions in order to do analysis correctly at any given time. Using standard or detailed window models did not remarkably affect the cost-effective façade solutions despite the differences in calculated primary energy. Therefore standard window models could be used in comparison of façade solutions at early-design phase, but the predicted energy use of an office building should be simulated with detailed models.

Keywords: office buildings, facades, energy efficiency, energy simulations, cost-effectiveness, solar shading, control algorithm.

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KOKKUVÕTE

Käesoleva töö eesmärk oli luua laiapõhjalisi teadmisi büroohoone fassaadide energia- ja majandusanalüüsi kohta, mis hõlmas energiakulu kontorite kütmisele, jahutamisele ja elektrivalgustusele, päevavalguse ligipääsu, kasutuskulusid ja ehitusmaksumust. Loodi lihtne büroohoone tüüpkorruse mudel, võrreldi erinevaid akna tüüpe ja suurusi, välisseina soojustuse paksusi, ehitusmaksumusi ja teostati majandusarvutused, et välja töötada kulutõhusad büroohoone fassaadilahendused külmas kliimas. Akna suurused valiti nii, et keskmine päevavalgustegur ei langeks alla 2% ja kulutõhususe kriteeriumiks oli madalaim 20 aasta nüüdisväärtus. Lisaks uuriti erinevaid automatiseeritud väliste ribikardinate juhtimise põhimõtteid ja teostati tundlikkuse analüüs, mille käigus hinnati akna mudelite, intressi, inflatsiooni, ehitus- ja energiahindade mõju büroohoonete fassaadi kulutõhususe analüüsi tulemustele.

Antud hetkel osutus majanduslikult mõistlikuks lahenduseks kolmekordsed kirkad aknad ja kulutõhus välisseina mineraalvilla paksus oli 150 mm. Optimaalne kolmekordse akna osakaal välisseinast oli 25–40% ja sealjuures võis põhjafassaadil kasutada suuremaid klaaspindasid oluliselt energiatõhusust kahjustamata. Parem energiatõhusus saavutati kirgaste nelja- ja viiekordsete akendega, mille soojusläbivus on vahemikus 0,3 kuni 0,2 $W/(m^2{\cdot}K)$. Sellistel klaaspakettidel on suhteliselt head päikesekaitse omadused, mistõttu akende suurenedes vähenenud kulu valgustuse ja mõningal juhul ka kütteenergiale kompenseeris suurenenud kulu jahutusele. Seega võis nendel juhtudel suurendada akende pindala.

Automaatselt juhitavad välised ribikardinad vähendasid efektiivselt jahutuskoormusi 40 kuni 70%, kuid kütte, jahutuse ja valgustuse energiakulu summaarseks minimeerimiseks on vajalik efektiivne juhtimispõhimõte. Töö käigus arendati välja selline juhtimisalgoritm, mille eesmärk on tööajal vältida valgusräigust ja hoida ruumitemperatuur alla jahutussüsteemi seadesuuruse, kui kedagi ruumis pole. Juhtimispõhimõttega saavutati primaarenergia vähenemine kuni 6 kWh/m^2.

Viimase sammuna selgitati välja, et intress ja inflatsioon ning ehitushinnad üksikmuutujana mõjutavad enim fassaadide kulutõhususe analüüsi tulemusi, kuid kõigi muutujate kombinatsioonil on suurim mõju. Energiatõhususe spetsialistid peaksid hoidma end kursis erinevate fassaadiga seotud lahenduste ehitushinnaga, et töötada välja antud hetkel sobivaim fassaadilahendus. Lihtsustatud ja detailse aknamudeli kasutamine simulatsioonides ei mõjutanud oluliselt kulutõhususe analüüsi tulemusi, kuid mõju arvutuslikule energiatarbimisele oli olemas. Seega pole aknamudeli valik oluline fassaadilahenduste võrdlemisel, kuid hoone tulevase energiatarbimise hindamisel tuleks kasutada detailset aknamudelit.

Märksõnad: büroohooned, fassaadid, energiatõhusus, energiasimulatsioonid, kulutõhusus, päikesevarjestus, juhtimispõhimõte

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Martin Thalfeldt

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CONTENTS

LIST OF PUBLICATIONS

This thesis is based mainly on data presented in the following publications in peer-reviewed journals:

I Thalfeldt, M., Pikas, E., Kurnitski, J., Voll, H. Façade design principles for nearly zero energy buildings in a cold climate. Energy and Buildings 67 (2013) 309–321.

II Pikas, E., Thalfeldt, M., Kurnitski, J. Cost optimal and nearly zero energy building solutions for office buildings. Energy and Buildings 74 (2014) 30-42.

III Thalfeldt, M., Kurnitski, J. External shading optimal control macros for 1- and 2- piece automated blinds in European climates. Building Simulation: An international Journal 8 (2015) 13-25.

IV Thalfeldt, M. Kurnitski, J., Voll, H. Comparison of simplified and detailed window models in office building energy simulations. Energy Procedia 78 (2015) 2076-2081.

V Thalfeldt, M., Kurnitski, J., Voll, H. Window model and price data sensitivity to cost-effective façade solutions. Journal of Building Performance Simulation (Submitted for publication, 18.01.2016).

AUTHOR'S CONTRIBUTION TO THE PUBLICATIONS

The author of the thesis is the main author of publications I, III, IV and V. The energy simulations and analyses of all publications were conducted by the author of this thesis. The methodology of all publications was developed together with all co-authors. The manuscript of papers I, III, IV and V was composed by the author. In I, II and V the construction cost and energy price information was obtained by co-author Ergo Pikas. Ergo Pikas also conducted financial calculations in I and II, however the author made financial calculations in V.

NOTATIONS

Abbreviations

DF	daylight factor
EPBD	Energy Performance of Buildings Directive
EU	European Union
HVAC	heating ventilation and air conditioning
NPV	net present value
nZEB	nearly zero-energy building
PV	photovoltaic
SEER	seasonal energy efficiency ratio
SFP	specific fan power
SHGC	solar heat gain coefficient
TRY	test reference year
VAT	value added tax
WWR	window-to-wall ratio

Latin letters

A	area, m^2
C_a	annual energy cost, €
C_g	global incremental cost i.e. net present value, €/m^2
C_I	energy performance related construction cost, €
D	average daylight factor, %
e	escalation of energy prices, %
E	emissivity
E_{ext}	outside horizontal illuminance under overcast or uniform sky
Ein	inside illuminance at a fixed point
$f_{pv}(n)$	present value factor for the calculation period of n years, -
M	clearness of glazing, -
R	mean surface reflectance, -; or market interest rate, %
R_R	real interest rate, %
R_I	inflation rate, %
T	scattered light transmittance, -
U	thermal transmittance, W/(m^2·K)

Greek letters

θ	sky angle, °
τ_{vis}	visible transmittance, -

TERMS

- **Nearly Zero-Energy Building according to EPBD [1], nZEB**
  "*A building that has a very high energy performance; the level of performance is defined by each Member State. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.*" Since EPBD does not give minimum or maximum harmonized requirements as well as details of energy performance calculation framework, it is up to the Member States to define what "a very high energy performance" and "to a very significant extent by energy from renewable sources" for them exactly constitutes.

- **Nearly Zero-Energy Building according to REHVA technical report no 4 [2]**
  "*Technically and reasonably achievable national energy use of >0 kWh/(m^2a) but no more than a national limit value of non-renewable primary energy, achieved with a combination of best practice energy efficiency measures and renewable energy technologies which may or may not be cost optimal.*" The report defines the system boundaries. The energy use system boundary includes all areas associated with the building where energy is used or produced, but excludes the building technical systems converting on-site renewable energy source, normally placed at least partially outside the building envelope. Building site boundary is the extension of the building technical systems converting on-site renewable energy source. Nearby boundary is the extension which has to be defined on national basis to include nearby energy production that is contractually linked to the building.

- **Nearly Zero-Energy Building in Estonia [3]**
  A building that has been constructed according to best available building practice using technically reasonable energy efficiency and renewable energy solutions. The primary energy of the building is above 0 kWh/m^2 and below a limit value that depends on the building type, which e.g. is 100 kWh/m^2 for apartment and office buildings and 50 kWh/m^2 for single-family houses respectively.

- **Net Zero-Energy Building, net ZEB**
  A building with non-renewable primary energy of >0 kWh/(m^2a).

- **Primary energy**
  Energy from renewable and non-renewable sources that has not undergone any conversion or transformation process [4]. Can be presented as measured (real use on TRY) or simulated (standard use on TRY) amount. PE takes into account the use of primary energy (for space heating, ventilation, domestic hot water, all electricity loads (including lighting and appliances (plug loads)) and environmental impact according to the energy source, with the weighting factors [2]. The Estonian regulation uses the following factors to calculate primary energy from delivered energy: wood, wood-based fuels, and other biofuels: 0.75; district heating: 0.9; fossil fuels (gas, coal etc.): 1.0; electricity: 2.0 [3].

- **Delivered energy**
  Annual energy delivered to the building from electricity or district heating network or by fuel in kilowatt-hours that corresponds to actual energy or heat content of delivered fuel. Delivered energy covers the buildings energy use that is not covered by local renewable sources. Delivered energy takes into account the efficiencies of building technical systems.

- **Energy need**
  Energy needed to assure required indoor climate, heat domestic hot water, electric lighting and plug loads without taking into account system efficiencies. In energy calculations energy needs consists of space heating and cooling, ventilation air heating and cooling, fans, domestic heat water, electric lighting and plug loads.

- **Cost-effective primary energy level**
  Primary energy value that corresponds to minimum life cycle cost that consists of construction cost and annual costs for energy and maintenance. 30 and 20 year life cycles are used for residential and non-residential buildings respectively.

1 INTRODUCTION

1.1 Background

Global warming and limited amount of fossil fuels are the main issues used to promote reducing global energy use. Although doubts have been stated whether the issues are critical, still energy use forms a significant proportion of the expenses of developed countries. Decreasing energy use can increase the competitiveness of countries, which makes it an essential target to aspire towards. According to different studies, buildings consume up to 40% of energy consumed nationally and produce 36% of the European Unions (EU) 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 according to the Energy Performance of Buildings Directive (EPBD) [1]. The directive states that EU countries must set minimum energy performance requirements for new buildings, for the major renovation of buildings and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls, etc.). Also all new buildings must be nearly zero energy buildings (nZEB) by 31 December 2020 (public buildings by 31 December 2018). The nZEB definitions, calculation principles and a few case studies have been described in [5] and the criteria for nZEB should be primary energy. Currently available quantifiable nZEB requirement available in 10 European countries have been described in [6]. There is remarkable high variation in the primary energy values due to different energy uses included and level of ambition, however in all cases the energy uses include heating and several also have cooling and lighting. Nevertheless it is obvious that in order to achieve nZEB requirements by 2021 in a cold climate energy-efficient façades are one important factor in the design of such buildings.

In Estonia, primary energy (PE) must be calculated to prove a buildings compliance with the energy performance minimum requirements. The PE is delivered energy minus exported energy multiplied by respective non-renewable PE factors and summed for each energy carrier used in the building. Non-renewable PE factors are 0.75 for biofuel excluding peat, 0.9 for district heat, 1.0 for fossil fuels and peat, 2.0 for electricity. The delivered energy is calculated using test reference year (TRY) and predefined standard use depending on building category [3, 7]. The energy use of all building categories includes space heating and cooling, supply air heating and cooling, domestic hot water (DHW), fans, pumps, electric lighting, appliances and plug loads. If a building has on-site renewable energy system, then its generation is reduced from energy use of heat or electricity depending on the system, resulting in the reduced delivered energy and in a surplus situation additionally in exported energy. An energy performance certificate is issued to apply/obtain a building permit and the energy performance class must be at least C for new buildings.

The definitions of energy performance classes of office buildings are the following:

1. Class D – PE≤210 kWh/m^2, minimum requirement for major renovation of office buildings
2. Class C – PE≤160 kWh/m^2, minimum requirement for new office buildings
3. Class B – PE≤130 kWh/m^2, low energy office buildings
4. Class A – PE≤100 kWh/m^2, nearly zero energy office buildings

Façade performance including windows, opaque elements and shadings has strong impact on heating, cooling and electric lighting energy needs as well as on daylight. In general energy-efficient facades can be designed with the following measures:

1. Appropriate size and type of windows
    a. Well-insulated multi-pane windows
    b. Vacuum insulated windows
    c. Electro-, thermochromics and other adaptable glazings
    d. Windows with phase change materials
    e. Etc.
2. Appropriate insulation of external walls
3. Solar shading
    a. Static horizontal and vertical shades
    b. Dynamic roller and venetian blinds installed externally, internally or between panes
4. Renewable energy production integrated to the façade
    a. Photovoltaic panels on the external walls or integrated into windows
    b. Solar thermal collectors

The list includes both conventional commonly used and innovative solutions, which still need research and development before the building industry is ready to implement them in a large scale. nZEB requirements become mandatory in a few years and therefore current thesis focuses mainly on the design of conventional solutions in a cold climate such as size and type of windows, external wall insulation thickness and control principles of dynamic shading. In addition we studied the effect of detailed window model, interest rates, energy and construction prices on cost-effective office building façade solutions.

1.2 Dimensioning of windows and insulation thickness

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. Unfortunately 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 level by 2021.

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. It is important to assure daylight and views outside which both have proven evidence on occupant satisfaction and productivity.

Several complex analyses have been made about façade design influence on buildings' energy consumption. Poirazis et al. [8] conducted office building energy simulations studying window-to-wall ratios (WWR) between 30% to 100%, different glazing, shading and orientation options. It was concluded that office buildings with lower WWR consume less energy. Similar analyses were made by Motuziene and Joudis [9] 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. [10] 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. [11] 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. [12] 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 heating, ventilation and air conditioning (HVAC) greatly. Boyano et al. [13] 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 [14]. 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 [15]. The results showed that lower U-values of windows result also in lower energy consumption and the optimum solar heat gain coefficient (SHGC) was 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. British Standard BS 8206-2:2008 "Lighting for buildings. Code of practice for daylighting" [16] states that average daylight factor should not be below 2% in office rooms. Voll and Seinre [17] 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 derived so that heating and cooling loads of office rooms would not exceed limit values.

1.3 Assessing cost-effectiveness

When buildings are designed, alternatives must be considered, including fenestration design, energy sources and building systems. In this context, cost-effectiveness 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-effectiveness.

The Energy Performance of Buildings Directive (EPBD) 2010 [1] recast stipulates that Member States should set requirements for energy performance of building at a cost-effective level in 20 and 30 year perspectives in case of non-residential and residential buildings respectively. The development of national requirements has been described by Kurnitski et al. [18], who presented calculation results for residential buildings using lowest net present value (NPV) of building costs as the criteria for cost-effectiveness. Kurnitski et al. [18] also studied cost-effective solutions for residential and office buildings. In the case of office buildings, 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-effective 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 labour 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 NPV, and this also allowed them to keep the calculations transparent. Other examples include Hamdy et al. [19], 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 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-effective 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. Ferrara et al. [20] did similar work using TRNSYS and a generic building optimization program GenOpt in case of a French detached house. Ganic and Yilmaz [21] used two Turkish climates to determine the cost-effective levels for an office building. In addition to cost-effective levels Becchio et al. [22] investigated solutions to reach net zero energy building level and calculated the extra costs of a detached house located in Turin, Italy. Zaca et al. [23] also conducted cost-effectiveness analysis of multi-residential buildings in a Mediterranean climate in. Baglivo et al. [24] studied the cost-effective solutions of a mono-residential building in a warm climate and in addition did some sensitivity analysis regarding discount rate and its development, which did not affect the optimal solutions. Basinska et al. [25] analyzed the effect of building shape, heat source, inflation, investment costs and energy prices on the optimal residential building solutions in Polish conditions and concluded that changes in all parameters lead to changes in energy efficiency requirements in time.

Pikas et al. [26] introduced a methodology to determine the cheapest solutions to reach cost-effective, low or nearly zero energy building level based on examples of two apartment buildings. They also showed that compared to [18] the cost-effective primary energy level had shifted from 140-150 kWh/m^2 to 110 kWh/m^2 during 2-3 years. In addition to studies on new buildings, similar analysis has been conducted for apartment building renovation projects in Estonia by Kurnitski et al. [27] and Kuusk et al. [28] and by Paiho et al. [29] for the location of Moscow. Stocker et al. [30] studied a school building and in addition to defining the cost-effective primary energy level concluded that energy prices and interest rates most influenced the results. Chidiaca et al. [31] considered the most effective energy retrofit measures for renovating office buildings. Energy retrofit measures range from physical changes to a building to changes in operational practices including advanced controls and efficient lighting. They concluded that conventional methods are adequate for saving energy, but they did not consider costs in their analysis. Life cycle cost analysis was proposed as a part of “Integrated Energy-Efficient Building Design Process” by Kanagaraj and Mahalingam [32]. It was found that considerable energy savings could be achieved using the process. Life-cycle cost analysis was also used by Kneifel [33] in his simulation-based case study of several building types including also office buildings.

Kim et al. [34] tried to develop a data mining approach for designing energy-efficient buildings in the early design stages by using building information models. 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.

1.4 Solar shading

External shading is considered an effective measure for improving indoor climate and energy performance of buildings. Cooling needs and summertime indoor temperatures are decreased by blocking direct sunlight and another benefit is that glare is avoided, on the other hand heating and lighting energy increases due to any kind of external shading. The energy performance of buildings under design is being evaluated more and more often with energy simulations. However, any kind of dynamic shading requires a proper control principle to increase the reliability of calculations and minimize future energy costs.

Dynamic shading may be adjusted either manually by building users or automatically with a control system. Besides the different nature of position adjustment of automated and manual blinds, there is no clear understanding how people operate the shades, which makes predicting the effect of shading difficult. Mahdavi et al. [35] studied the behaviour of occupants in 3 Austrian office buildings and stated that the manner of controlling shades may differ significantly building by building. Several other studies have pointed out that the position of motorized shading is changed more frequently than that of manual blinds, whereas when not controlled automatically a significant proportion of people formulate their decisions about blind position over a period of weeks or months, and not days or hours as was concluded by Van Den Wymelenberg [36]. Yao [37] studied the energy performance of manually controlled solar shades and concluded that using ideal control principle in energy simulations might result in overestimating energy savings by 16-30%. This suggests that if energy and indoor climate are considered, automated blinds prove to be a better solution than manually controlled ones. Colaco et al. [38] referred to a common belief that the use of “artificial intelligence” for building automation can elevate energy saving besides optimizing visual and thermal comfort. Lee et al. [39] reported significant reductions in cooling loads after studying the effect of window opening and blind operation, whereas one of the influences pointed out was choosing operating hours and proper cavity control. Similarly, Shen and Hong [40] reported possible savings up to 43% as a result of integrated electric lighting, window transmission and HVAC control. Yao [41] combined field measurements with energy and indoor climate simulations and reported that movable solar shades offer reaching substantial improvements in both energy efficiency and indoor environment quality.

In a cold climate it is essential to utilize as much of sun radiation during heating period as possible, however the heating need of low or nearly zero energy office buildings depends remarkably on the office use and internal gains [42]. The possible energy penalty caused by external shading in the climate of

Scotland was reported by Littlefair [43]. Therefore simple control principles of automated blinds depending only on external conditions may not be optimal and might even increase energy consumption [44]. The importance of proper control strategy especially in the case of balanced heating and cooling has been also stressed by da Silva [45]. One of the crucial aspects of automated dynamic solar shading is choosing the control parameters. In their study, Daum and Morel [46] emphasize that at least two parameters should be used and the importance of internal temperature stands out. Controlling shades based on solar radiation is often used, however illuminance threshold might be a more appropriate solution [47]. According to recent studies, the control principle of shading is essential, which makes a need for studies regarding blind control algorithms evident.

1.5 Detail and accuracy of simulation models

Several countries in the European Union require making energy simulations to prove new buildings compliance with energy performance minimum requirements. It is reasonable to use the energy model of a building under design to optimize architectural and technical solutions. Simulation-based analysis helps to minimize energy use or reach a certain level of energy efficiency at lower cost. However energy and financial calculation results always include a certain degree of error due to simplifications made in the methodology and simulation models and in addition aspects that we cannot predict very accurately such as the occupancy profile or the economic situation. Some of these errors may affect the choice of solutions to be used in the building and it is important to identify the factors that need to be focused on more thoroughly during the early stage design analysis.

As stated previously façades have a large effect on the building energy use while the size and properties of glazed areas are especially important. Numerous papers on optimizing window areas have been published of which some have also have treated dynamics of glazing parameters depending on the weather conditions. Kurnitski et al. [48] showed in their article that the temperature difference between inside and outdoor conditions affects the thermal transmittance of glazing significantly. Petersen [49] calculated the heating energy of a building using a constant declared U-value of glazing and a more accurate dynamic U-value that varied for each hour of the climate year. Constant U-value could lead to significant under estimation of heating energy in cold climates and Petersen suggested using the described dynamic method for energy calculations. Grynning et al. [15] calculated the U- and g-values of glazing, which assured the positive effect of window area on the energy use of a building. They compared three methods in their investigation and concluded that results depended on the method used. Arıcı et al. [50] carried out a numerical study of the properties of double, triple and quadruple glazing and pointed out that the nature of energy balance of glazing depends on external conditions.

All the previously mentioned articles used energy simulations and it essential to determine that the used software is validated. Roux et al. [51] developed a glazed space simulation model and successfully validated it. We are using a dynamic energy and indoor climate modelling tool IDA-ICE [52] in our analysis and several studies have also included this software in the analysis. In 2003-2007 Loutzenhiser et al. [53] validated several dynamic energy and indoor climate simulation tools and made suggestions for improving the softwares. IDA-ICE 4.0 was among the studied programs and it performed well in comparison with other softwares. Validation processes of IDA-ICE have been described in [54] and [55]. Crawley et al. [56] compared 20 energy simulation softwares and the study indicated that IDA-ICE is suitable for analysis of glazed areas. Hilliaho et al. [57] measured air temperatures in glazed and unglazed balconies and compared them with simulated ones, which were obtained by using IDA-ICE 4.6. The correlation was good and highest modelling accuracy was reached by using detailed window and zone climate models.

Generally energy specialists use standard window models with constant U-values in energy simulations, however the thermal resistance of glazing varies depending on the outdoor temperature, wind speed and direction. Several dynamic simulation softwares including IDA-ICE [52] allow creating detailed glazing models consisting of panes, cavities and shading devices. Detailed window models take the changes in external conditions into account and calculate the energy balance of glazing more accurately than simple models. In [58] we conducted energy simulations to determine the differences in calculated energy use of a detached house in Estonia if standard and detailed window models were used and concluded that gaps in heating and cooling needs were up to 7% and 23% respectively. We recommended using detailed glazing models, but also suggested a correction factor of 1.15 for standard triple glazing model, when calculating only the heating energy.

1.6 Objective and content of the study

The purpose of our work was to:

- Create holistic understanding about total economy of facades including heating, cooling, electric lighting, daylight and operational cost.
- Give guidelines of office buildings façade design from the perspective of energy-efficiency and daylighting to architects, engineers, real-estate developers etc.
- Determine an optimal control principle for external shading on different facades

- Quantify the gap between the calculated energy need of a building model with simplified and detailed windows and suggest a method for reducing the gap
- Identify the most important variables affecting the outcome of cost-effectiveness analysis of office building facades

The main research questions were:

- What are financially most reasonable window types, sizes and external wall insulation thicknesses?
- How to control automated dynamic venetian blinds?
- What should be the detail of window models used in energy simulations and how does it affect calculated energy use?
- Which factor most influences cost-effective façade solutions?

The work done to answer the questions has been published in four peer-reviewed journal papers and one peer-reviewed open-access journal paper that was presented at the 6th International Building Physics Conference "Buildings Physics for a Sustainable Built Environment".

In papers I and II 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 $W/(m^2 \cdot K)$ 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 analyse energy performance. Lower limit of window size was determined by the average daylight factor criterion of 2%, but cases with larger windows were also analysed. 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. Required investment costs and NPV were calculated for a period of 20 years (non-residential buildings) by considering current construction and energy costs, escalation and inflation.

In paper III an effective control principle for a cold climate suggested by Thalfeldt and Kurnitski [59] was developed further and in addition the façade performance in the climates of Paris and Athens were studied. The key criterion for shading control principles assessment was energy use, however the duration of unobstructed view from windows and the simplicity of the shading system were also considered. Detailed shading control macros were developed in simulation software IDA-ICE. A generic office floor was analysed and the cases were chosen so that the proportion of cooling in total energy use varied. The numbers of window panes, window-to-wall ratios (WWR) and external wall U-values ranged from 3 to 5, 25% to 60% and 0.09 to 0.16 W/(m^2 K) respectively.

In paper IV simulated energy needs with detailed and standard window models were compared. We composed a generic open-plan office floor model in IDA-ICE 4.6 [52] with triple, quadruple and quintuple windows with varying sizes. All cases were created with both standard glazing and detailed glazing models of which the latter took into account the changing external and internal conditions while simulating the energy balance of glazing. The results presented in this article are the bases for further work regarding the effect of window model on the outcome of façade analysis.

In paper V the information about cost-effective facade solutions developed in papers I and II was updated. The purpose was to illustrate the importance of different variables on the outcome of such analysis. The variables include accuracy of window models in simulations, construction costs, energy prices, interest rate and inflation. The article presents office building facade analysis with standard and detailed window models and also advanced shading control algorithms developed in paper III. In addition we updated energy prices, construction costs, interest and inflation rates to identify the most important variables in facade design and determine the possible changes in optimal facade solutions. The NPV of a 20 year period was calculated for each studied facade solution to assess financial feasibility and we compared the solutions while changing the variables. Triple and quadruple windows with varying sizes, with and without external shading in South, East, West and North orientations were studied. In addition we investigated external walls with insulation thicknesses 150, 200 and 250 mm.

2 METHODS

The outcome of this thesis was reached in the following steps:

1. Investigating energy-efficient and cost-effective façade solutions in Estonian climate based on energy simulations with a generic office floor model combined with economic calculations.
2. Developing an efficient control algorithm for external venetian blind in the climates of Tallinn, Paris and Athens.
3. Describing the effect of standard and detailed models, interest rates, energy and construction prices on energy calculations and cost-effective office building solutions

We used similar office floor models, glazing and shading types and methods for energy and economic calculations throughout the study. The methodology section begins with description of initial data about the simulation models, calculation principles and variables used in the sensitivity analysis. The last paragraph describes the case selection procedures.

2.1 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 (Figure 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 x 16.8 m.

As there are more than 200 district heating networks in Estonia, the main locations of new office buildings are covered by district heating networks. Therefore district heating was used in all cases as a heat source. The rooms were heated with radiators (ideal heaters in the model).The cooling system consisted of a chiller and room conditioning units (ideal coolers in the model), which is a common solution in case of new office buildings. Mechanical supply and exhaust ventilation with heat recovery was used with supply air temperature 18 °C, which allowed to efficiently cover a large proportion of space cooling needs. The supply air temperature 18 °C does not cause draught with properly chosen room conditioning units such as active chilled beams, if common sizing guidelines are followed [60]. The heating and cooling room temperature setpoints were 21 and 25 °C respectively, which are common in Estonian HVAC systems design practice and compulsory values when proving new office buildings' compliance with the energy performance requirements [3]. 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. The position of workplaces used for the control is shown in Figure 1. The initial data of simulation model is shown in Table 1. The energy simulations were conducted with well-validated simulation tool IDA-ICE 4.5, 4.6 and 4.7 depending on the time when simulations were conducted [17] and the test reference year of Estonia was used [18]. Some simulations were made for comparative purposes with Central European climate data, ASHRAE TRY for Paris and Athens was used [19]. The non-renewable primary energy factor for district heating was 0.9 and for electricity 2.0.

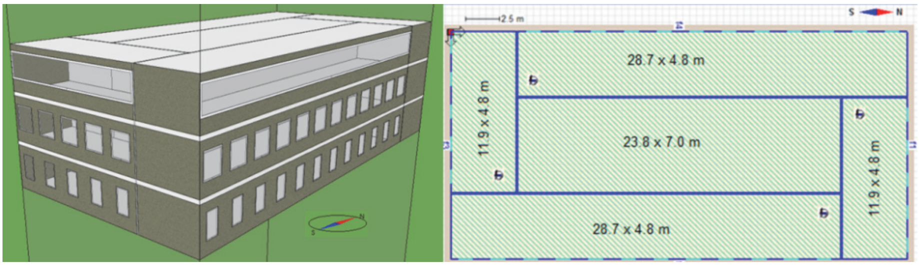


Figure 1 The generic model of single floor of an office building constructed with 2.4 m room module – plan and 3D view. The locations of workplaces used for control of lighting are marked in the plan.

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

Occupants, W/m^2	5
Equipment, W/m^2	12
Lighting, W/m^2	5[a]
Temperature set point for heating and cooling	+21 and+25 °C
Air flow rate	1.5 $l/(s{\cdot}m^2)$; 35 l/s
Illumination setpoint, lx	500[a]
Frame ratio of windows, %	15
Heating system (radiators) efficiency, -	0.97
Heat source (district heating) efficiency, -	1.0
Cooling system losses, % of cooling energy need	10
Mechanical cooling SEER, -	3.5
Ventilation SFP, $kW/(m^3/s)$	1.3
Temperature ratio of heat recovery, %	80

[a] – initial comparison of standard and detailed window models was conducted with lighting installed power 7 W/m^2 and without demand-based control.

2.2 Daylight calculations and minimum window size

Daylight factor is the ratio of illuminance at a point on given plane due to the light received directly or indirectly from a sky of assumed or known luminance distribution, to the illuminance on a horizontal plane due to an unobstructed hemisphere of this sky, excluding the contribution of direct sunlight to both illuminances [61]. In other words, the daylight factor on desktop of a room is the relationship of illuminance measured on the desktop and on the roof of the building during overcast sky conditions (Figure 2). Since direct radiation does

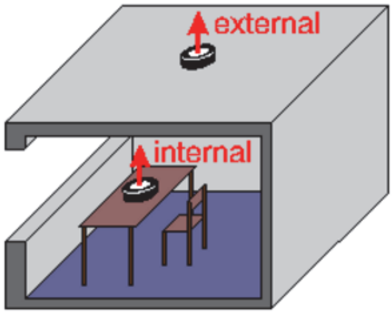


Figure 2 The daylight factor is the relationship of illuminances measured on the desktop (internal) and on the roof (external) during overcast sky conditions [62].

not affect the daylight factor, it is not dependant on façade orientation, but is affected by surrounding objects. In this study we assumed that there were no adjacent buildings. The standard BS 8206-2:2008 states that the average daylight factor in offices should not be below 2% and with daylight factor of 5% and above, usually there is no need for electric lighting during daytime.

The formula for calculating daylight factor based on measurement is the following [62]:

$$DF = 100 \cdot E_{in} / E_{ext} \quad (1)$$

Where DF – daylight factor at a fixed point, %; E_{in} – inside illuminance at a fixed point, lux; E_{ext} – outside horizontal illuminance under an overcast or uniform sky, lux.

The average daylight factor of office rooms is calculated according to the following formula [9]:

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

where, D - average daylight factor, -; T – scattered light transmittance (90% of visible transmittance τ), -; Θ – sky angle, 80°; m – clearness of the glazing, 0.9; A – total area of all interior surfaces (incl windows), 109.4 m^2; A_w – total glazed area of windows, m^2; R – mean surface reflectance, 0.5

The glazing area can be calculated with the following formula:

$$A_W = \frac{D \cdot A \cdot (1 - R^2)}{T \cdot \theta \cdot m} \qquad (3)$$

Formula 2 does not take into account room geometry, overestimates the effect of glazed areas below work plane [63] and is not very accurate with rooflights, especially domes [64]. However, in case of side lit rooms, the error

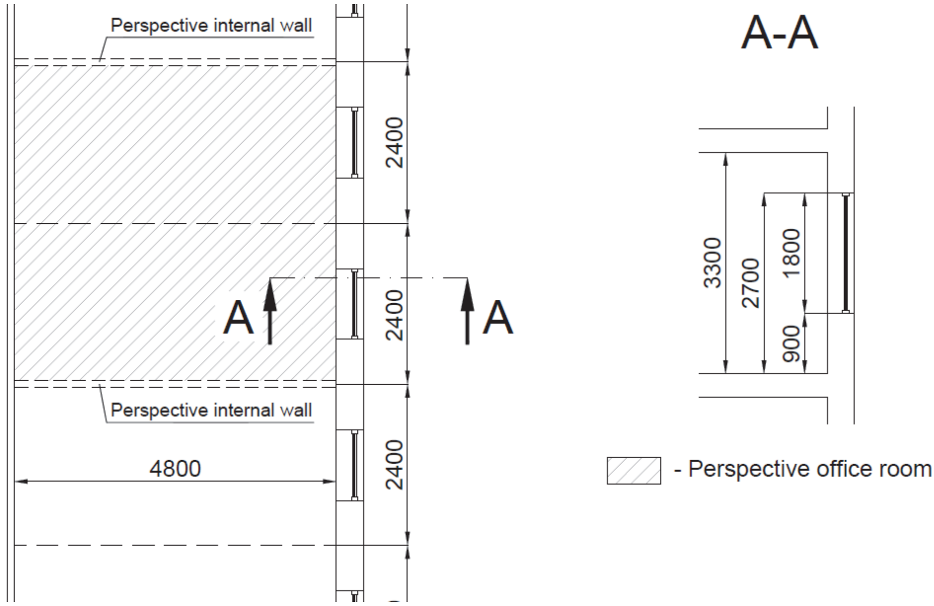


Figure 3 Floor plan of the open plan office module (2.4 m) and the section showing window and room height.

remains within ±10% and the methodology is suitable for early stage design [64]. The development of the formula has been reported in [64, 65].

The criterion of 2% average daylight factor [9] in the daylight zone (up to 4 m from the external wall) was used to calculate minimum window sizes. The window widths were chosen as small as possible with a step of 50 mm so that average daylight factor would meet the criterion. The open-plan offices were divided into 2.4 meter wide modules and office rooms consisting of two modules were used in daylight and cooling load calculations. The bottom edge of all windows was 0.9 m from the floor and the height was 1.8 m. The description of perspective office room is shown in Figure 3.

A few softwares allow doing precise daylight calculations with and Radiance developed by Lawrence Berkley National Laboratory is a commonly used program using ray-tracing methods [66]. IDA-ICE 4.7 can be coupled with Radiance for daylighting calculations so, that input data is inserted into IDA-ICE, which feeds it into Radiance and the results can be obtained through IDA-ICE user interface. We used this possibility to compare the simplified daylight factor calculations with modelling and these presented in the Results section. The average daylight factor of zones consisting of 2 modules was calculated with various glazing types and window sizes.

Dynamic daylight calculations are rather time-consuming and coupled with energy and indoor climate modelling the duration of simulations increases further. Therefore, currently IDA-ICE makes several simplifications, when calculating daylight levels during dynamic simulations, which are illustrated in Figure 4. First of all, if a window is partly shaded, the transmitted part of the

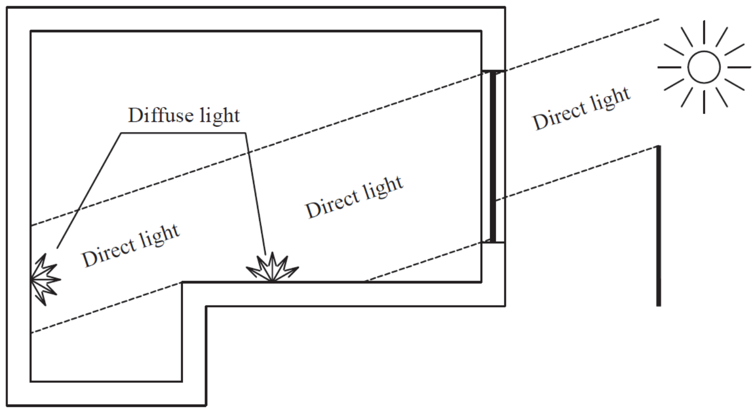


Figure 4 Daylight calculation principles of IDA-ICE.

light is emitted uniformly over the other side of the window in the specific direction. When the transmitted light hits a surface in the zone, then it is reflected as diffuse light uniformly over its entire area in every direction. In “Energy” zone models, view factors are calculated on the basis of surface areas only, which results in an overestimation of radiation exchange between surfaces far away from each other and vice versa. In “Climate” zone model, the correct view factors are calculated, but only for shoebox zones and this has been implemented in the latest versions of IDA-ICE. We used “Energy” zone models in all calculations.

Another parameter to evaluate daylighting quality is daylight autonomy, which describes the percentage of working hours, when electric lighting is not needed. In the current study we did not calculate daylight autonomy, however it was assessed indirectly through lighting electricity use. The lighting was controlled according to daylight levels and lower lighting energy use meant longer periods of time, when electric lighting was unnecessary, thereby higher daylight autonomy.

2.3 Detailed and standard window models

IDA-ICE offers the opportunity to model buildings with either detailed or standard window models, which affect the outcome of simulations. Both window models were used in the studies that this thesis is based on. The glazing properties in product sheets are generally given at standard conditions according to ISO 15099 i.e. at temperature difference of 20 °C [67]. When room temperature is 21 °C, then in static conditions the declared U-value corresponds to the actual one if outdoor temperature is 1 °C. In case of lower temperatures, the glazing thermal transmittance is higher. The outdoor temperatures are below 1 °C for most of the heating period in a cold climate of Estonia, which is described by the test reference year [68] (Figure 5). Therefore the thermal transmittance of windows during the heating period is generally larger than in standard conditions.

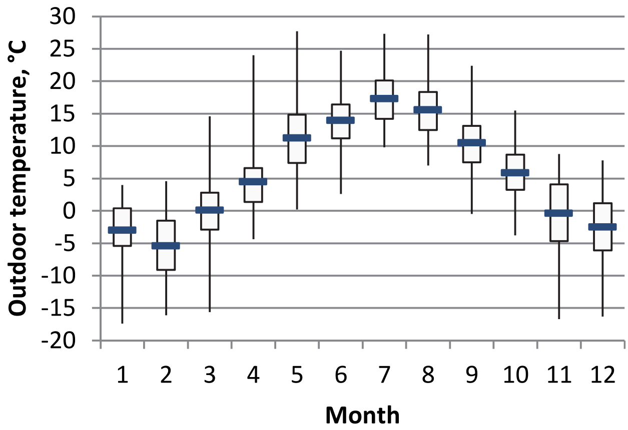


Figure 5 The minimum, maximum and average temperatures of each month of Estonian test reference year. The average values are indicated with dark markers and the 25th and 75th percentiles are also presented.

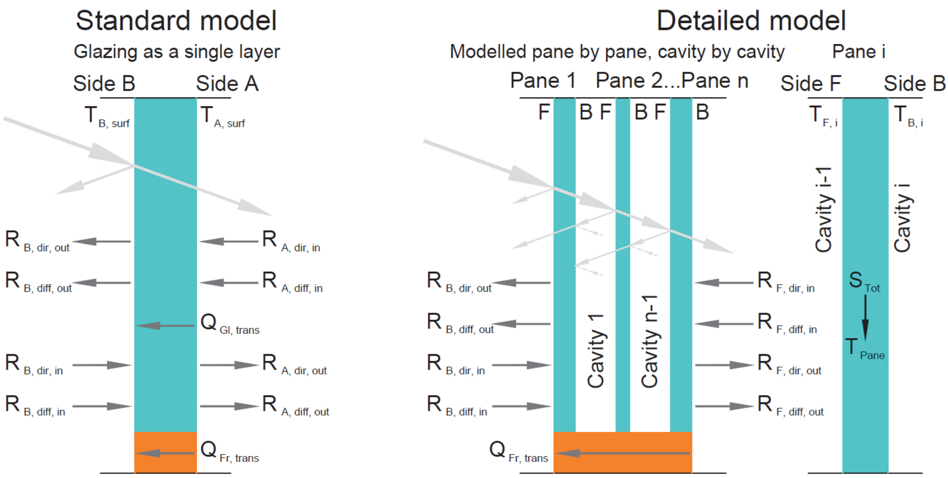


Figure 6 The calculated variables of standard and detailed glazing models in IDA-ICE. Code: T – temperature of a surface or pane; R – diffuse/direct radiation in/out of a pane/glazing; Q – heat transmission of glazing/frame from surface to surface; S – total absorption heat flux.

Another important difference is that standard glazing models use and an angle dependence to calculate the solar transmittance and absorptance of glazing, while the energy balance of detailed window models is calculated based on physical formulas. Each pane and their interactions of detailed glazing are taken into account with detailed window models as shown in Figure 6.

The figure also describes the standard window model. Detailed window model calculation principle has been composed according to the methodology of ISO 15099 [67], which however does not cover the calculation of a single pane angular properties. The implemented methodology for calculating the angular properties has been documented in ASHRAE Fundamentals [69]. The current description of detailed and standard window models was also published in [70].

2.4 Building envelope

2.4.1 External walls

The type of wall selected for the research was the concrete sandwich panel, being one of the most typical solutions found in Estonian office buildings. The structural layer and outer layer of the selected element type were kept constant, and insulation thickness was made a variable. The gross section of the typical wall is shown in Figure 7 and the U-values of the structure depending on the insulation thickness are given in Table 2. Unit prices for the exterior walls including materials, installation and project management costs are given in Section 2.4.4.

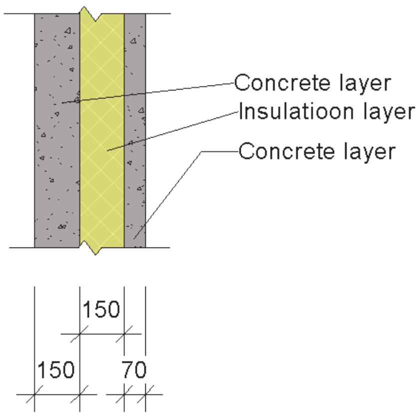


Figure 7 Gross section of the typical exterior wall.

Table 2 Insulation thicknesses and U-values of external wall.

Insulation thickness, mm	U-value, W/($m^2 \cdot K$)
150	0.20
200	0.16
250	0.13
300	0.11
390	0.09

2.4.2 Windows and glazing

The current work analysed various glazing types with number of panes ranging between 2 and 5, glazing U-values between 0.21-1.4 W/($m^2 \cdot K$) and SHGCs between 0.31-0.61. The description of all glazing types studied is shown in Table 3. Variant names are made up so that the first number stands for the number of panes, “C” for clear, highly transparent, “D” for tinted solar protection and “SC” transparent solar protection windows. “2/C or 2/Arg“ stands for a double glazed, clear window. The double, triple and quadruple glazing properties were calculated using window manufacturers’ calculation tools and verified with IDA-ICE calculating the detailed window model parameters at standard conditions of ISO 15099 [67]. Generally low emissivity coating (ε=0.03) was used in all gaps between panes (except for glazing with air fillings). In case of solar protection window cases the outer pane was a solar protection glass with low emissivity also. The quintuple glazing representing not a standard product was calculated with detailed window model of IDA-ICE which is based on the method of [67].

We studied double and triple glazed windows that were both highly transparent or with solar protection panes. It is remarkable that the highly transparent quadruple and quintuple glazing cases have solar heat gain coefficient (g-value) as low as 0.37 and 0.31 respectively, so basically they can also be considered as solar protection glazing, therefore quadruple and quintuple glazings with solar protection panes were not considered.

Table 3 Description of clear and solar protection glazing types.

Glazing type	No of panes, coatings	U-value, W/(m^2·K)	GSHC, -	τ_{vis}, -	Gas filling	Gap width, mm
2/C or 2/Arg[b]	2, 1x low-e	1.1	0.61	0.78	90% Ar	18
2/Air	2, -	1.4	0.61	0.78	100% air	18
2/D	2, 1 x tinted solar	1.0	0.27	0.50	90% Ar	18
3/C[a] or 3/Arg[b]	3, 2 x low-e	0.58[c]	0.46[c]	0.70	90% Ar	18
3/Air	3, 1 x low-e	1.1	0.52	0.70	100% air	18
3/SC	3, clear solar+low-e	0.55	0.36	0.60	90% Ar	18
3/D	3, tinted solar+low-e	0.55	0.24	0.45	90% Ar	18
4/C[a] or 4 Kry[b]	4, 3 x low-e	0.32	0.37[c]	0.63	95% Kry	12
5/C[a] or 5/Kry[b]	5, 4 x low-e	0.21	0.31[c]	0.56	95% Kry	12

[a] – Detailed window models were created during the analyses and the parameters in this table are given according to ISO 15099:2003/E at internal and external temperature difference of 20 °C. The U-value was dynamic during simulations in case of detailed windows and was calculated also according to ISO 15099:2003/E.
[b] – The glazing type name including the gas filling argon (Arg) or krypton (Kry) was used in the external wall insulation thickness analysis in Section 3.1.5.
[c] – The values given in the table were used in case of standard window models in [71, 72]. The GSHC of glazing types 3/C, 4/C and 5/C was 0.49, 0.36 and 0.24 respectively in due to a “bug” in the detailed window model of IDA-ICE in the previous versions. These values were used in [44, 73].

Figure 8 displays the most studied triple and quadruple highly transparent glazing types and the positioning of low-emissivity coatings. The outer pane coating had low transmittances in case of solar protection glazing types. The detailed window models were modelled pane by pane and the parameters of the panes used in this study are illustrated in Table 4.

Currently, there are aluminium window frames with U-values 0.7 W/m^2K) and higher available on the market [74] and some of the examples are shown in Figure 9. The windows can be either openable or not and we assumed that windows are not openable as is common in new office buildings. This decreases the frame ratio and we assumed that the frame ratio was 15% in all cases to simplify the calculations. Local supplier provided information about window frames with U-value 1.2 $W/(m^2K)$ at the time of the study, which were used with double windows. In case of triple windows we used frames with U-value 0.8 $W/(m^2K)$. As quadruple and quintuple windows are at present rarely used, we assumed that the frame technology develops further by the time such technology gains a significant market share. Therefore we assumed that the U-values of the respective frames equals the U-value of glazing.

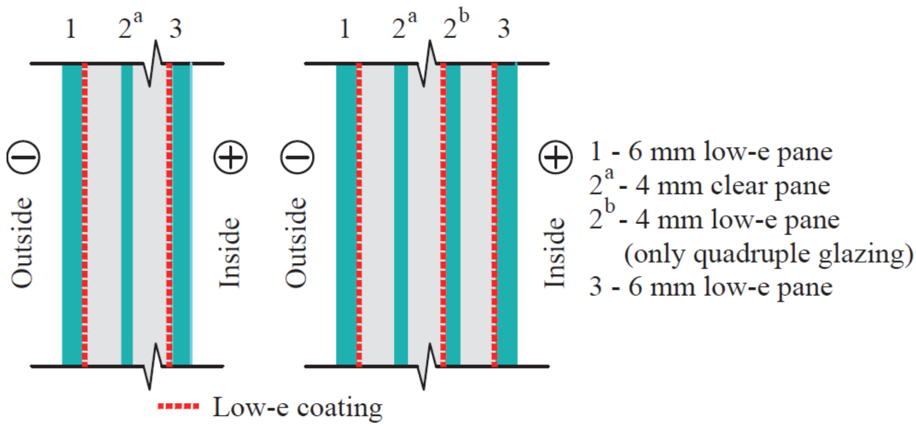


Figure 8 The construction of triple and quadruple glazing and positioning of low-emissivity layers. The same glazing types were also studied in [70].

Table 4 Glass pane properties of detailed window models.

	Low-e	Clear
Thermal conductivity, W/(mK)	1.0	1.0
Total shortwave transmittance, -	0.62	0.85
Total visible transmittance, -	0.88	0.90
Outside total shortwave reflectance, -	0.23	0.08
Outside visible reflectance, -	0.06	0.08
Outside longwave emissivity, -	0.89	0.89
Inside total shortwave reflectance, -	0.27	0.08
Inside visible reflectance, -	0.05	0.08
Inside longwave emissivity, -	0.03	0.89

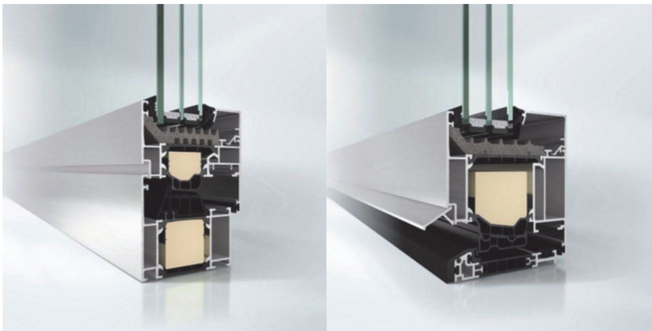


Figure 9 The construction of an aluminium window frame with U-value 1.2 W/(m^{2}K) (left) and 0.7 W/(m^{2}K) (right)[75, 76].

2.4.3 Shading devices

The studied façade solutions had either internal or external blinds. When detailed window models were used, then we used venetian blinds constructed of opaque slats with 80 mm width and 70 mm distance between them and the performance of windows was modelled according to physical formulas. The parameters of the slats are given in Table 5. When standard window models were used, then the parameters of the glazing were multiplied by respective factors. During initial façade analyses we used the multipliers of IDA-ICE database resources “Internal blind (BRIS)” and “External blind (BRIS)”. However the final simulations with standard window models were done using the multipliers calculated based on detailed window model properties at reference conditions of ISO 15099 [67]. The used multipliers for glazing properties of standard windows are shown in Table 6.

Table 5 Slat material properties of detailed window models.

Shortwave, longwave and visible transmittance, -	0.0
Upper side reflectance, -	0.7
Lower side reflectance, -	0.4
Emissivity, -	0.9
Slat thickness, mm	0.6
Heat conductivity, W/(m·K)	160

Table 6 Multipliers of standard window model parameters to take into account the effect of shading when drawn.

Window type	Shading type	Multiplier, -			
		SHGC	Solar transmittance	U-value	Diffusion
Any	Internal blind (BRIS)	0.65	0.16	1.0	1.0
Any	External blind (BRIS)	0.14	0.09	1.0	1.0
3/C	Internal venetian blinds	0.86	0.32	1.0	0.397
3/C	External venetian blinds	0.28	0.26	1.0	0.261
4/C	Internal venetian blinds	0.91	0.32	1.0	0.402
4/C	External venetian blinds	0.28	0.26	1.0	0.247

2.4.4 Construction costs

This section describes all the necessary information about construction costs obtained from Estonian manufacturers. We performed some sensitivity analysis, which included cost data from years 2013 and 2015 and we have presented the costs of both years for relevant cases. Table 7 illustrates the insulation thicknesses, U-values and construction costs the studied external wall cases.

Three window manufacturers recommended a list of glazing types for this study. The offer with lowest price was selected as a basis for the calculations, as shown in Table 8. Together with unit prices for glazing, the manufacturer provided a profile system with a U-value of 1.2 W/(m²K) and a price of 25 €/m². In general, the cost of windows increases as the quality and number of panes increases.

Table 9 presents the cost of windows including glazing, aluminium profiles, materials, installation and project management costs. The window affects the specific cost remarkably due to the changing proportions of glazing and frame. The table presents the cost information about all the window types and sizes investigated.

Unit costs for motorized shading systems were provided by a local reseller (Table 10). Front-mounted external venetian blinds with 80 mm slats were used. Unit prices for the motorized blinds include materials, installation and project management costs.

Table 7 Insulation thicknesses, U-values and investment costs of external wall.

Insulation thickness, mm	U-value, W/(m²·K)	Investment cost, €/m² 2013	2015
150	0.20	131.2	144.3
200	0.16	136.0	149.6
250	0.13	140.8	154.9
300	0.11	145.7	-
390	0.09	154.4	-

Table 8 Glazing investment cost per m².

Glazing type	Investment cost, €/m² 2013
2/Air	30.1
2/C or 2/Arg	37.1
3/Air	42.4
3/C or 3/Arg	46.6
4/C or 4/Kry	118.8
5/C or 5/Kry	201.5[a]

[a] - The cost of quintuple glazing is hypothetical

Table 9 Cost data of windows, including both glazing units and aluminium profiles with thermal breaks.

Glazing type	Window size, mm	Window-to-wall ratio, %	Window cost, €/m^2	
			2013	2015
2/Air	950 x 1800	21.6	110.5	-
2/C or 2/Arg	950 x 1800	21.6	117.5	-
3/Air	1050 x 1800	23.9	117.8	-
	1050 x 1800	23.9	122.0	109.8
3/C or 3/Arg	1650 x 1800	37.5	104.7	94.2
	11900 x 1980	60.0	78.6	70.7
	1150 x 1800	26.1	190.1	209.1
4/C or 4/Kry	1650 x 1800	37.5	176.9	194.6
	11900 x 1980	60.0	150.8	165.9
	1300 x 1800	29.5	267.7	-
5/C or 5/Kry	1650 x 1800	37.5	259.6	-
	11900 x 1980	60.0	231.0	-

Table 10 External venetian blind costs depending on the size of the window.

Window size, mm	Cost per window, €/pc	
	2013	2015
1050 x 1800	603.0	542.7
1150 x 1800	618.0	556.2
1300 x 1800	643.0	578.7
1650 x 1800	703.0	632.7
11900 x 1980	3372.0	3034.8
27800 x 1980	8132.0	7318.8

2.5 Shading control principles

In the current study we assumed that external venetian blinds were automated, whereas internal blinds were controlled manually. Regardless of the control method, we needed to model the behavior of blinds during the simulations. The initial façade analysis was done with a simple control principle. Either external or internal blinds were automatically drawn, when total irradiance on the façade exceeded 200 W/m^2 to avoid glare. The lighting and shading control principle was adopted from [77].

Our initial studies showed that simple shading control algorithms are ineffective and decided to develop an advanced control algorithm for the climate of Tallinn, Paris and Athens. The work was based on a simple office room model with external and internal venetian blinds. Figure 10 depicts such a solution where motorized venetian blinds (marked with 1) have been installed outside the window that are controlled using a multi-sensor on the ceiling (2) for detecting occupancy and measuring illuminance levels on desktop and the room user can choose the control parameters from control panel on the wall (3), where also room temperature is measured. The slat angle of venetian blinds may be adjusted evenly over the entire shade or it can be divided into two parts to block direct radiation on the workplace with the lower part but allow access of daylight from the upper part, whereas 2-piece blinds also need an additional actuator. The primary goal of occupancy monitoring is to prevent unnecessary electric lighting when nobody is present, however it can be used for blind control also to determine whether avoiding glare is necessary. Besides the elements shown in Figure 10 there also might be sensors for measuring vertical irradiance on facades for effective blind control and wind measuring is also necessary for detecting conditions that might harm the blinds.

The study of Thalfeldt and Kurnitski [59] confirmed that in a cold climate external shading should be controlled according to internal temperature and desktop illuminance. While drawn shading decreases cooling needs, it increases heating and especially lighting energy use, furthermore the view is obstructed. The question of which is more important - maximizing daylight utilization or minimizing cooling needs – remained unanswered. The main goal of this study was to develop a simple control algorithm for minimization of total energy use.

We developed control algorithms that have different rules about permitting shading position changes according to either room temperature or desktop illuminance, which are shown in Table 11. The table provides information about the blind types (1- or 2-piece), when shading is permitted to be drawn due to too high room temperatures or desktop illuminance values respectively and how or with what slat angle is controlled. The strategies 1-4 were used in all climates –

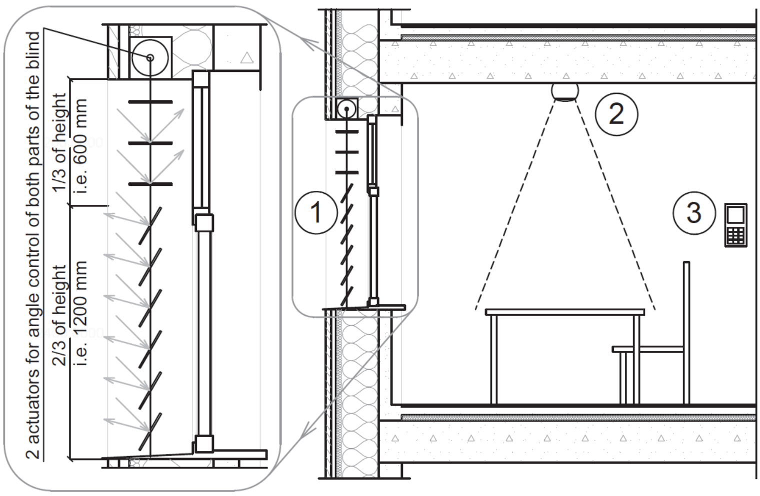


Figure 10 Cross-section of an office room. 1 – Motorized external venetian blind with two actuators for changing position and slat angle, 2- multisensor for detecting occupancy and measuring illuminance at desktop, 3 – control panel with built in temperature sensor

Tallinn, Paris and Athens; 5-7 were used for Tallinn and 8-10 for Paris and Athens. In addition case 0 with internal venetian blinds was created to assess the benefits of dynamic external shading compared to internal. We created shading control macros in IDA-ICE for each algorithm and the components of all macros were presented in [78]. Only the energy use of space heating and cooling, supply air heating and cooling and electric lighting was considered when comparing the primary energy of zones in the shading control analysis. The energy use of domestic hot water, fans, pumps and appliances was disregarded since it was not affected by shading control.

Table 11 Blind types, shading position and slat angle control rules of studied control principles. Abbreviations: OW – outside working hours, DW – during working hours, UP – upper part, LW – lower part.

No	Blind type	Shading position control		Slat angle control
		Temperature	Illuminance	
0	Internal	Drawn when vertical irradiance on facade exceeds 200 W/m²		Constantly 45°
1	1-piece	At all times	DW	PI-controller
2	1-piece	OW	DW	PI-controller
3	1-piece	OW & when illuminance is not too low DW	DW	PI-controller
4	1-piece	OW (same as 2)[a]	DW	Suntracking
5	2-piece	At all times (same as 1)	DW	UP PI-controller according to illuminance LP suntracking
6	2-piece	OW (same as 2)	DW	UP PI-controller according to illuminance LP suntracking
7	2-piece	OW (same as 2)	DW	UP 0° DW; suntracking OW LP suntracking
8	1-piece	Drawn when vertical irradiance on facade exceeds 200 W/m²		Suntracking
9	1-piece	OW & vertical irradiance on facade exceeds 200 W/m² DW	DW	PI-controller
10	2-piece	OW & when illuminance is not too low DW (same as 3)	DW	UP illuminance DW & temperature OW with PI-controller LP PI-controller

[a] - In case of Athens, room temperature based shading position control was also allowed when illuminance was not too low

2.6 Economic calculations

The main criterion for suggesting office building façade solutions was cost-effectiveness, which took into account investment and energy cost of a 20-year period, which has been suggested by the EU commission delegated regulation No 244/2012 supplementing the EPBD [79]. In order to identify cost-effective solutions, we calculated total investment cost of external walls, windows and external shading and modelled the respective cases' heating energy and electricity use. The next step was to calculate the discounting factor, which took into account the length of time period, interest rates, inflation and energy price escalation compared to inflation. By summing investment cost with annual energy cost multiplied by discounting factor, net present value (NPV) was reached. We compared the NPV of various façade solutions and its minimum value was the criterion for cost-effectiveness. We disregarded the maintenance costs, because it would not differ significantly with different solutions and it did not influence the NPV significantly as was pointed by Kurnitski et al. [18]. The formula for calculating NPV was the following:

$$C_g = \frac{C_g^{ref}}{A_{floor}} - \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \quad (4)$$

where C_g - global incremental energy performance related cost included in the calculations, NPV, €/m^2; C_I - energy performance related construction cost included in the calculations, €; C_a - annual energy cost during the starting year, €; $f_{pv}(n)$ - present value factor for the calculation period of n years, -; C_g^{ref} - reference fenestration design solution's global energy performance related cost, NPV, €/m^2; A_{floor} - heated net floor area, m^2.

To calculate the present value factor $f_{pv}(n)$, the real interest rate R_R must be calculated. R_R depends on the market interest rate R and inflation rate R_i [80]:

$$R_R = \frac{R - R_i}{1 + R_i/100} \quad (5)$$

For energy performance calculations, it is common to consider different values for escalation and inflation rates. To calculate the percent value factor, the escalation rate e must be subtracted from the real interest rate R_R, as described by Abel and Voll [81].

The present value factor $f_{pv}(n)$ for the calculation period of n years is calculated as follows [16]:

$$f_{pv}(n) = \frac{1 - \left(1 + (R_R - e)/100\right)^{-n}}{(R_R - e)/100} \quad (6)$$

where R_R - the real interest rate, %; e - escalation of the energy prices, %; n - the number of years considered i.e. the length of the calculation period, 20 years.

The market interest rate for façade analysis in the first part the investigation was 4,0 % (R). An inflation rate of 3.5% (R_i) was used in the calculation of the real interest rate. In the second part of our study during 2015 we used market

Table 12 Economic parameters and energy prices in 2013 and 2015. All costs include value added tax 20%.

	2013	2015
Interest rate *R*, %	4.0	2.7
Inflation rate R_i, %	3.5	1.7
Energy price escalation *e*, %	2.0	0.0
Electricity price, €/MWh	149.4	156.2
District heat price (Tallinn), €/MWh	75	72

Interest rate of 2.7 % (*R*) and inflation rate of 1.7 % (R_i) used for this analysis is based on the rates reported by the Bank of Estonia. Energy price escalation of 0 % (*e*) was obtained from the Statistics Estonia agency. Since 2013, the economic situation has changed remarkably, money has become cheaper, interest and energy escalation rates have decreased. In addition, electricity prices have slightly increased and heat prices decreased. The previously used [73] and updated 2015 data has been presented in Table 12.

2.7 Case selection procedures

2.7.1 Initial façade analysis

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.

In the present study, a step-wise approach was used to derive the energy and cost-effective solutions. This helped to reduce the vast amount of possible combinations. We started 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-effective 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-effective and most energy-efficient solutions for each façade.

In first step, it was determined whether highly transparent or tinted solar protection windows allow reaching better energy efficiency. For that purpose, double and triple glazed window cases with minimum window sizes were simulated (results reported in Section 3.1.3). The window size assuring daylight factor 2% was chosen as the smallest allowed. Larger window sizes were not studied, because these common windows have U-values several times higher than external walls and therefore using highly transparent windows with lowest possible size is in heating dominating climate more energy-efficient than using large windows with good solar protection.

In the second step, simulation cases with several WWRs were created to find the optimal size of windows, because with the U-values closer to external wall U-values, the smallest possible window might not be the optimal. As large windows may cause high cooling need, then the influence of external shading was also tested. Initially, 200 mm external wall insulation thickness (U=0.16) was used with 2 and 3 pane windows and 300 mm insulation thickness (U=0.11) with 4 and 5 panes. Simulated cases (results in Section 3.1.4) covered:

1. The range of WWR of 23.9 to 60% for each façade;
2. Glazing from 3 to 5 pane with U-values between 0.55–0.21;
3. With and without external shading on East, South and West facades.

In the economic analyses, in order to find balance between insulation thicknesses and glazing types, the investment cost of façade element combinations was compared to energy cost and primary energy of each combination as the third step of the analysis. The results are reported in Section 3.1.5. Estonian cost data of windows showed that double windows and triple glazing with air filling cost approximately as much as triple glazing with argon filling. For that reason, optimal WWR analyses were conducted with triple glazing with argon filling or quadruple and quintuple glazing with krypton filling and all insulation thicknesses were studied only for these two glazing types.

The fourth step was to find out the most energy-efficient and cost-effective fenestration design cases for each orientation. Simulation cases with double,

Table 13 Final simulation cases

Variant	Glazing type	External wall U-value, W/(m^2·K)	WWR, %	External shading	Window width, m
3/C/Ar/-	3/C	0.16	23.9/ 37.5	No	1.05
4/C/Kry/-	4/C	0.13	26.1/ 37.5[a] 60.0(N)	No	1.15/ 1.65[b]
5/C/Kry/-	5/C	0.09	29.5/ 37.5(W)/ 60.0[b]	No	1.30/ 1.65[a]
3/C/Ar/e	3/C	0.16	23.9[a]/ 37.5[a]	Yes	1.05
4/C/Kry/e	4/C	0.13	26.1[a]/ 37.5[a]	Yes	1.15
5/C/Kry/e	5/C	0.09	29.5[a]/ 37.5[c]/60.0(W)	Yes	1.30/ 1.65[a]

[a]- South, East and West façades only
[b] - South, East and North facades only
[c] - South and East facades only
(N) - North façade only
(W) - West façade only

triple, quadruple and quintuple glazing variants with the best properties and minimum WWRs were created. Furthermore each glazing variant was simulated with and without external shading. The description of simulation cases is given in Table 13 and results are reported in 3.

2.7.2 Development of external shading control algorithm

As the next part of our study we started developing a new control algorithm for external venetian blind as previous façade analysis pointed out that the simple principle did not perform efficiently. We simulated the performance of external automatically controlled dynamic venetian blinds with the goal of developing optimal control algorithms. The study was conducted by simulating 4 different generic office floors with varying façade properties - window sizes, number of panes and external wall insulation thickness. The most efficient control principles were chosen based on the energy performance, simplicity and the duration of unobstructed view. In addition the cooling capacities of zones were calculated to assess the effect of shading principle on the sizing of cooling units.

The office floor façade solutions were chosen so that the balance of heating and cooling energy need would vary, which is achieved with differing thermal properties of windows and external walls and also window-to-wall ratios as can be seen in Table 14. The case names used in cold climate simulations (3-23.9%, 4-37.5%, etc.) were derived from the number of window panes and WWR used in the specific case. Additional cases were created to analyse the shading performance in the climates of Paris and Athens, whereas in the Tallinn case 4-37.5% was used in the comparison of different locations. Detailed window models were used, which means that the thermal resistance of glazing depended

Table 14 Description of simulation cases.

Case code	Glazing type	WWR, %	U-value of external walls, W/(m^2 K)
3-23.9%	3/C	23.9	0.16
4-37.5%	4/C	37.5	0.13
5-37.5%	5/C	37.5	0.09
5-60%	5/C	60.0	0.09
Paris	3/C	37.5	0.20
Athens	2/C	37.5	0.33

Table 15 Design outdoor temperatures for cooling capacity calculations.

Date	Design outdoor temperatures (max/min), °C		
	Tallinn	Paris	Athens
June 21st	24.7/13.8	28.0/17.9	35.8/24.8
July 21st	27.3/15.8	30.0/18.5	35.0/23.9
August 21st	27.2/15.1	30.0/16.8	37.2/28.1
September 21st	22.4/11.7	24.3/18.0	33.6/24.9

on the temperature difference between internal and external conditions. The development of studied control algorithms was described in Section 2.5.

Cooling capacities of all cases were simulated besides the energy use. Four dates were simulated for each case – 21.06., 21.07., 21.08., 21.09. and the diurnal design outdoor temperatures for each location and date are given in Table 15. The maximum outdoor temperatures of each month in the climate files were used as outdoor temperatures at midday. To calculate the minimum diurnal outdoor temperature, three days of each month with highest average outdoor temperature were selected and the average temperature amplitude of those days was subtracted from the maximum monthly temperature. Also the internal gain usage factor of 55% was used for the open-plan offices.

2.7.3 Standard and detailed window model effect on energy need

Subsequently we studied the behaviour of triple, quadruple and quintuple glazing with varying window sizes to quantify the effect of standard and detailed window model on office building energy needs. We used the same generic office floor plan as previously. Each office module had one window with height of 1.8 meters and the bottom edge was 0.9 meters from the floor. No shading was used during this part of the study and the lighting with installed power 7 W/m^2 was controlled only according to the schedule without any automated control. Quadruple and quintuple glazing did not prove to be economically reasonable, however they might be one possible solution to design and build nearly zero energy buildings in the future. The studied window types and respective external wall insulation thicknesses are given in Table 16. The window width was increased with a step of 0.3 meters up to width of 2.4 meters.

The investigated window sizes for different glazing types were:

1. 3 pane window widths 1.05, 1.2, 1.5, … 2.4 meters; window-to-wall ratio 24% … 55%
2. 4 pane window widths 1.15, 1.2, 1.5, … 2.4 meters; window-to-wall ratio 26% … 55%
3. 5 pane window widths 1.3, 1.5, … 2.4 meters; window-to-wall ratio 30% … 55%

Table 16 The properties of studied window types and the U-value of external wall used with respective window types.

Glazing type	Frame U-value, W/(m^2·K)	External wall U-value, W/(m^2·K)
3/C	0.8	0.16
4/C	0.32	0.13
5/C	0.21	0.09

2.7.4 Sensitivity analysis

Finally we investigated if window models and other variables affect the optimal façade solutions. The work included comparison of new results to the work conducted in late 2012 and early 2013. Overall, the work has been carried out in following steps:

1. Whole office floor simulations with insulation thicknesses 150, 200 and 250 mm to determine the cost-effective insulation thickness in the current situation
2. Energy simulations with the following variables (Table 17):
    a. Triple and quadruple windows
    b. Window-to-wall ratio in the range of 25-60%
    c. Internal shades and automated external venetian blinds
    d. Standard and detailed window models
3. Assessing financial feasibility of the cases by calculating 20 year net present value with the following variables:
    a. Construction costs from 2013 and 2015
    b. Energy prices from 2013 and 2015
    c. Interest rates from 2013 and 2015
    d. Inflation rates from 2013 and 2015
    e. Energy price rates from 2013 and 2015
4. Comparing the NPVs of studied cases

Table 17 The properties of studied window types. All the window parameters are given according to calculations of ISO 15099:2003/E. The parameters of detailed windows were dynamic and simulated according to ISO 15099:2003/E.

	Triple glazing (3/C)	Quadruple glazing (4/C)
Glazing U-value[a], W/(m^2·K)	0.58	0.32
Glazing SHGC without shading, -	0.46	0.37
Glazing SHGC with internal shading, -	0.39	0.34
Glazing SHGC with external shading, -	0.12	0.10
Gap between panes, mm	18	12
Gas filling	90% argon	95% krypton
Frame U-value, W/(m^2·K)	0.8	0.32
Frame fraction of window area, %	15	15
Total window U-value, W/(m^2·K)	0.61	0.32
Studied window-to-wall ratios, %[a]	23.9, 37.5, 60.0	26.1, 37.5, 60.0
External wall U-value, W/(m^2·K)	0.20	0.16

[a] – Smallest window-to-wall ratios assure average daylight factor 2% in an office consisting on two 2.4 m wide modules [44].

3 RESULTS

3.1 Initial façade analysis

3.1.1 Daylight calculations

Daylight calculations with formula 2 showed that minimum window-to-wall ratio (WWR) of highly transparent windows was between 21% and 29.5%. Minimum WWR increased together with the number of panes as visible transmittance decreases. The minimum WWRs of solar protection windows exceeded 30%. The WWR dependency of visible transmittance of window glazing has been shown in Figure 11.

Figure 12 presents the average daylight factors of a zone calculated with the simplified daylight factor formula and with IDA-ICE coupled with Radiance. It shows that the simplified formula resulted in lower daylight factors by 0.4-1.6%. By using the simplified formula, we underestimated the daylight availability and the simplified daylight factor formula could be used without the risk of not achieving the target value. The suggested average daylight factor range of an office room according to BS 8206-2:2008 [16] is 2-5%. Simplified calculations and modelling can give significantly varying results if only target daylight factor value is used for dimensioning glazed area e.g. the WWR of a zone with daylight factor and triple windows was 45% when using modelling, but 60%, when using simplified calculations.

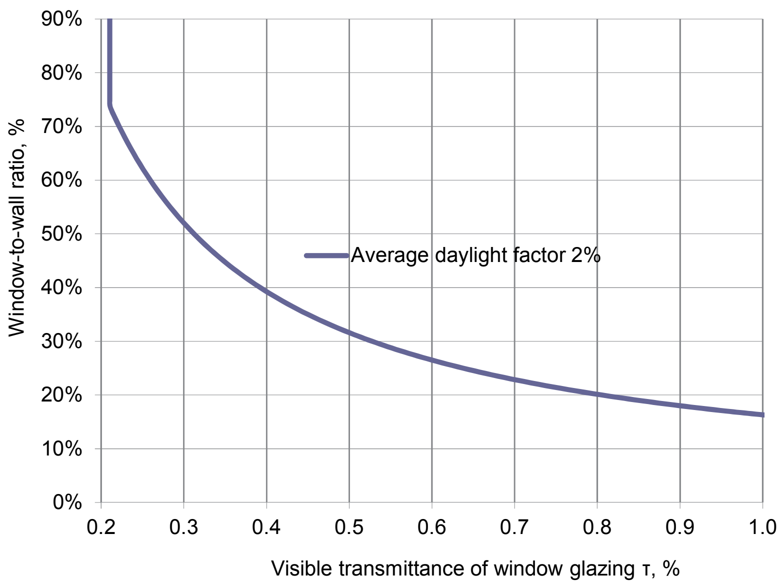


Figure 11 Minimum window-to-wall ratio depending on visible transmittance of glazing in case of an office room consisting of two 2.4 meters wide modules.

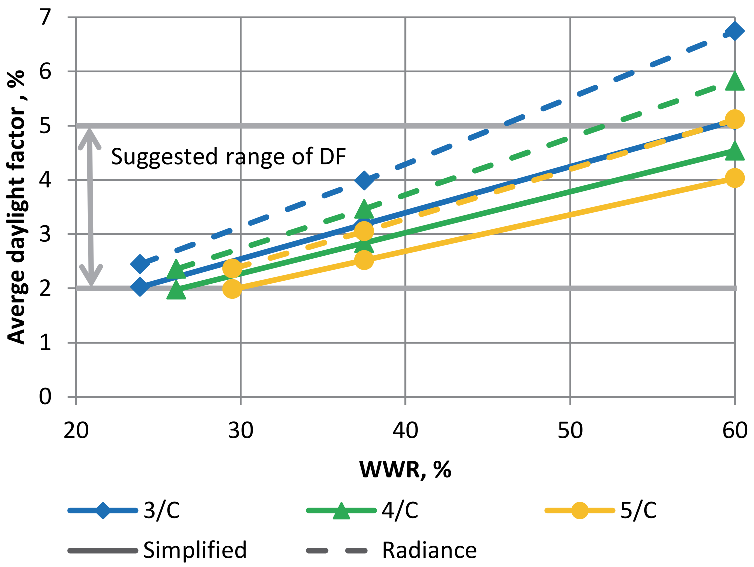


Figure 12 The average daylight factors calculated with the simplified formula and with IDA-ICE coupled with Radiance. Code: 3/C – triple highly transparent window; 4/C – quadruple highly transparent window; 5/C – quintuple highly transparent window.

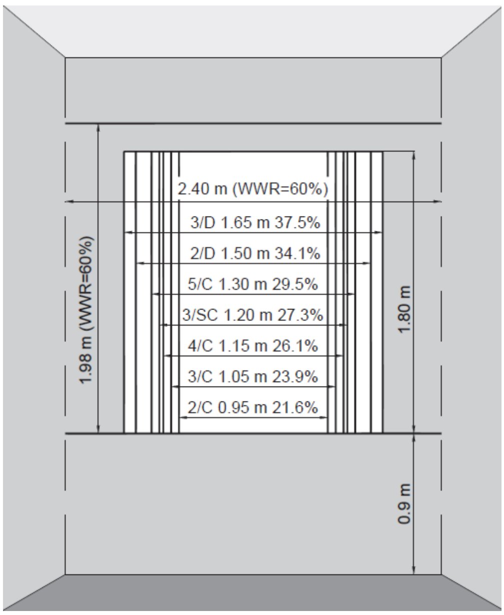


Figure 13 Window sizes of glazing variants (Variant codes correspond to Table 2, e.g. 2/C 0.95 m 21.6% means double, highly transparent window with width of 0.95 m and the window-to-wall ratio 21.6%). 2.4 m is the maximum width of the window providing WWR 60%.

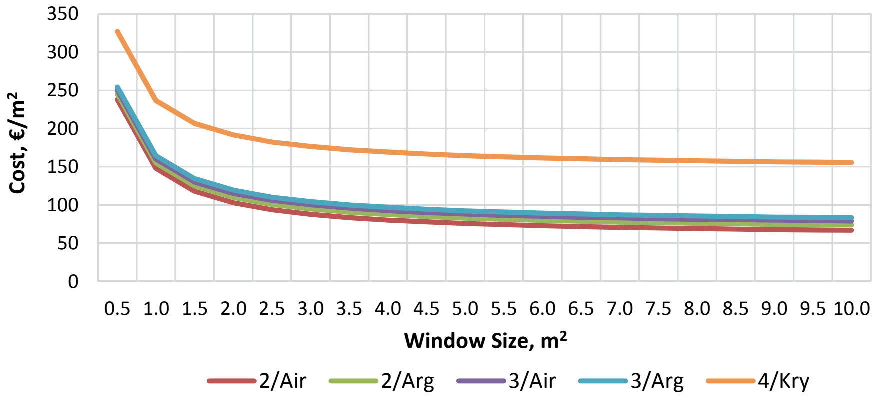


Figure 14 Specific window cost as a function of window size.

3.1.2 Window cost ratio analysis

Figure 14 shows that he cost differences between windows up to triple glazing were marginal but on average a window with four panes was 41 % more expensive than a window with three panes. It was preferable to use windows with a larger glazing area, if only cost of 1 m^2 of window is considered, because the influence of frame cost decreased. Quintuple glazing was not considered in this analysis as it was not available as a standard product.

3.1.3 Highly transparent vs. solar protection windows

In all cases room heating dominated the energy use and it was greatly affected by the size of windows as shown in Figure 15. Supply air heating and cooling had next largest energy needs followed by lighting. Tinted windows with larger size remarkably increased space heating need. Lighting electricity varied by orientations, but was practically the same for each glazing variant as the windows have been sized according to daylight criterion. The space cooling energy need fluctuated several times, however the influence on total energy use was low. Compared to highly transparent glazing, clear solar protection windows showed slightly worse energy use on each façade. Clear highly transparent windows performed better than solar protection windows with lower visible transmittance. The reason for that was that smaller windows could be used to reach daylight factor 2% with higher glazing transparency. More detailed information about the calculations can be found in [44].

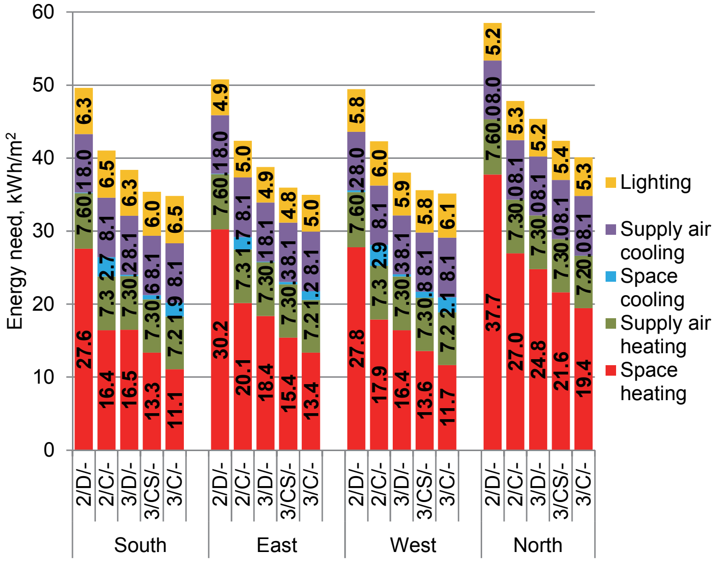


Figure 15 Energy need in zones with highly transparent and solar protection windows with minimum size according to the daylight criterion of 2%. Case codes: number 2 or 3 means double or triple panes, D, C and SC mean tinted solar protection, clear highly transparent and clear solar protection glazing respectively and "-" represent internal shading.

3.1.4 Optimal window-to-wall ratio

The simulation cases with fixed insulation thickness resulted in primary energy shown in Figure 16. Generally increasing WWR increased cooling energy use and decreased lighting electricity. Space heating energy use increased with triple windows, fluctuated with quadruple windows and decreased slightly with quintuple windows if WWR was increased. The use of external shading with a simple control principle in all cases increased heating and lighting energy use and decreased cooling energy, whereas it improved primary energy use only in case of larger window sizes. In addition the positive effect of external shading was higher for East and West orientations. For the North façade external shading was not studied. In Figure 16 the effect of external shading is shown only for cases where primary energy decreased compared to the case without external shading. Detailed information about delivered energy can be found in [44]. For triple windows the increase of WWR increased delivered energy, which made WWR 24.1% the most energy-efficient case. However in the North façade WWR 37.5% gave lower primary energy than 24.1% due to lower lighting electricity despite slight increase in heating and cooling energy.

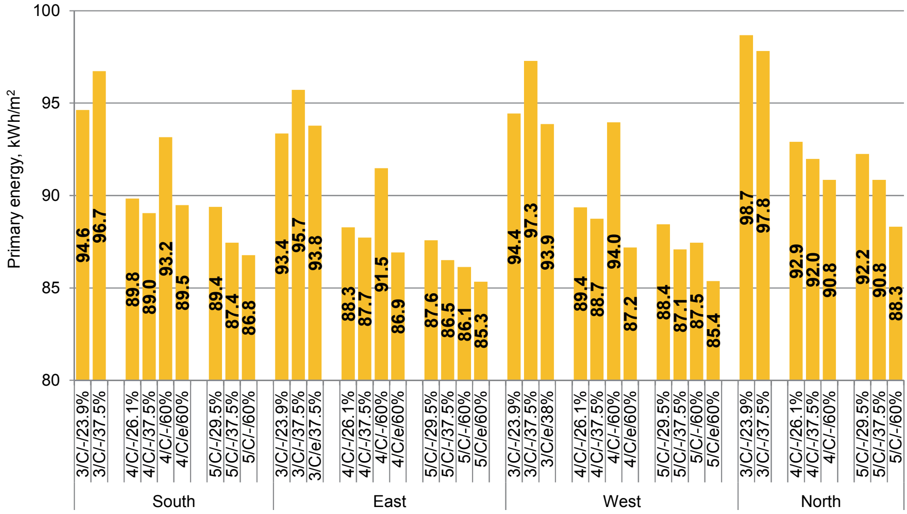


Figure 16 Primary energy results of the cases used to determine optimal WWR with initial fixed insulation thickness (200 and 300 mm for 3 and 4 pane respectively). Primary energy is given in each zone as a function of window type, external shading, orientation and window size. Case codes are described in Table 2, e.g. 3/C/-/23.9% means 3-pane, clear solar protection glass, no external shading and WWR=23.9%.

In case of quadruple windows the following results can be pointed out:

1. In all cases, heating and lighting primary energy decreased when WWR was increased from 26.1% to 37.5%. At 60% WWR, the cooling energy started to dominate on South, East and West facades.
2. Most energy-efficient South orientated case was with WWR 37.5% and without external shading
3. East and West facades most energy-efficient case was with WWR 60% and external shading, whereas without external shading WWR 37.5% provided slightly higher primary energy.
4. On the North façade WWR 60% resulted in lowest primary energy because of significant decrease in lighting energy without any important increase in cooling energy.

In case of quintuple windows the following results can be pointed out:

1. Most energy-efficient South and North orientated cases were with WWR 60% and without external shading.
2. East and West facades most energy-efficient case was with WWR 60% and external shading.

3.1.5 Optimal external wall insulation thickness

The calculations by now have been done with insulation thickness of 200 mm for 3 pane and 300 mm for 4 and 5 pane windows. To determine the most sensible external wall insulation thickness façade investment cost and net present values for a 20 year period were calculated. The primary energy, investment cost and NPV of all cases are shown in Figure 17 and Figure 18. The insulation thickness which resulted in lowest NPV was 200 mm for most cases, which was chosen for final analysis for triple glazing variants. However compared to case with quintuple 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 was chosen for final analysis of 4 pane glazing.

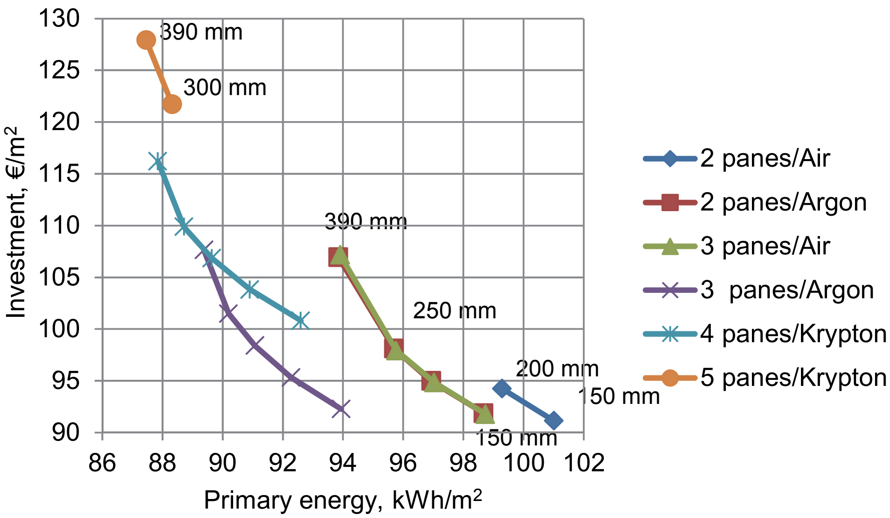


Figure 17 Investment cost and primary energy of different glazing (all without external shading) and external wall insulation cases. Insulation thicknesses from left to right 150, 200, 250, 300 and 390 mm if not otherwise specified.

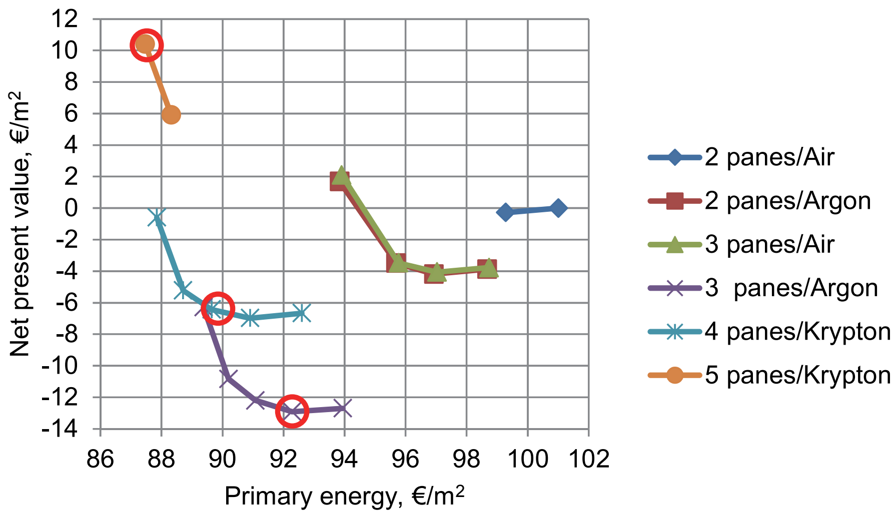


Figure 18 Net present value and primary energy for the cases of Figure 17.

A similar situation appeared between 4 panes/390 mm insulation and 5 panes/300 mm insulation cases so 390 mm of insulation thickness was chosen for quintuple glazing. Therefore the following glazing and insulation thickness combinations were selected for final analyses (marked with red circles in Figure 18):

1. Triple glazing with argon filling and 200 mm – the cost-effective
2. Quadruple glazing with krypton filling and 250 mm – the most relevant for 4 pane (in between the cost-effective and the most energy-efficient)
3. Quintuple glazing with krypton filling and 390 mm – the most energy-efficient

3.1.6 Most energy-efficient and cost-effective cases.

For the window types and insulation thicknesses selected in Section 3.1.5 energy simulations and economic analyses were repeated for optimal range of WWR with and without external shading. These results allow determining optimal solutions refining the results of calculations done in Sections 3.1.3 and 3.1.4 with initial, not optimal combinations. Compared to previous results the external wall insulation thicknesses of quadruple and quintuple window cases have been changed to 250 and 350 mm respectively. Also the energy needs of different systems have been given (see Figure 19) and in addition the effect of external shading has been shown for all cases except North orientation.

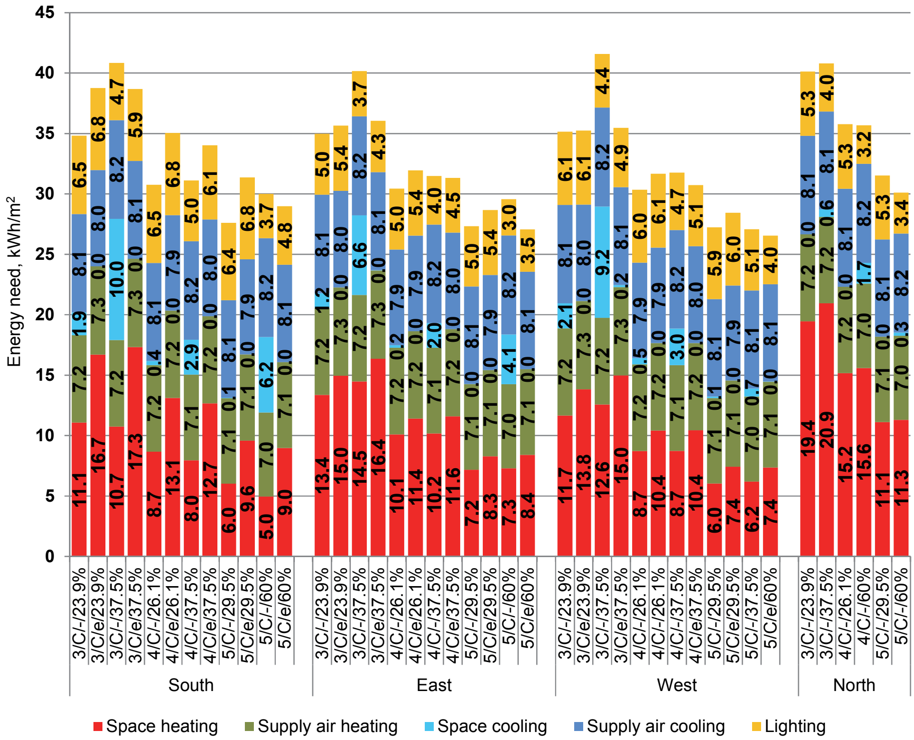


Figure 19 Energy needs of final simulation cases for all zones. Insulation thicknesses determined in Section 3.1.5 were used.

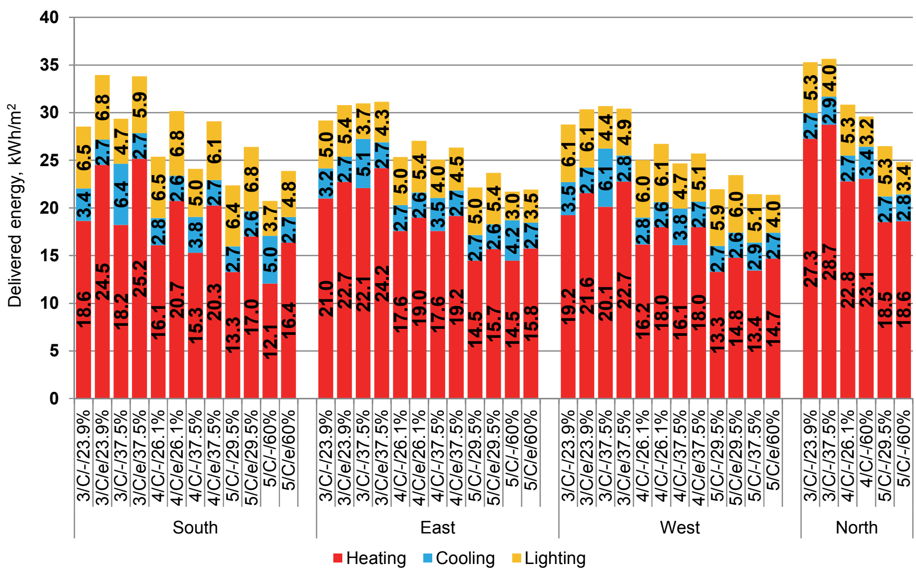


Figure 20 Delivered energy of final simulation cases.

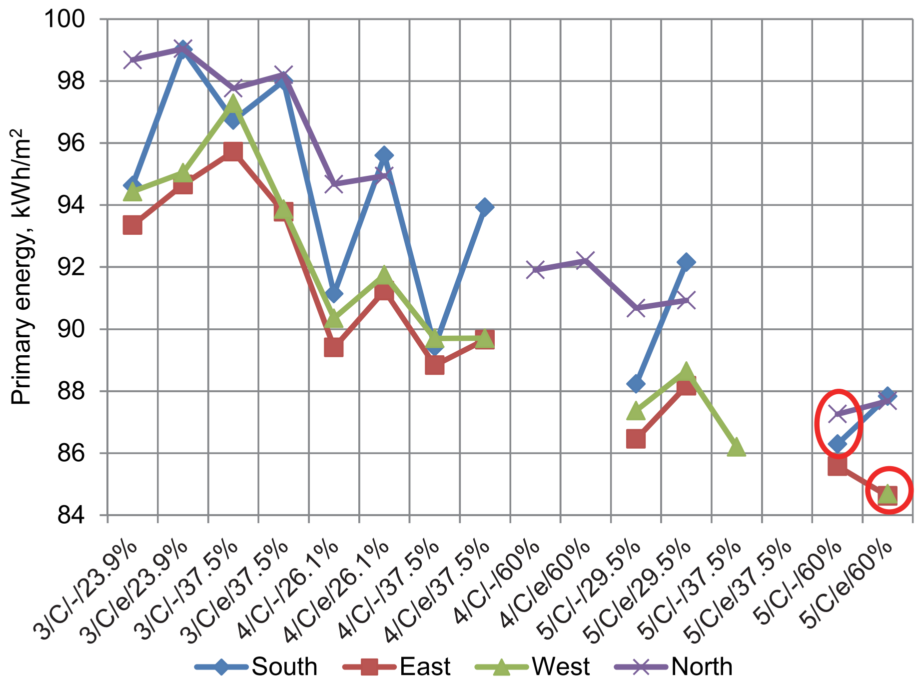


Figure 21 Primary energy of final simulation cases.

External blinds increased space heating energy need in all cases, whereas the effect was largest on the South façade. The largest space cooling needs appeared in case of triple glazing with WWR 37.5% and when windows were dimensioned according to daylight requirements the space cooling needs were rather insignificant. The increase of WWR caused remarkable reduction in lighting energy use, whereas external shading slightly increased it.

Heating dominates the delivered energy of all cases (see Figure 20). The effect of external shading in case of smaller window sizes on energy use becomes more obvious. Only the cases that have high space cooling needs receive positive effect on energy efficiency from added external blinds.

In Section 3.1.4 it was determined whether WWR 37.5% or 60% result in better energy efficiency for each glazing type on each façade and in figure 15 only the results of the more energy-efficient WWR cases has been shown. For example in case of quadruple glazing the results for WWR 37.5% have been shown for South, East and West and in case of WWR 60% for only North.

The primary energy relationship to investment cost and NPV are shown in Figure 22 and Figure 23 respectively. The cases shown in the figures have been connected with lines if not otherwise specified in the following order: 3/C/37.5%, 3/C/23.9%, 4/C/26.1%, 4/C/37.5% and 5/C/29.5%. Case 5/C/-/37.5% has been added for West facades as it resulted in better primary energy and NPV than similar case with lower WWR.

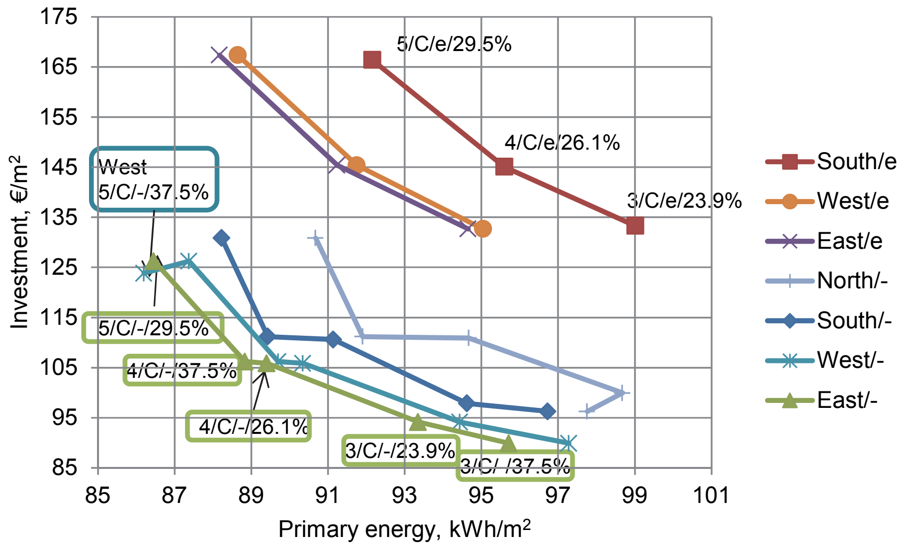


Figure 22 Investment and primary energy of final simulation cases. Three upper curves are with external shading (marked with e) and lower curves with internal blinds.

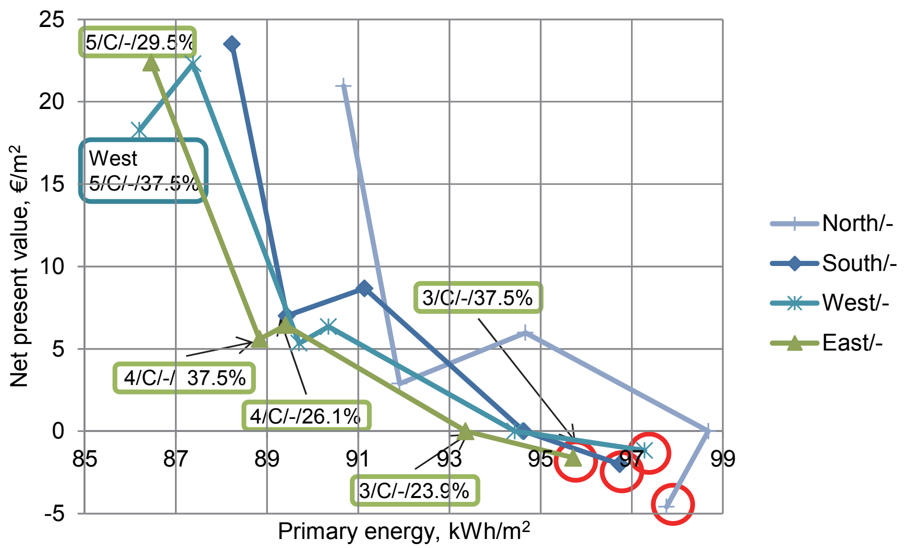


Figure 23 Net present value and primary energy of final simulation cases without external shading.

Financially most feasible cases that had lowest NPV were by orientation the following (also marked with red circles in Figure 23):

1. South – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
2. East – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
3. West – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm
4. North – 3 panes with no external shading, WWR=37.5%, external wall insulation 200 mm

In South, East and West facades with triple glazing and no external shading WWR 37.5% resulted in worse energy performance than 23.9%, however the cost per area for windows was smaller than of external walls and therefore WWR 37.5% was most financially feasible. If triple windows would be more expensive than external wall with insulation thickness 200 mm, then the cost-effective WWR would be 23.9% in South, East and West facades.

3.1.7 Cooling load with and without external shading

External shading was not a cost-effective solution considering only the shading cost and potential energy savings. However external shading also decreases investments through reduced capacity of chiller and cooling system. The effect of external shading on sensible cooling capacity of a 4.8x4.8 m room with 2 persons in it is shown in Figure 24. External shading helped reaching low sensible cooling capacities around 20 W/m^2 and below. Quadruple and quintuple glazing with minimum window sizes allowed reaching reasonable cooling capacities around 40 W/m^2 without external shading, whereas WWR may be increased to 37.5% in case of 5 panes. Small sized double and triple glazing and quadruple windows with WWR of 37.5% resulted in cooling capacities around 50 W/m^2 and higher. These cases also showed significant rise in room cooling needs compared to other simulation variants (see Figure 19).

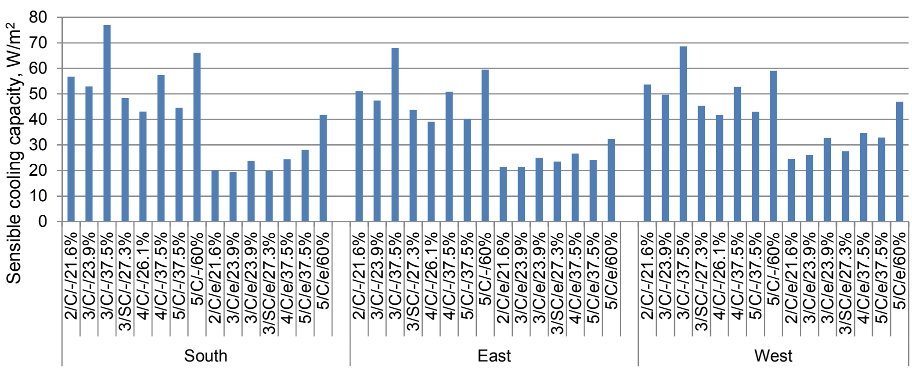


Figure 24 Office room cooling capacities of final simulation cases

3.1.8 Extending single floor model to full building model

The maximum allowed annual primary energy use of office buildings in Estonia is 160 kWh/m^2 and the requirements for low and nearly zero energy buildings are 130 and 100 kWh/m^2 respectively [82]. The primary energy consumption of most simulated cases shown in Figure 21 remain below the nZEB requirement of 100 kWh/m^2, whereas the information is shown in zones by orientations and the whole office floor has generally even lower energy consumption than the zones separately.

The generic floor model used in the analysis was very compact because of adiabatic floor and ceiling. The model is relevant for studying façade solutions, but the results may give a misleading impression about the simplicity of meeting nZEB requirements. In order to characterize the fluctuations in delivered energy related to compactness of buildings, external ceiling was added to the generic floor model. Two models were created: one had the most financially feasible solutions for each façade and the other the most energy-efficient solutions. The roof U-values used for financially optimal and energy-efficient cases were 0.10 W/(m^2·K) and 0.09 W/(m^2·K) respectively.

Adding roof had expectedly the biggest effect on heating energy increase, decrease of cooling energy was smaller and lighting practically did not change at all. The increase of the delivered and primary energy was about 35% and 20% respectively for both cases, whereas the influence on the energy-efficient case was slightly higher as its initial energy use was lower. The fluctuation in the energy use of the simulation models is shown in Figure 25 and Figure 26.

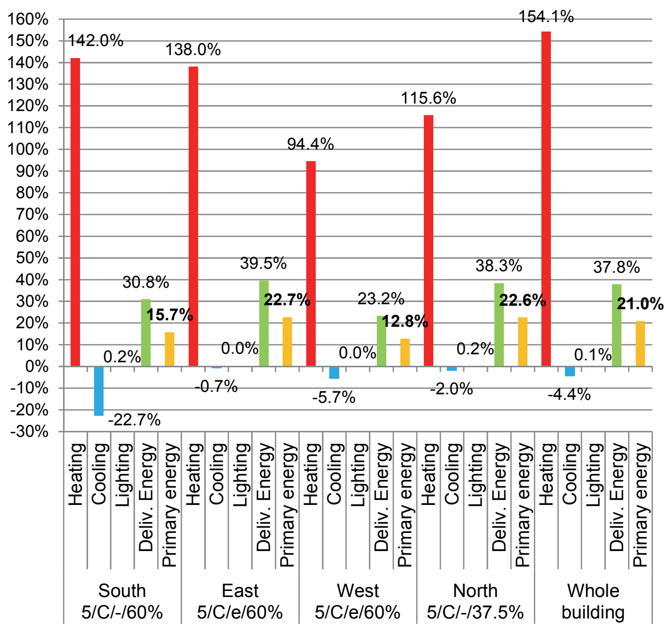


Figure 25 Energy use fluctuation of the most energy-efficient cases

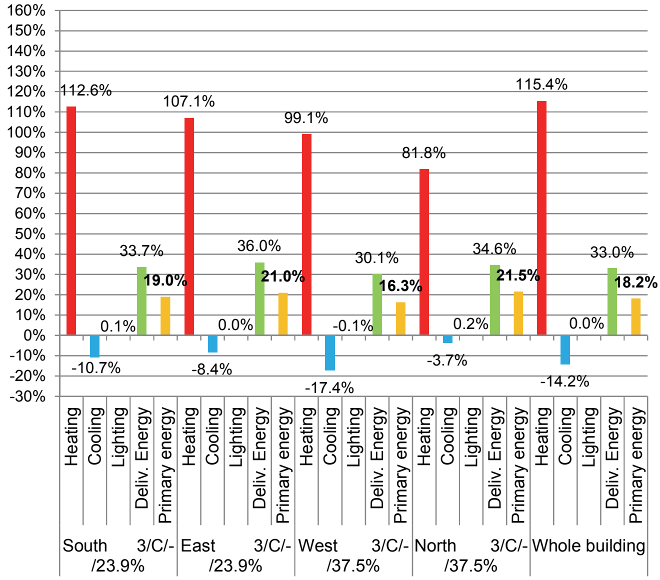


Figure 26 Energy use fluctuation of the financially most feasible cases

The heating energy increase of the whole building is higher than of any other zone located on the facades, which is caused by heat loss through the ceiling of the zone located in the centre of the floor. The influence on cooling energy varies much from orientation to orientation, however the change is higher when initial space cooling energy forms a larger part of total cooling energy. According to the results of these two cases, a safety margin of 20% can be applied for the primary energy calculated with a typical floor model.

With these models simulating a full building, the primary energy use was 103.4 kWh/m^2 and 110.9 kWh/m^2 for energy-efficient and economically feasible cases respectively which means that they fulfil low energy building requirements (PE≤130 kWh/m^2) instead of nZEB ones (PE≤100 kWh/m^2). In order to reach nZEB level, on-site energy production e.g. PV-panels, which are suitable for office buildings must be used.

Results show that the single floor model used for façade analyses was not relevant to describe a full building, because of very high compactness. Normally office buildings are not that compact as they have areas with large glazed areas (e.g. lobbies) and also the shape is less compact. An attempt was made to transfer the results from this model to a full building, by adding external roof to the model. In two calculated cases the delivered energy increased approximately 35% and primary energy 20%. These values depend on a specific building and were not analysed further, because the aim of the study was to find optimal façade solutions. Previous experience shows that calculated 20% margin in primary energy could be slightly on the safe side for most of real office buildings, but still can be recommended for the scaling results from single floor model until the final results would be calculated with a full building model.

3.2 External shading control algorithm

This section presents the primary energy use of all cases to compare the influence of control principles' on energy performance. To compare the control principles, besides energy use, the quality of view was used, which was assessed by the amount of hours while the blinds were down during working hours. The simplicity of the control principle/macro was used as the criterion to choose the optimal algorithm, if the energy performance and view quality of control principles did not differ significantly.

3.2.1 Optimal control principle in a cold climate

The results presented in Figure 27 show that generally external blinds noticeably improved energy efficiency compared to internal ones, whereas the effect was larger in case of larger glazing areas and higher g-values. The primary energy of the whole floor decreased between 0.3-2.8 kWh/m^2 and improvements were between 1.2-6.2 kWh/m^2 on the West façade. When only the cases of external shading were compared, which was the main purpose of the study, then the greatest difference between annual primary energy use of the analysed control principles was 1.3 kWh/m^2 i.e. only 3% of heating, cooling and lighting energy. The largest fluctuations in the energy use appeared in the case of 5-pane windows with WWR 60% followed by 4-pane windows with WWR 37.5%. The variations in the annual primary energy use remained within

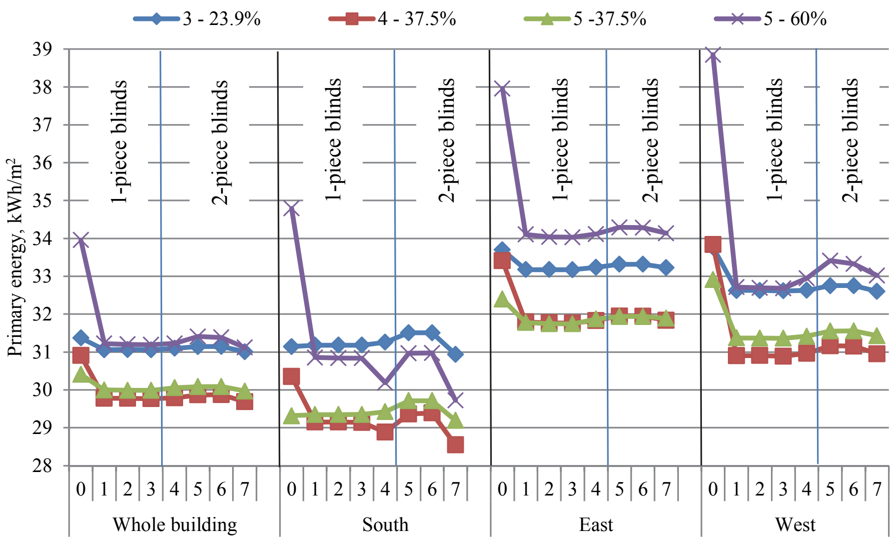


Figure 27 The primary energy use of control principles 1-7 in the climate of Tallinn. Case 0 stands for internal venetian blinds. Only the energy for space heating and cooling, supply air heating and cooling and electric lighting are included.

0.6 kWh/m^2 in the case of 3-pane windows with WWR 23.9% and 5-pane windows with WWR 37.5%. The variations in the primary energy use of cases with external blinds was up to 4.2%, 2.2% and 0.8% in South, West and East facades respectively, making South the most sensible orientation.

No significant improvement was found in the energy performance if 2-piece blinds were used instead of 1-piece blinds, whereas 2-piece blinds could slightly even increase energy use. Therefore in the cold climate of Tallinn using 2-piece blinds are not recommended. Controlling slat angle according to the sun angle i.e. using solar tracking can be recommended as it did not increase energy use and is by its nature a more simple method than using PI-controllers.

The small impact of studied control methods on the energy use can be explained with the information provided in Figure 28, where the reasons for drawing shading during worktime have been given in case of control principle no 1. Control principle 1 means that shading could be drawn due to too high room temperatures at all times and due to high illuminance values during worktime. The largest need for drawing blinds appeared in the South facade where blinds were drawn for 27-36% of total 2860 working hours. South was followed by West and East with the obstructed view duration of 15-25% and 14-18% respectively The duration of drawn blinds at different facade solutions increased as follows – 5-37.5%, 3-23.9%, 4-37.5% and 5-60%. If there was a need for drawing the shades, then it was prevailingly due to too high illuminance values, which is why controlling shading only according to illuminance during working hours did not affect energy use considerably.

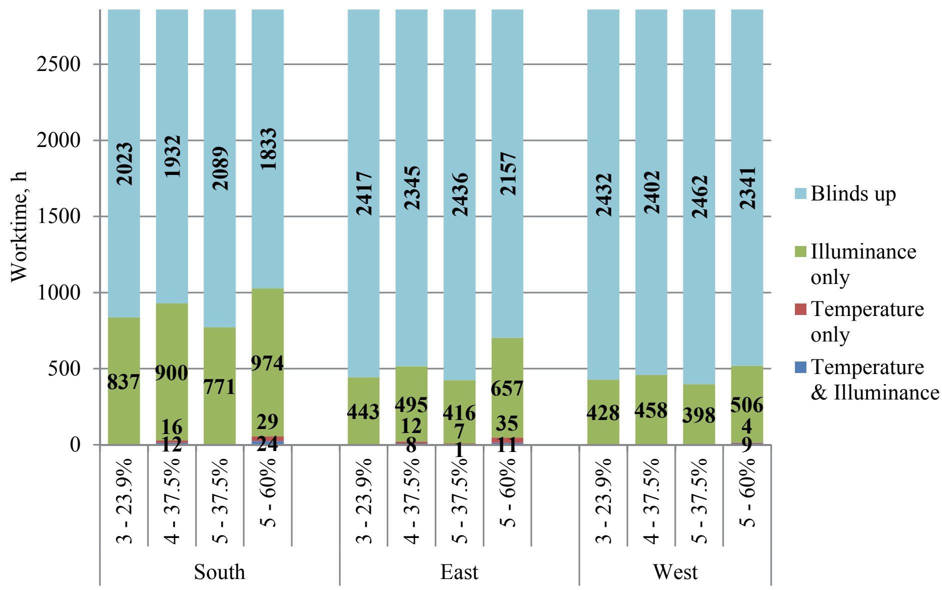


Figure 28 The illustration of shading need on different facades in the climate of Tallinn in case of control principle no 1.

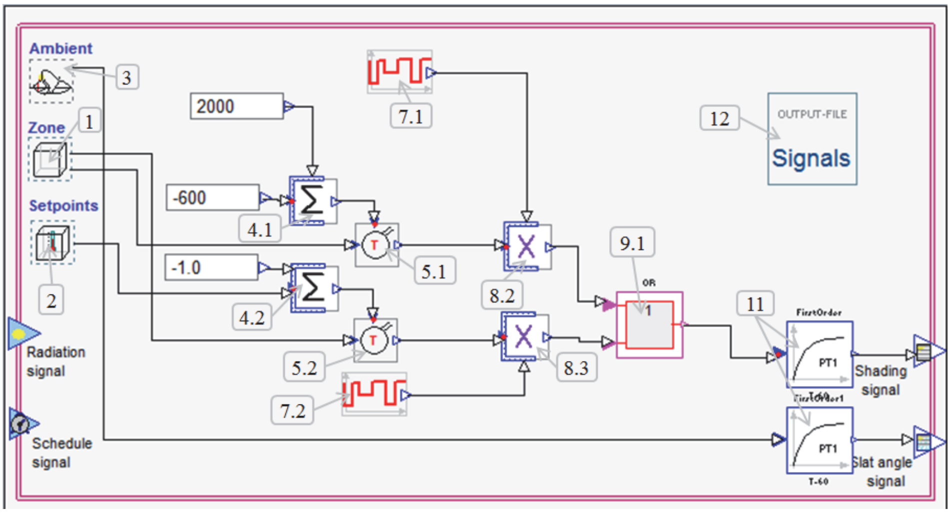


Figure 29 The macro of optimal control principle in Tallinn and Paris (control principle no 4 in Table 11).

As varying control strategies and using a 2-piece blinds did practically not affect energy use , then the most simple control principle i.e. strategy no 4 was chosen as the optimal one. The external blinds should be controlled according to desktop illuminance during working time (occupancy), room temperature outside working hours and solar tracking should be used for slat angle adjustment. The control macro of the principle is presented in Figure 29, whereas in case of actual installation the information about working time should be provided from occupancy sensor instead of time schedules (elements 7.1 and 7.2 in Figure 29).

3.2.2 Comparison of different climates

The simulation results presented in Figure 30 show that external shading significantly improved energy efficiency of an office building in other climates similarly to the climate of Tallinn. The range of primary energy reduction in Paris was on average 1-2 kWh/m^2 which was slightly larger than in Tallinn. However, in case of Athens the overall reduction in primary energy of the whole floor was 11.9 kWh/m^2 and as high as 32.1 kWh/m^2 in the West façade. The control principles had a significantly larger effect on the energy use in the warm climate of Athens compared to Tallinn and Paris. Out of control principles 8-10 which were only simulated with the climates of Paris and Athens, no 8 proved to be clearly the least energy-efficient in all cases with external shading. The algorithm used only total irradiance on the facade for shading position control and similar results were obtained with the climate of Tallinn in [78]. Athens was the only climate where principle no 8 did not cause higher energy consumption than case 0 with internal blinds. When other control principles were considered, then the fluctuations of primary energy remained within 0.2 kWh/m^2 in case of Tallinn and Paris, but in Athens the difference in primary energy depending on the control principle was as high as 13.5 kWh/m^2.

Disabling room temperature based shading position control during occupancy did not affect primary energy noticeably in the Paris climate similarly to Tallinn. However, in Athens allowing drawing shades due to too high temperatures when the illuminance levels were high enough during working hours, had a significant positive effect on the energy performance of all zones. Also solar tracking increased the energy use in Athens significantly unlike to Tallinn and Athens. In Paris and Athens the effect of external shading was in the West façade offices, whereas in Tallinn the decrease in energy was largest in the South. A similarity for all climates was that controlling shading based on indoor conditions provided the lowest energy use and using 2-piece blinds gave no significant improvements in energy efficiency.

Relatively larger impact of studied control methods on the energy use in Athens can be explained with the information provided in Figure 31, where the reasons for drawing shading during worktime have been given in case of control principle no 1. While the duration of drawn shading in Paris was higher than in Tallinn, the reasons for drawing the blinds were similar. However in Athens necessity to prevent overheating became evident even when there was no excessive daylight. That explains why a slightly more complicated control algorithm is needed in the hot climate of Athens, which at certain conditions also allows adjusting shading position according to room temperature during occupancy.

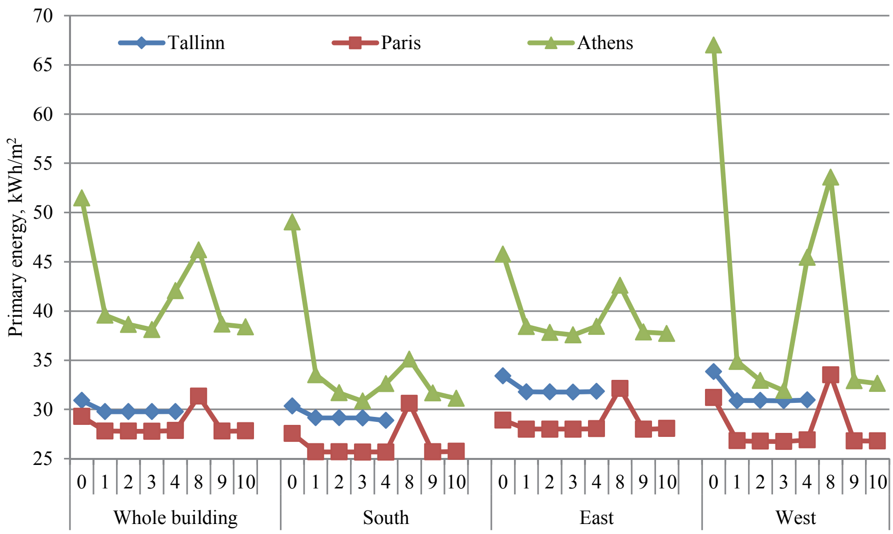


Figure 30 The primary energy use of control principles 1-4 and 8-10 in the climates of Tallinn, Paris and Athens. Control principles 8-10 were not simulated in case of Tallinn. Only the energy for space heating and cooling, supply air heating and cooling and electric lighting are included in the graph.

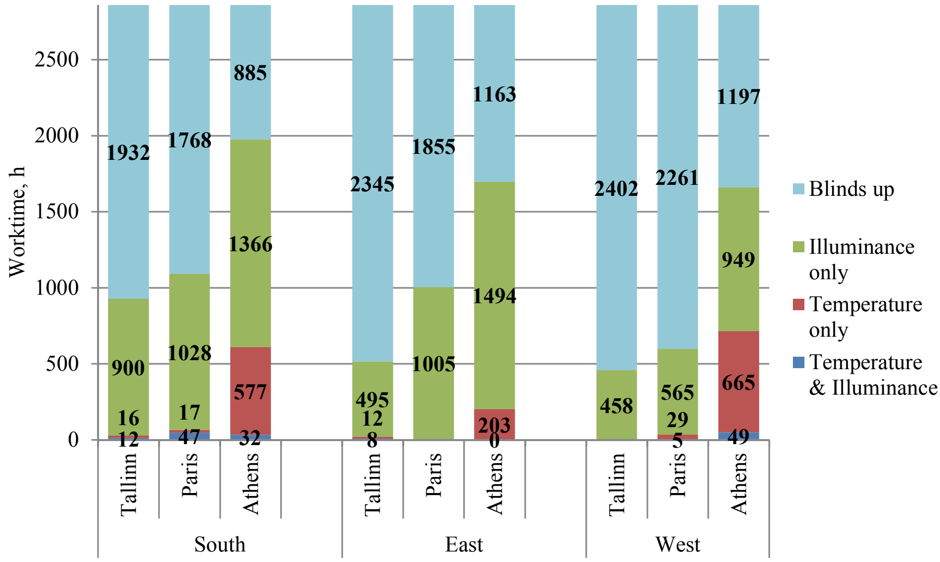


Figure 31 The illustration of shading need on different facades in all climates in case of control principle no 1.

Figure 31 demonstrates that in Tallinn and Paris the duration of drawn blinds did not depend much on whether shading was controlled according to room temperature during occupancy besides illuminance levels or not. However in case of Athens there were substantial differences between control principles no 1-3. Naturally, adjustment of blinds only according to illuminance during occupancy resulted in the shortest time of drawn shading. In addition to Figure 31, Figure 32 also shows the differences in the need for shading depending on the climate and location. In Tallinn and Paris the duration of blinds being in down position did not exceed 40% during occupancy for any case, whereas in Athens the duration could be as high as 70% of working time.

In East and West orientations of buildings located in Tallinn and Athens, the duration of drawn blinds did not differ much. However, in Paris drawn shading was required for a significantly longer time period in the East facade than the West. While Tallinn and Athens are located at East longitudes 24.8° and 27.3° respectively which correspond well to their Eastern-Europe time zone, Paris is located near the Greenwich meridian, but its time zone is Central-European. Due to that in Paris the sun azimuth is further North when work time begins in Paris and the East facade receives more sunlight during the beginning of a work day than it does in Tallinn and Athens. The same effect does not appear on the West facade because generally the sun has not set yet when work days end in all of the studied locations.

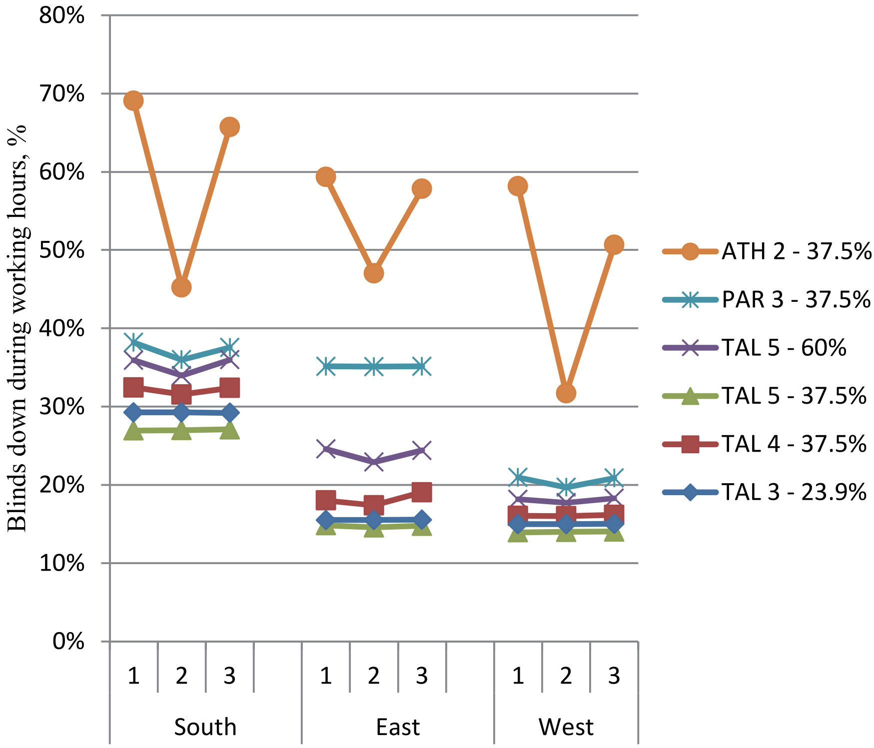


Figure 32 The effect of control principle, facade solution, orientation and climate on the time that blind are down during working hours.

The results of the analysis for the climate of Paris were alike to Tallinn and therefore similarly the most simple control principle i.e. strategy no 4 was chosen as the optimal one. The control macro can be found in the end of previous Section in Figure 29. In case of Athens using 2-piece blinds or control methods based on external conditions also did not achieve better energy efficiency than algorithms based on room temperature and illuminance. However, allowing drawing shades according to room temperature when illuminance was not too low during working hours i.e. control principle no 3 resulted in lowest primary energy use. Although control principle no 2 assured longer periods of unobstructed view, it also had high cooling needs. Low energy need and better thermal comfort usually are connected and therefore control principle no 3 was chosen as the optimal one and occupants could always manually redraw the blinds if they prefer view over thermal comfort. The control macro of the principle no 3 is presented in Figure 33, whereas in case of actual installation the information about working time should be provided from occupancy sensor instead of time schedule (element 7.1 in Figure 33).

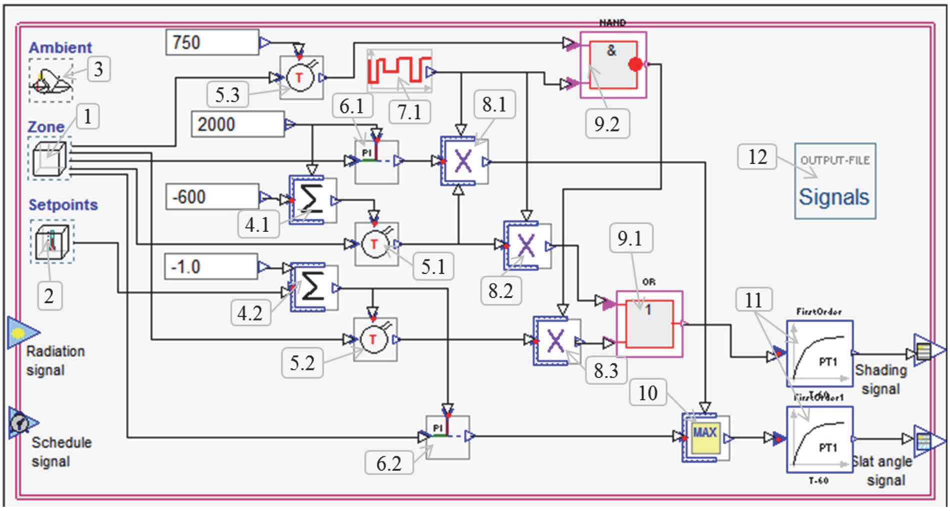


Figure 33 The macro of optimal control principle in Athens (control principle no 3 in Table 11).

3.2.3 Cooling loads

Optimizing the control principles increased the energy savings achieved with external blinds, however we believe that it is not enough to assure the financial feasibility if only energy use is taken into account. The reduction in cooling system investment cost resulting from the decreased cooling capacities may become the crucial aspect when the feasibility of external blinds is considered in the early stages of building design.

It is important to know if and how different control principles affect the design cooling capacities illustrated in Figure 34 and Figure 35. Using external blinds decreased sensible cooling capacities by 19-49 W/m^2 i.e. 47-75%, which allows reducing investment on the cooling equipment significantly while increasing its efficiency as it becomes easier to utilize free cooling sources. Using PI-controllers for slat angle control assured cooling capacities around 15-20 W/m^2, whereas suntracking resulted in slightly larger cooling capacities between 20-30 W/m^2. Sensible cooling of 15 W/m^2 can be assured by supplying 1.5 l/(s m2) of +17 °C fresh air into a +25 °C room. Simulated situation applies for average use in an open plan offices as the internal gains usage factor of 55% was applied. In cooling design of smaller offices a usage factor close to 100% should be used and therefore it cannot be said that supplying cool air only is enough for assuring +25 °C throughout the year. In addition, a very efficient lighting system was used and in case of a common lighting system internal heat gains might prove to be also too high for eliminating room conditioning units. As cooling capacities are affected by several building parameters, the values shown in this section are not universal, but they indicate external blinds' effectiveness of reducing solar gains instead.

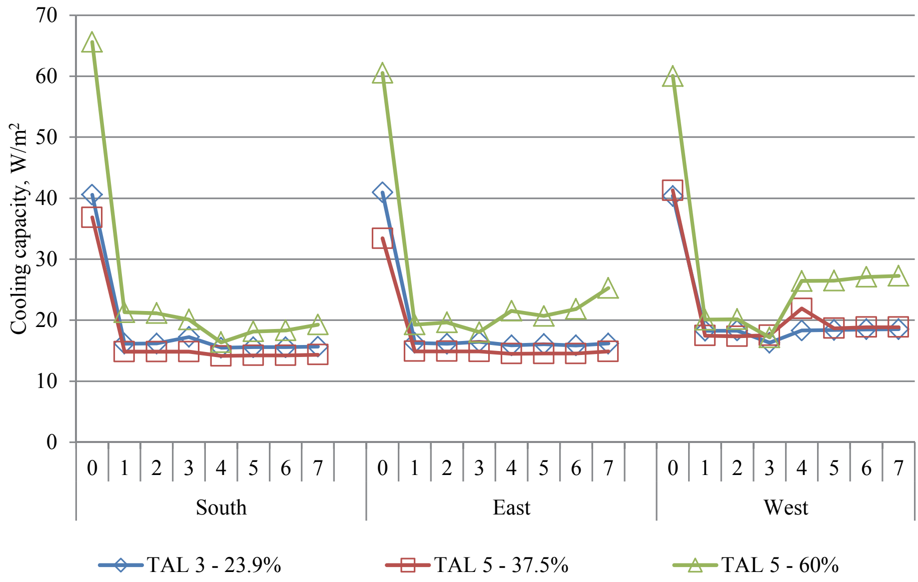


Figure 34 The cooling capacities of different control principles in Tallinn cases with triple and quintuple windows. The case with quadruple glazing is shown in Figure 35.

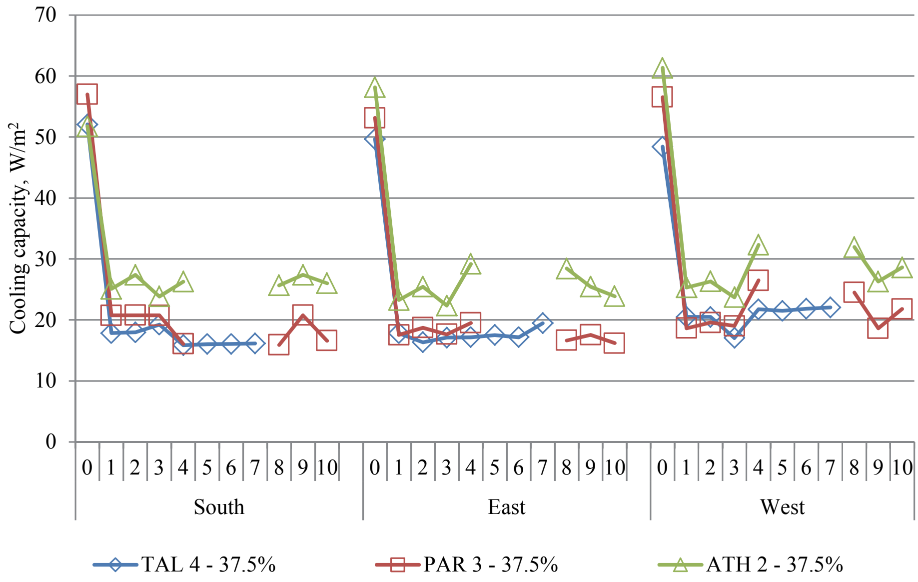


Figure 35 The cooling capacities of different control principles in different climates.

Currently it is common practice to size room cooling units by simulating only one design date for the whole building, however sun angles differ significantly throughout the year. In cold climates the temperature differences

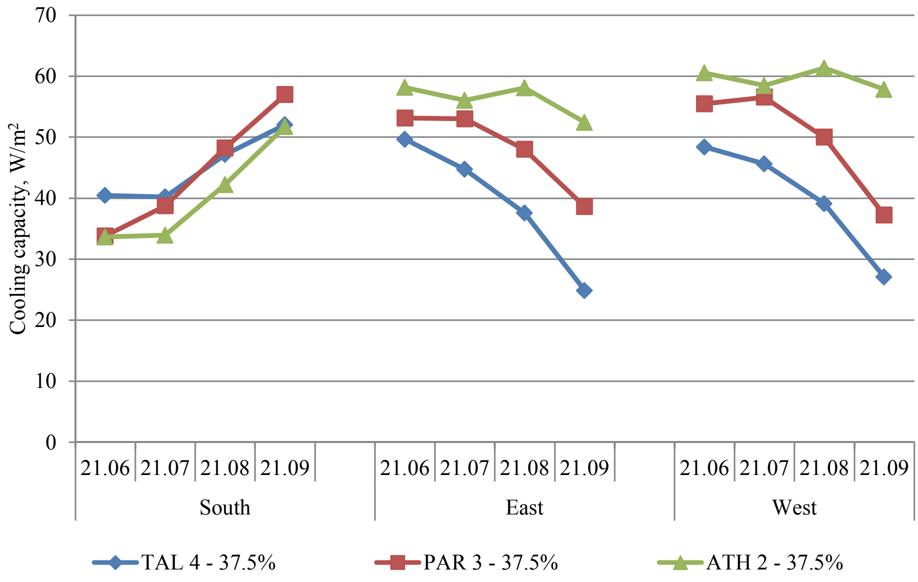


Figure 36 The cooling capacities in different climates depending on the design day.

between indoor and outdoor conditions during summer are not large and solar gains have a much larger effect on cooling capacities compared to external temperature. Figure 36 describes how sensible cooling capacities depend on the sun angles on different dates. Clear sky conditions were used and the solar radiation was calculated by IDA-ICE. It can be seen that the highest solar gains in the South facade appear in spring and autumn of all locations when the sun angle is lower in midday. In the East and West the critical time is the summer in Tallinn and Paris, however in Athens 21st of August could be appropriate for designing the capacity of space cooling. The results of cooling capacity calculations characterize the complexity of the issue as the highest heat gains due to solar radiation might appear in the cooler seasons if there are no surrounding objects blocking the sunlight. Thus the design dates must be carefully chosen to design the cooling units on different facades and the chiller of the whole building. Design periods for calculating cooling capacities should be developed for different months to also take into account the cooling or heating effect of diurnal outdoor conditions.

The properties heating, ventilation, cooling and lighting system and the parameters of the venetian blinds remained the same throughout the study. At the same time, the results may be sensible for changing any of these parameters. Aspects for further analysis are the control setpoints and deadbands, especially when considering workplace illuminance levels. The small deadband for drawing shading due to glare might cause redrawing the shading shortly after it was drawn and too frequent position changes reduce the life span of actuators and might also disturb the office worker. In addition conflicts might occur if there are workers present near the window that need glare protection and also at the back wall needing daylighting. Therefore, we propose the developed control macros for testing in other studies in order to find optimal control principles satisfying office workers which then could be generally implemented in design guidelines and manuals.

3.3 Standard and detailed model effect on energy needs

In the methods paragraph we showed that standard and detailed window models result in different energy needs. In the current section the gaps in room heating and cooling needs were quantified. The analysis show that similarly to detached houses [83] using standard triple and quadruple window models result in lower heating needs and higher cooling needs. However in case of 5 pane windows, the results are the opposite – standard quintuple glazing results in higher heating need and lower cooling need. Figure 37 presents space heating and cooling energy needs with standard and detailed glazing models in case of South, East, West and North oriented zones respectively. The proportions of heating and cooling vary depending on the façade orientation and window type. Therefore simulated total energy need could be higher with either glazing model type in comparison to the other.

Total energy need with triple windows was generally higher with standard glazing models in South, East and West facades due to relatively large proportions of cooling energy. In South the difference total energy need ranged between 0.8-4.9 kWh/m^2, in East between 0.1-1.1 kWh/m^2, in West between 0.0-1.6 kWh/m^2, whereas total energy need was slightly lower with standard glazing in East and West orientated zones with small triple windows. The results were the opposite in the North façade as heating need dominated. Triple standard glazing in North façade resulted in lower total energy need by 0.9-1.1 kWh/m^2. In case of quadruple glazing, the only orientation where detailed models provided lower total energy need was the South, where the difference was between 0.2-1.2 kWh/m^2. In East detailed glazing resulted in higher energy need by 0.3-0.5 kWh/m^2, in West by 0.4-0.8 kWh/m^2 and in North by 0.1-0.2 kWh/m^2. In the North façade, smaller standard 5 pane windows resulted in total energy need higher by up to 0.2 kWh/m^2 and in case of larger standard windows the energy need was smaller by up to 0.4 kWh/m^2.

Analysis of heating and cooling need demonstrated that differences in heating are smaller than in cooling. Figure 38 presents the simulated energy need difference of detailed window models from respective standard window models. Values over 50% are not presented in figure 3b, because the absolute difference was smaller than 0.4 kWh/m^2 in such cases and increasing the range of vertical axis would have made the figure harder to read. Largest differences in heating energy appeared with triple glazing and the increase with detailed glazing ranged between 0.9-1.9 kWh/m^2 i.e. 9.3-13.8%. In case of 4 and 5 pane windows the differences in heating need remained within 0.5 kWh/m^2 i.e. 0.1-8.2%. Detailed windows resulted in lower cooling need by up to 6.4 kWh/m^2 in case of large South oriented triple windows and in higher cooling need by up to

3.8 kWh/m^2 in case of large quintuple windows in the West façade. Cooling energy difference with quadruple glazing remained below 1.3 kWh/m^2. Relative differences in cooling energy were higher with smaller. Therefore bringing out the largest differences in cooling energy is not reasonable, but if absolute difference in cooling energy was higher than 1 kWh/m^2, then the relative differences up to 40% occurred.

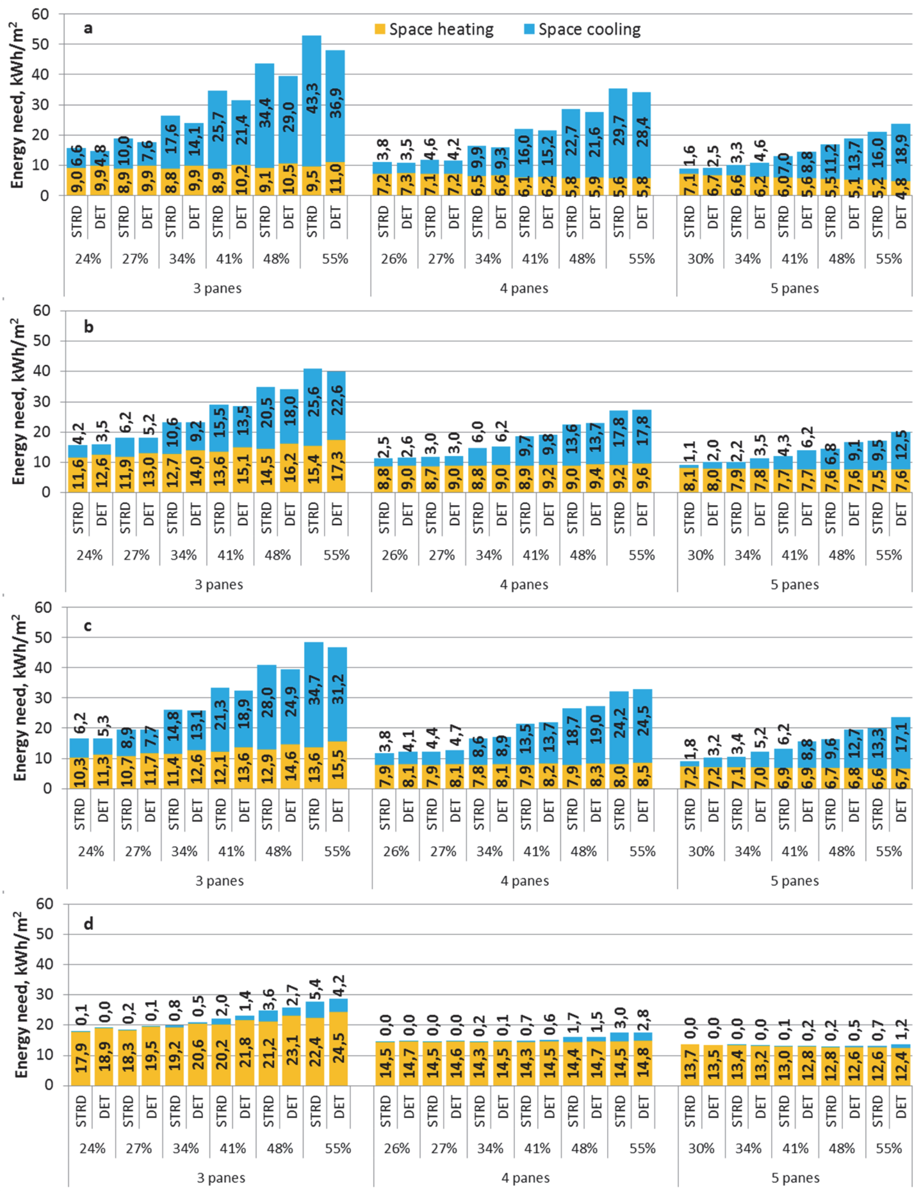


Figure 37 Space heating and cooling needs in the (a) South, (b) East, (c) West and (d) North oriented zones in case of standard and detailed window models. Code: STRD – standard window model, DET – detailed window model; 24% means window-to-wall ratio 24%.

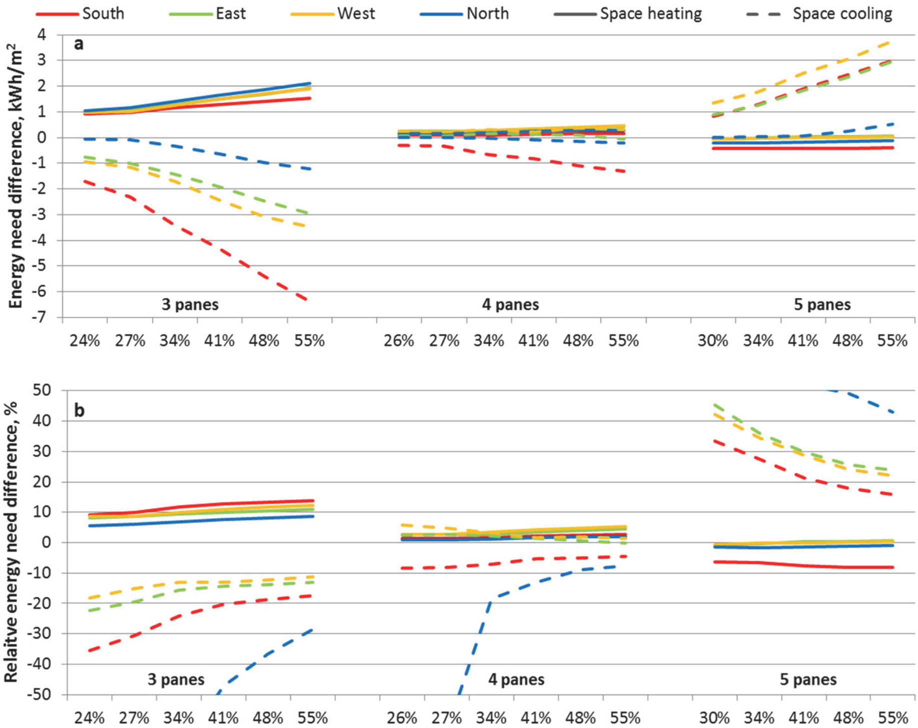


Figure 38 Detailed window models space heating and cooling need difference from standard window models in zones with different orientations and window types. (a) energy need of detailed window models has been deducted from standard window models respective value; (b) value shows how much the energy need with detailed glazing differs from standard glazing. Code: 24% means window-to-wall ratio 24%.

We have identified the differences in the simulated energy need however it is unknown if the differences have significant effect on the outcome of office building façade analysis. In initial façade analysis we presented financially feasible solutions office building façade design, however standard window models were used. This part of the study revealed that in would be reasonable to repeat previous studies with detailed window models and compare the results to determine the importance of simulation models in façade analysis.

3.4 Cost-effective façade solution sensitivity analysis

The sensitivity analysis was conducted to see the effect of difference in façade solutions obtained based on energy simulations.

Compared to our initial work we did several changes to the office floor model. The main changes concerned window models, however two changes also influenced the ventilation system. The changes were:

1. Detailed window models were used in addition to standard window models
2. More realistic solar heat gain coefficient (SHGC or g-value) and solar transmittance multipliers that depict the effect of shading on the standard window properties were used
3. Advanced control algorithm was used to control external blinds
4. Minimum exhaust air temperature after the heat recovery unit was decreased from +1 °C to -5 °C
5. Ventilation rate outside working hours was decreased from 0.30 $l/(s\cdot m^2)$ to 0.15 $l/(s\cdot m^2)$

3.4.1 Reasonable external wall insulation thickness

In section 3.1.5 we showed that cost-effective external wall mineral wool thickness was 200 mm and that it was reasonable to use 250 mm insulation layer in case of quadruple windows. The cost-effective insulation thickness has decreased to 150 mm due to changes in the economic situation, construction and energy prices. Figure 39 illustrates the primary energy and 20 year net present value of a whole office floor in case of different facade solutions. Lowest NPV was reached with insulation thickness 150 mm with all facade solutions, which made it the financially feasible solution. However if we used 150 mm insulation

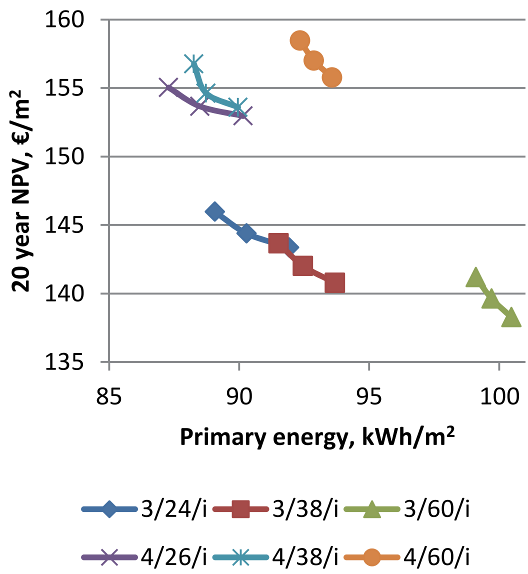


Figure 39 The 20 year NPV and primary energy depending on the external wall mineral wool thickness. The points of each facade represent 150, 200 and 250 mm from left to right respectively. The case codes illustrate window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading.

thickness with quadruple windows, then a more energy-efficient and also cheaper solution could be reached with triple windows and larger insulation thickness e.g. case 3/24/i with 250 mm insulation layer. Therefore it is reasonable to use 200 mm mineral wool layer in external wall with quadruple windows. All the subsequent facade analyses of the sensitivity analysis were done with insulation thicknesses 150 mm and 200 mm with triple and quadruple windows respectively.

3.4.2 Energy simulation results

The results given in Figure 40 show that space heating dominated the energy need of most cases except for ones with large window and internal shading in South, East and West orientations, which had large cooling needs. Lighting energy need did not dominate in any of the cases. Overall, the results are similar to initial façade analysis, however in the previous work external shading increased lighting need, but in the current case using an advanced control algorithm utilized daylight more efficiently and therefore automated blinds decreased lighting energy need compared to respective cases with internal blinds. The decrease in lighting energy was largest in the South orientation ranging between 24-35% i.e. 0.7 and 1.7 kWh/m^2, followed by East and West facades with 11-22% i.e. 0.3-1.0 kWh/m^2. In the North orientation the effect on lighting energy did not exceed 0.1 kWh/m^2.Compared to results presented in the previous section, the heating need had increased and cooling need decreased, which can be explained by decreased lighting installed power from 7 to 5 W/m^{2,} demand-based control and added shading.

Figure 41 presents the primary energy of all studied cases and it shows that increasing the sizes of windows equipped with internal shades also increased primary energy use except for the North orientation with quadruple windows, where primary energy decreased slightly. Previously lowest primary energy with quadruple windows and internal blinds was achieved with WWR 37.5%, while now in South, East and West facades smallest four pane windows assured lowest primary energy. In previous work we stated that external shading increased the energy use of some cases, however no such case appeared in the current analysis. Finally the primary energy in the current study was slightly lower caused by increased efficiency of ventilation heat recovery, however this did not remarkably affect the choice of facade solutions.

Another aspect was that the size of a window with external venetian blinds had a significantly smaller effect on primary energy than the size of a window with internal blinds. Increasing the WWR of windows with internal blinds could increase primary energy by up to 7.1-16.1 kWh/m^2 in South, East and West orientations depending on the window type e.g. the gap in primary energy of South orientated cases with triple window WWRs of 24% and 60% was 16.1 kWh/m^2. However, if windows were equipped with external blinds then increasing the WWR could increase primary energy by up to 2.4 kWh/m^2 (triple windows in East facade) or decrease it by up to 4.8 kWh/m^2 (quadruple windows in South facade). This shows that if the designers of an office building in a Nordic climate decide to use automated external shading with an efficient control algorithm, then the architects could have more freedom in dimensioning windows.

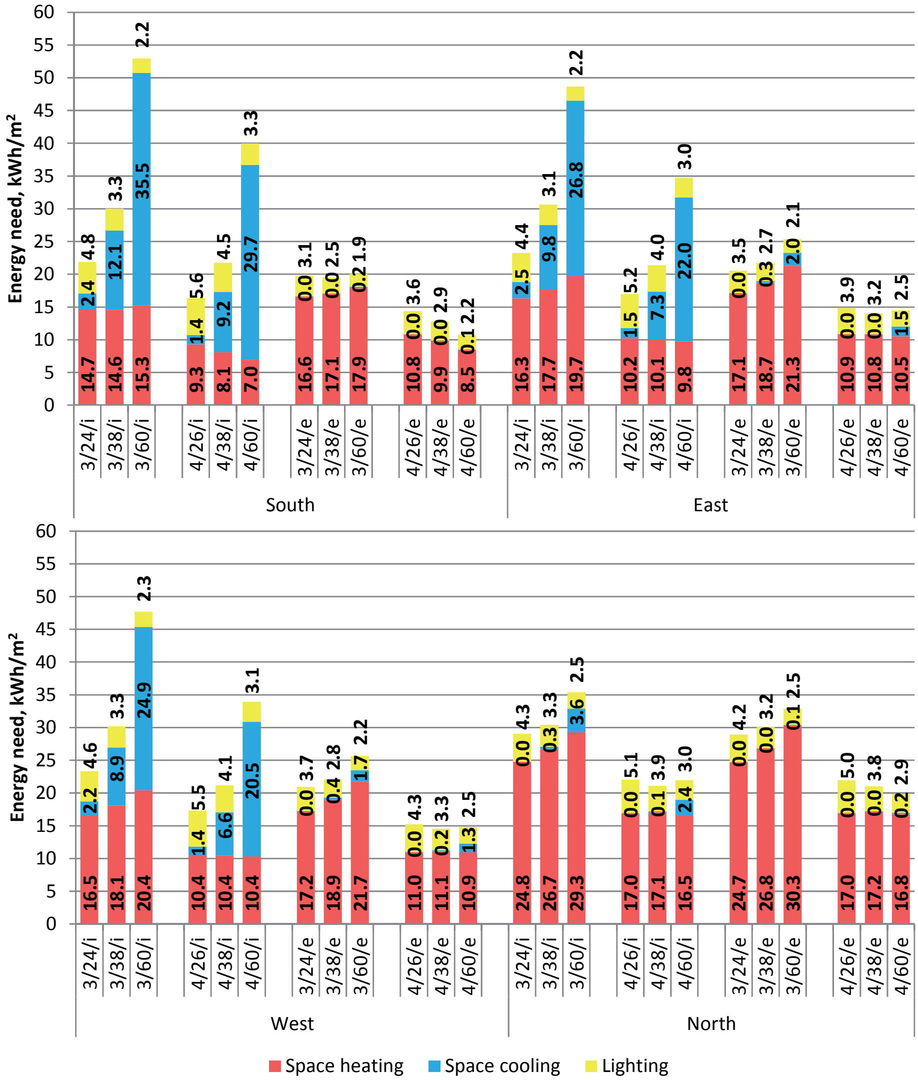


Figure 40 Energy needs of all studied cases. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e“ means external shading.

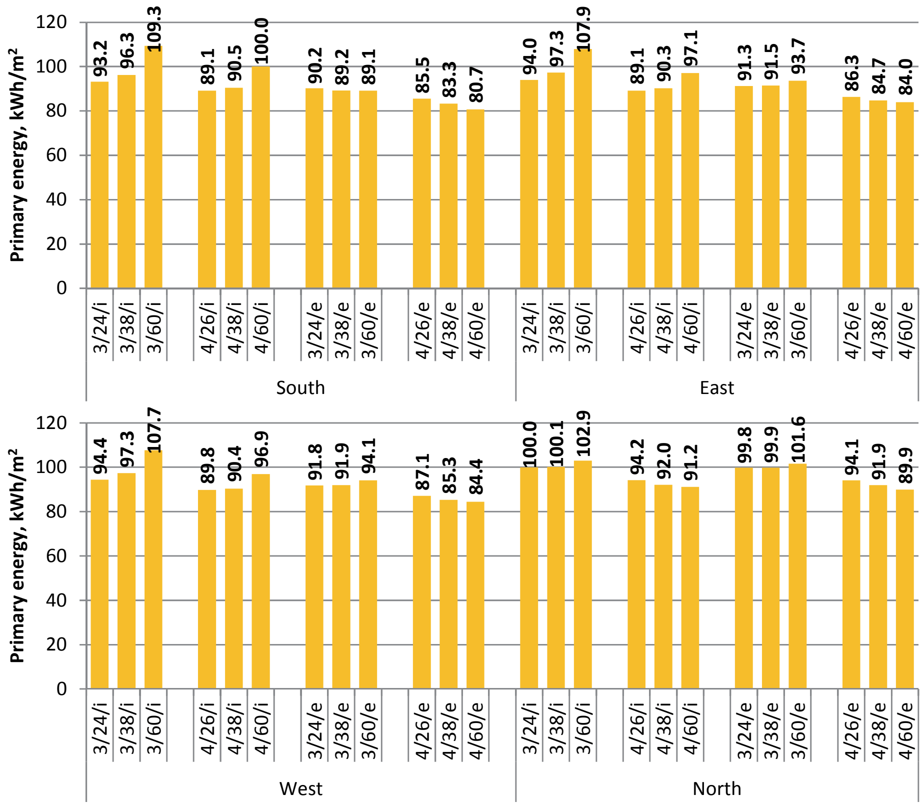


Figure 41 Primary of all studied cases. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e“ means external shading.

3.5 Economic calculation results

Figure 42 presents the results of the NPVs of all studied cases with detailed window models and current economic situation, energy and construction prices. External wall insulation thicknesses 150 and 200 mm were used with triple and quadruple windows respectively. The cost-effective façade solution i.e. with lowest NPV was triple windows without external shading and the optimal WWR was 37.5% in the South orientation and 60% in East, West and North. The NPV was formed by the construction costs of external walls, windows, shading and energy costs including space heating, cooling and electric lighting, which were multiplied by discount factor of 18.0. The construction costs made up the majority of the NPV in all cases and the proportion decreased when WWR increased. The largest proportion of construction cost was formed by external walls and the proportions of other components varied. Windows made up the smallest part if triple glazing was used and external shading cost was significant when used. The relatively low cost of triple windows compared to external wall was the reason why larger windows resulted in lowest NPV despite increased energy costs.

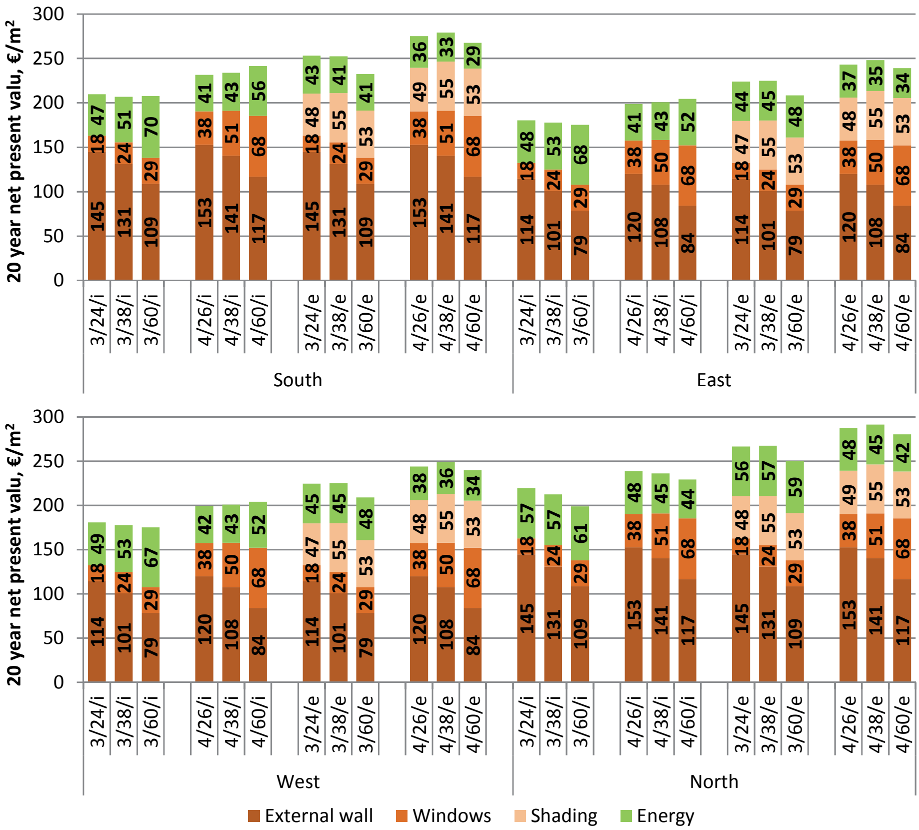


Figure 42 Net present value of all studied cases per floor area of respective zones. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e“ means external shading.

3.5.1 Calculated energy use differences between standard and detailed window models

The energy needs calculated with standard and detailed windows differed by up to 4.0 kWh/m^2, whereas largest gaps appeared in cooling and smallest in lighting as is seen in Figure 43. Generally heating need with detailed windows was higher reaching 1.6 kWh/m^2 and largest differences appeared with triple windows. The only cases with detailed window models resulting in lower heating energy were South oriented externally shaded triple and quadruple windows with WWR 37.5% and 60%. Detailed window models generally resulted in smaller cooling needs by up to 4.0 kWh/m^2, whereas largest differences appeared in case of large internally shaded South and East orientated windows. Standard window models resulted in smaller cooling needs only in case of externally shaded East and West orientated windows with the gaps reaching 0.5 kWh/m^2. The lighting energy need was generally smaller with detailed window models. The largest differences in lighting reached 0.9

kWh/m^2 and standard windows only resulted in smaller lighting need in case of small internally shaded quadruple windows in South, East and West facades. Compared to the results presented in the previous section the absolute differences in space heating and cooling needs remained similar.

Generally lower primary energy was achieved with detailed window models compared to standard window models. The difference increased if window sizes were increased in all cases of the South facade and in case of internally shaded quadruple windows in East and West orientations. The case of South oriented internally shaded quadruple window with WWR 60% resulted in the largest primary energy difference of 2.7 kWh/m^2, followed by South facade triple windows with WWR 60% with internal and external shading which had differences of 1.9 kWh/m^2. All these cases resulted in lower primary energy with detailed window models. Usually detailed window models resulted in higher primary energy use in case of large externally shaded windows in East and West facades.

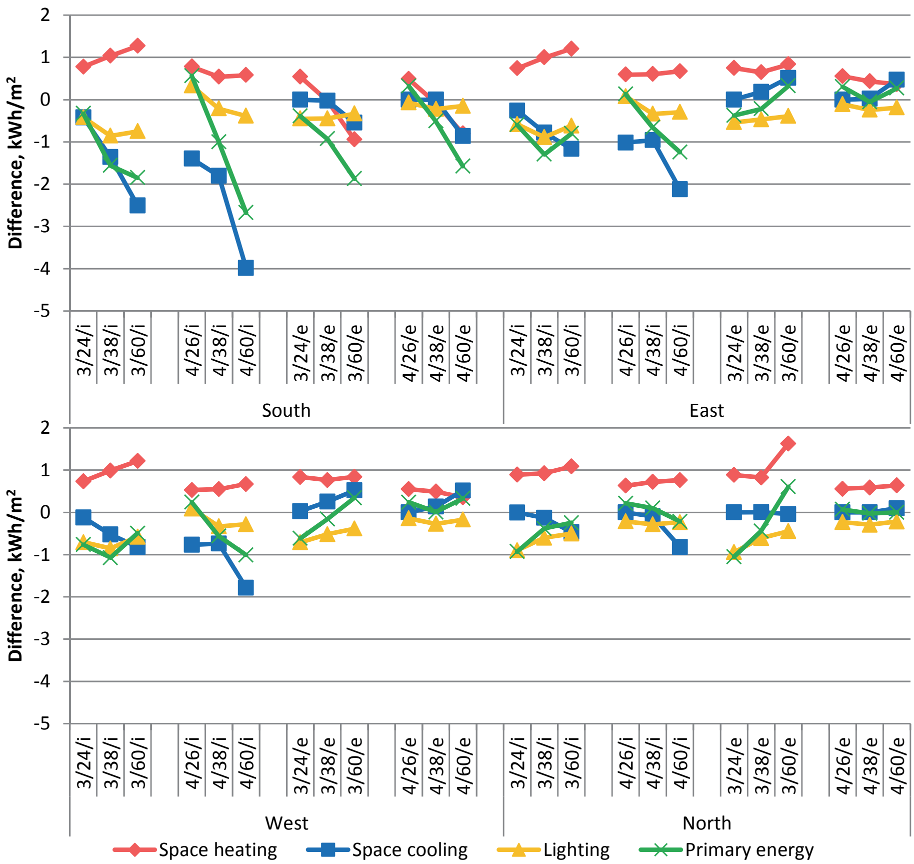


Figure 43 The difference of energy simulation results obtained with standard window models compared to simulations with detailed window models.

3.5.2 Comparison of NPVs

Table 18 presents façade solutions with three lowest NPVs. The cases are given facade by facade in the order of the most financially feasible cases i.e. with the lowest NPV. The base case NPVs were calculated with detailed window models and updated energy prices, interest rate, inflation, energy price escalation and construction prices. The cases included:

1. Model with detailed window models and data from 2015 (Base)
2. The results from the previous study [44, 73] (2013)
3. Standard window models were used instead of detailed models, other data from 2015 (StaW)
4. The energy prices of 2013 were used, other data from 2015 (Energy)
5. The interest rate, inflation and energy price escalation from 2013 were used, other data from 2015 (Economy)
6. The construction prices of 2013 were used, other data from 2015 (Construction)
7. The energy simulation model results of the base case model were used in combination with all other information from 2013 (2013+DetW)

The NPVs of the most cost-effective façade solution are given as absolute values and the difference of NPV from the best case in the row are given for the second and third best solutions. The façade solutions in the table are marked with colors. Green means that changing the respective variable did not affect the outcome of the three most cost-effective façade solutions compared to the base case. Orange indicates that the respective variable affected the cost-effective façade solution.

Compared to the previous study the cost-effective solution remained the same in the South facade, but the optimal window size increased in the other orientations. The triple window case with WWR 60% was not presented in the figures of previous study, because it was neither the most financially feasible nor energy efficient case. Using standard window models instead of detailed models did not affect the optimal solution in any orientation and thus had the smallest effect on the ranking of the cases despite the differences in simulated energy use. Also using the previous energy prices did not have any influence on the ranking order of the facade solutions. However the 2013 economic variables and construction prices both decreased the optimal window size in South, East and West facades. When we used energy prices, economic variables and construction costs combined with the energy simulations of the base case, the optimal facade solution was altered most.

Triple windows with WWR 37.5% and without external shading was ranked first in the South façade for most cases and similar solution with WWR 23.9% was prevailing as the second best choice, while the NPV difference between 1st and 2nd choice remained below 2 €/m^2. The 3rd choices generally had larger increases in the NPV especially with WWR of 60% and therefore triple windows with WWR in the range of 25% and 40% should be used in the South façade.

In the East and West orientations triple windows with WWR 37.5% and 60% without external shading were mostly represented in the columns with two lowest NPVs. Only energy simulations with detailed windows and a few years old price data and economic situation resulted in the lowest WWR of 23.9% as the cost-effective solution, whereas this façade solution dominated the column with 3rd lowest NPVs. Therefore larger windows could be used in East and West orientations compared to the South if only NPVs presented in this table is considered.

The North façade was least influenced by changing of variables and the dominating solution was triple windows with WWR 60% and without external shading. The NPVs increased remarkably if the window sized decreased in the orientation. Therefore the North façade tolerates the largest glazed areas.

Table 18 The façade solution with three lowest NPVs of all orientations in case of updated energy prices, economic parameters and construction costs (Base case). The table also includes cases from the previous study (Previous), and when the standard window model (StaW), old energy prices (Energy), interest rate, inflation and energy price escalation (Economy), construction prices (Construction) were changed. The case 2013+DetW includes all old variables, but the energy simulations were conducted with detailed window model.

		1st choice		2nd choice		3rd choice	
		Solution	NPV, €/m^2	Solution	ΔNPV, €/m^2	Solution	ΔNPV, €/m^2
South	Base	3/38/i	206.6	3/60/i	1.0	3/24/i	3.0
	2013	3/38/i	200.1	3/24/i	0.2	-	-
	StaW	3/38/i	208.8	3/24/i	1.3	3/60/i	1.4
	Energy	3/38/i	206.5	3/60/i	0.3	3/24/i	3.2
	Economy	3/38/i	222.2	3/24/i	1.7	3/60/i	6.6
	Construction	3/38/i	196.9	3/24/i	1.0	3/60/i	3.6
	2013+DetW	3/24/i	212.1	3/38/i	0.0	3/60/i	8.3
East	Base	3/60/i	175.4	3/38/i	2.4	3/24/i	5.0
	2013	3/38/i	169.7	3/24/i	2.1	-	-
	StaW	3/60/i	176.5	3/38/i	3.0	3/24/i	4.7
	Energy	3/60/i	175.1	3/38/i	2.8	3/24/i	5.5
	Economy	3/38/i	193.8	3/24/i	1.2	3/60/i	2.2
	Construction	3/38/i	170.9	3/60/i	0.3	3/24/i	0.6
	2013+DetW	3/24/i	186.3	3/38/i	0.7	3/60/i	5.0
West	Base	3/60/i	175.2	3/38/i	2.6	3/24/i	5.8
	2013	3/38/i	171.8	3/24/i	1.4	-	-
	StaW	3/60/i	175.8	3/38/i	3.4	3/24/i	6.1
	Energy	3/60/i	174.9	3/38/i	3.0	3/24/i	6.1
	Economy	3/38/i	193.8	3/60/i	1.9	3/24/i	1.9
	Construction	3/38/i	170.8	3/60/i	0.0	3/24/i	1.2
	2013+DetW	3/24/i	187.0	3/38/i	0.1	3/60/i	4.1
North	Base	3/60/i	199.1	3/38/i	13.4	3/24/i	20.5
	2013	3/38/i	205.3	3/24/i	13.0	-	-
	StaW	3/60/i	199.4	3/38/i	13.6	3/24/i	21.5
	Energy	3/60/i	200.1	3/38/i	13.3	3/24/i	20.2
	Economy	3/60/i	217.6	3/38/i	12.2	3/24/i	19.2
	Construction	3/60/i	191.9	3/38/i	10.8	3/24/i	15.9
	2013+DetW	3/60/i	208.6	3/38/i	10.0	4/60/i	15.3

The façade solution is the same as the Base case after changing the variable

The façade solution changed compared to the Base case after changing the variable

4 DISCUSSION

4.1 Boundary conditions for office building façade design

Facades design is finding a compromise between energy efficiency, thermal comfort, daylight, view and architectural appearance. All these aspects affect the costs of building owners and employers either directly through energy bills or indirectly through building occupants' satisfaction and productivity. In general, every project must start with the end goal in mind, which the owner/client must be sure to articulate clearly to designers. This helps to come up with design solutions that are within budget limits. Obviously, this is not always the case due to various reasons, and often decisions are made with only the short term in mind. That is why building codes set general requirements and rules for the design of buildings, including office buildings. According to Estonian regulation [3], new office buildings must comply with a minimum energy performance requirement of primary energy ≤160 kWh/m^2, if no stricter requirements by the client have been specified, as in the case of a low energy building with primary energy ≤130 kWh/m^2, or a nZEB with primary energy ≤100 kWh/m^2.

The studies described in this thesis showed that increasing currently common triple window sizes has positive effect on daylighting and view, but the effect is negative on energy use and thermal comfort. Due to that we need to set boundary conditions for designing glazed areas, which can be:

1. Regarding daylighting:
    a. Average daylight factor above a certain level (e.g. 2%) and/or
    b. Daylight autonomy during working hours above a certain level (e.g. 50%)
2. Regarding thermal comfort:
    a. Predicted percentage of dissatisfied below a certain level (e.g. 10%) and/or
    b. Room cooling capacities below a certain level (e.g. 40 W/m^2)
3. Regarding energy efficiency
    a. Primary energy below a certain level (e.g. minimum requirement, low energy or nearly zero energy building level) and/or
    b. Construction costs or net present value at cost-effective level

We took all these aspects into account and based on these analyses, several recommendations for construction industry and designers can be offered.

4.2 Recommendations for façade design

The results of this study indicated that the financially most feasible solutions change in time and therefore cost-effectiveness calculations should be updated every few years. The largest influences were caused by changes in the economic situation and construction prices. It is natural that new technical solutions increase their market share and thus become more affordable, which we believe is the main reason why cost-effective solutions change in time. Triple windows are a good example, which have become remarkably cheaper due to being the primary solution used in new building in Estonia. It is essential for building designers to keep themselves informed with the costs of different technical solutions to more accurately assess the financial feasibility of various facade solutions especially if interest rates remain low.

The NPV calculations showed that optimal window sizes have increased, however they are also less energy-efficient, decrease thermal comfort and require higher heating and cooling capacities thus increase the cost of these systems. As the current situation with inflation, interest rate, energy escalation seems exceptional, we think that the cost-effective cases achieved with an accurate building model, but 2 year old economic situation should be used for giving suggestions for office building facade design. The described case resulted in the following cost-effective solutions – triple internally shaded windows with WWR 38% in South, East and West facades and a similar solution with WWR 60% in North orientation. The daylight factor requirement 2% would allow decreasing the WWR to 24%, which would assure lower cooling capacities and investment costs and increased thermal comfort. Therefore we advise that currently WWRs in the range 25-40% should be used in South, East and West orientations to assure comfortable indoor climate and relatively low energy costs. Larger windows could be used in the North facade.

We can see that some technical solutions such as external venetian blinds are becoming more affordable and such solutions would give architects more freedom in choosing the window size. Also larger market uptake of quadruple glazing or windows with similar parameters would increase architectural freedom, if energy use, thermal comfort and cost-effectiveness are considered in facade design. Using dynamic external blinds also requires an efficient control algorithm and Figure 44 describes such control principle suitable in a cold climate. The algorithm requires measuring the presence of occupants, room temperature and assessing probability of glare. Current technologies offer reasonable means for occupancy detection and temperature measurements, but at the moment assessing glare probability in real office buildings still requires research.

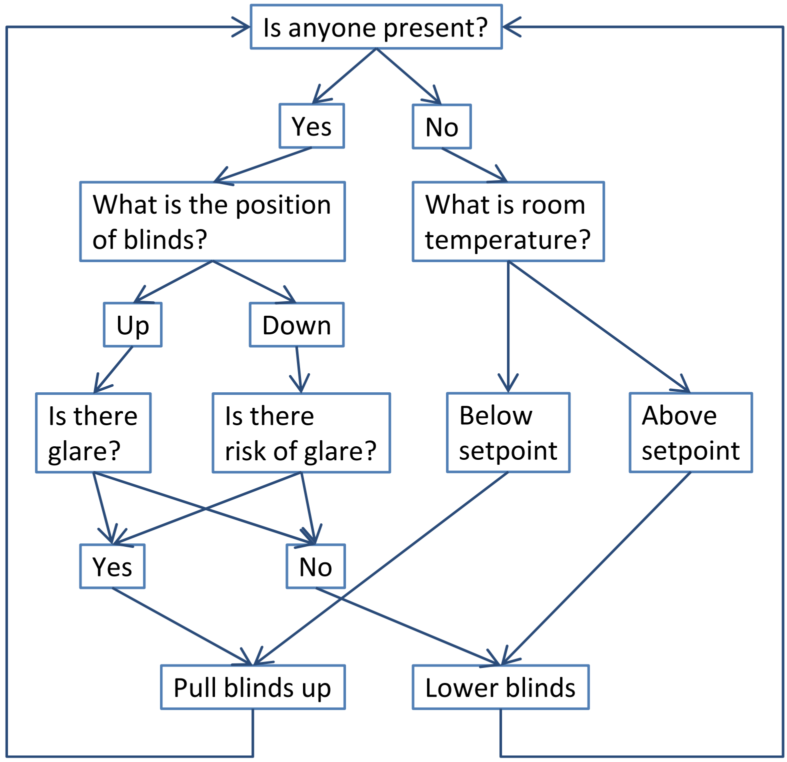


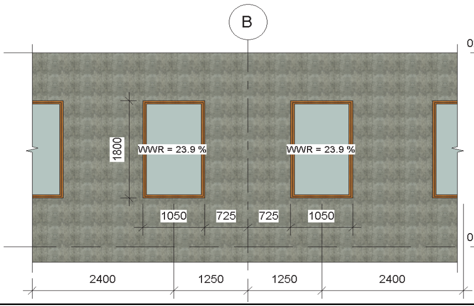
Figure 44 Description of control algorithm suitable for dynamic external blinds in an office building located in a cold climate.

Table 19 visualizes the results of this study for a low energy building and nZEB solutions. In the current context, cost-effective solutions lead to low energy buildings; however, achieving nZEB level requires additional costs and therefore, results in higher NPV values. Solution A describes the solution with lowest WWR that leads to lowest energy use, cooling capacities with triple windows and is therefore one of the recommended solutions. Solution B has a higher WWR of 37.5% in most orientations thereby assuring better view and daylighting. In addition case B with triple windows is an economically reasonable choice and with quadruple windows energy efficiency could be improved significantly. Solution C was the most energy-efficient one we achieved, however it is uncertain whether window manufacturers could provide quintuple windows at current time.

Table 19 also gives heating and sensible cooling capacities of respective solutions. Heating capacities of open-plan offices without external roof or slab on ground were at design outdoor temperature -21 °C in the range of 9-19 W/m^2. The values are relatively low, however a case-study of a nearly zero energy office building in Estonia showed that a heating systems are still needed in energy-efficient office buildings [42]. Our study revealed that generally internal and solar heat gains successfully keep room temperature above 21 °C, while most of the heating need occurs during weekends and nights. A conventional heating system e.g. with radiators or other devices was a reasonable choice and heating with warm supply air caused over-heating in some rooms, increased energy use and investment cost. Sensible cooling capacities (Table 19) with smaller window were in a reasonable range of 40 W/m^2. However the cooling capacities could increase up to 70 W/m^2 with larger windows, especially in the most energy-efficient case with 5 pane windows and WWR 60%. This shows that in the future we might have to find a compromise between low energy use and high cooling capacities or the other way around.

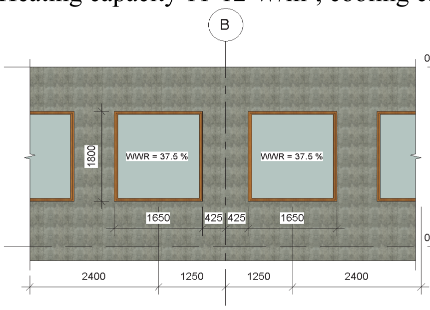
Table 19 Summary of fenestration design solutions for a low energy building. Façade layouts are given for a room module 2x2.4 m (a partition between every second 2.4 m) and floor height of 3.3 m.

A. Recommended solution within cost-effective range that provides highest thermal comfort: triple glazing (U_{gl}=0.57 W/(m^2·K), SHGC=0.49, τ_{vis}=0.70), WWR 23.9% (37.5% in North façade) and 150 mm thick insulation (U=0.20 W/(m^2·K)). Heating capacity 12-13 W/m^2; sensible cooling capacity 34-42 W/m^2 (except North façade).

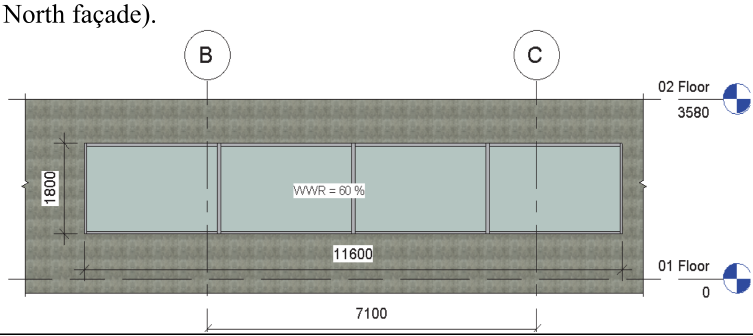


B1. Cost-effective solution with higher cooling load than recommended solution: triple glazing (U_{gl}=0.57 W/(m^2·K), SHGC=0.49, τ_{vis}=0.70), WWR 37.5% (60% in North façade) and 150 mm thick insulation (U=0.20 W/(m^2·K)). Heating capacity 14-16 W/m^2, 19 W/m^2 in the North facade; sensible cooling capacity 53-62 W/m^2 (except North façade).

B2. An interesting energy-efficient solution: quadruple glazing (U_{gl}=0.32 W/(m^2·K), SHGC=0.36, τ_{vis}=0.63), WWR 37.5% and 200 mm thick insulation (U=0.16 W/(m^2·K)). Heating capacity 11-12 W/m^2; cooling capacity 44-54 W/m^2 (except North façade).



C. The most energy-efficient solution: quintuple glazing (U_{gl}=0.21 W/(m^2·K), SHGC=0.24, τ_{vis}=0.56), WWR 60% in all orientations and 390 mm thick insulation (U=0.09 W/(m^2·K)). Heating capacity 9-10 W/m^2; cooling capacity 58-69 W/m^2 (expect North façade).



4.3 Detail of simulation models

During the study we simulated the energy use with both simplified standard window models and more accurate detailed window models. The choice of the window model did not affect the cost-effectiveness ranking of facade solutions. Therefore an energy efficiency specialist could use both of them in early-stage façade design analysis. However their results had a gap in simulated primary energy reaching 2.8 kWh/m^2. Although the number itself does not seem large it still can have a significant influence on the building design. In Estonia the primary energy requirement for nearly zero office buildings is 100 kWh/m^2, which is 30 kWh/m^2 lower than the primary energy target 130 kWh/m^2 of low energy buildings. The difference in calculated energy use could be approximately 7-8% of difference between a nearly zero energy building and low energy building. Therefore the choice of window model can have a remarkable influence on dimensioning the renewable energy systems (e.g. PV panels) to reach nearly zero energy building level. We recommend using detailed window models to calculate the total primary energy and more accurately predict the energy use of a building.

4.4 Future work

In the current work we mostly studied the façade materials, window types and technical solutions currently commonly used in constructing office buildings. We did not analyze such solutions as double-skin facades, vacuum glazing, adaptable windows (electro-, thermochromatic, etc.), phase change materials and innovative insulation materials, because these are not common. However, if any of these or other technologies would become business-as-usual, similar studies should be repeated. In addition we made several simplifications regarding window frames such as constant frame ratio. Since the frame generally has lower U-value than glazing and it is opaque it is the "weakest" part of a window and further studies should be made to reduce the frame ratio and a cost-effectiveness analysis would be relevant.

We also did not consider other heating and cooling sources besides district heating and mechanical cooling with a chiller. The results of this study can be applied for building with gas boilers because of something similar primary energy factors (0.9 vs. 1.0 for district heat and gas respectively). However the results do not apply for office buildings, which have heating and cooling supplied by ground or air source heat pumps. Such systems are all-electrical and electrical lighting energy may have a larger impact on the façade cost-effectiveness analysis. Therefore similar studies with different heating and cooling sources should be repeated.

The current study used a simplified daylight factor formula, which is a common daylight standard approach. However being a basic daylight parameter, daylight factor does not describe daylight autonomy and daylight glare probability. Daylight autonomy describes the percentage of working hours when no electrical lighting is needed. One can assume that at some point making large windows larger increases the quality of view, but does not significantly increase daylight autonomy, however the risk of glare might still increase in addition to energy use. Based on our experience energy-efficiency might be less important for architects in contrast to daylighting. Therefore materials that describe the relationship between window sizes/types and daylight autonomy, glare probability in addition to energy use, should be developed. Such guidelines could further decrease the probability that fully-glazed office buildings with poor working conditions and high energy use would be built.

We showed that automated external shading decreased or even diminished the energy penalty of increasing windows. However it is essential to remember that we used an energy-efficient control algorithm, which still needs further development. One of the future goals is to develop a method to assess glare probability in real conditions. In laboratory condition a camera, several illuminance sensors and analysis software is needed to assess glare probability at a single workplace, however it is not applicable in real offices. In this study we measured illuminance at desktop or average over the zone floor and such sensors are available on the market, however this method is not applicable in practical installation, because the solar angle varies in a large range annually and thus direct solar radiation might not fall on a desktop. A study should be conducted to study the relationship between glare probability and other variables such as desktop illuminance, solar irradiance or illuminance on a façade and time. In addition the cloudness may change rather rapidly, which might cause frequent changes in shading position and disturbance of office workers. Therefore besides installing external shades an effort has to be made to control them in an efficient way, which in addition would not disturb the office workers. The algorithm we used has to be developed further to utilize it in real projects and further studies have to be made regarding this aspect.

Besides façade design, achieving a good energy performance level of an office building also depends on technical solutions such as HVAC system efficiencies, electric lighting installed power and control principle and renewable energy generation. Currently the cost of nZEBs is an essential topic and often specialists speculate on the extra cost compared to conventional buildings. Besides façade optimization, the cost and energy savings of various technical solutions should be compared to develop cost-effective nearly zero office building packages and to quantify the extra construction cost. None of the cost calculations of this study took into account the façade solution impact on cooling system construction cost, however our study showed that smaller windows and external shading reduce cooling capacities and thus investment costs. In addition the cooling capacity is influenced by electrical lighting power and its control principle. Regarding the façade analysis, the cost of cooling system should be also taken into account to further develop the façade design guidelines.

5 CONCLUSIONS

Facade performance including windows, opaque elements and shadings has strong impact on heating, cooling and electric lighting energy needs as well as on daylight. Design of energy-efficient office building facades needs careful consideration at early-stage design phase taking into account energy efficiency, indoor climate and economic aspects. The purpose of this thesis was to provide architects, engineers, energy efficiency specialists and real-estate developers some guidelines about office building façade design in a cold climate. Cost-effective and most energy-efficient façade solutions, including window properties, external wall insulation, window-to-wall ratio (WWR) and external shading were determined with energy and daylight simulations in the cold climate of Estonia. We also simulated the performance of external automatically controlled dynamic venetian blinds with the goal of developing optimal control algorithms. Finally a sensitivity analysis was conducted regarding the accuracy of simulation models, economic variables, energy and construction prices.

Currently, triple windows are the most common and reasonably priced solution used in Estonian construction sector making it financially feasible. The thermal conductivity of 3 pane windows is significantly higher compared to external walls, therefore increasing the window size increases heating energy use in addition to cooling energy, which in not compensated by decreased lighting energy use. The average daylight factor should not be below 2% in office rooms, which can be reached with WWR of 25%. At the moment triple window cost per area is smaller than of external walls and increasing the size of glazed area decreases investment cost, on the other hand it increases investment in the cooling system. Taking into account costs on energy, daylighting and construction we concluded that recommended cost-effective facade solutions were:

- South, East and West facade: Triple windows with internal shading and window-to-wall ratio 25-40%, external wall mineral wool insulation thickness 150 mm.
- North facade: Triple windows with internal shading and window-to-wall ratio 40-60%, external wall mineral wool insulation thickness 150 mm.

In the case of high performance windows with quadruple and quintuple glazing and U-values of 0.3-0.2 windows heat losses become similar to opaque elements of external walls and the minimum window-to-wall ratios did not necessarily show any more the best energy performance. 4 and 5 pane clear low emissivity glazing provided also naturally good solar protection, because of high number of panes and coatings. Therefore the positive effect of larger windows on electric lighting and in some cases even on heating energy exceeded the negative effect of cooling energy increase. Quadruple windows with about WWR 40% and external wall insulation thickness 200 mm provided an interesting alternative in between cost-effective and most efficient energy performance level.

Automated external venetian blinds were an effective method to improve energy efficiency significantly and reduced room cooling loads by 40-70%. However, ineffective automated control method could increase energy use compared to a similar case with internal blinds. By using an advanced control principle primary energy savings up to 6 kWh/m^2 were reached in the climates of Tallinn and Paris, whereas the savings in Athens reached 32 kWh/m^2. The positive effect of shading was larger in case of larger windows and warmer climates, but regardless of the control principle automated external venetian blinds are currently still too expensive to be considered a financially reasonable solution. The proposed control algorithm in Tallinn and Paris had the following principles:

1. During working hours shading should be drawn only when illuminance levels on desktop are too high.
2. Outside working hours shading should be drawn when room temperature is ca 1 °C below the cooling setpoint
3. Sun tracking should be used i.e. the slat angle should be equal to the sun angle at any given time

In Athens room temperature should be followed also during working hours and slat angle control with PI-controllers should be used.

We conducted sensitivity analysis with varying external wall insulation thicknesses, standard and detailed window models, updated energy prices, construction costs, interest and inflation rates. We identified that economic variables and construction costs had the largest influence on the cost-effective façade solutions as a single variable, however the combination of all variables had the largest impact on the outcome of façade analysis. Energy efficiency specialists should keep themselves up to date about the prices of different façade-related solutions in order to do analysis correctly at any given time. Using standard or detailed window models did not remarkably affect the cost-effective façade solutions despite the differences in calculated primary energy, which could reach 2.8 kWh/m^2. Therefore standard window models could be used in comparison of façade solutions at early-design phase, but the predicted energy use of an office building should be simulated with detailed models.

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Special courses

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Keelteoskus

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inglise	kõrgtase
vene	algtase
soome	algtase

Täiendusõpe

Õppimise aeg	Täiendusõppe korraldaja nimetus
11.-13.06.2011	Simulation Summit 2015, Equa Solutions AB, Engelberg, Switzerland
03.-04.09.2015	IDA-ICE Power User Days 2015, Equa Solutions AB, Stockholm
16.-17.10.2014	IDA-ICE Power User Days 2014, Equa Solutions AB, Stockholm
11.-13.06.2011	Sustainable and energy-efficient building design and refurbishment, Tallinn University of Technology
13.-16.12.2010	Net-zero-energy-buildings and on-site renewable energy, Aalto University, Finland
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2007 - 2013	EstKonsult OÜ	Kütte- ja ventilatsiooni insener

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PAPER I

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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.

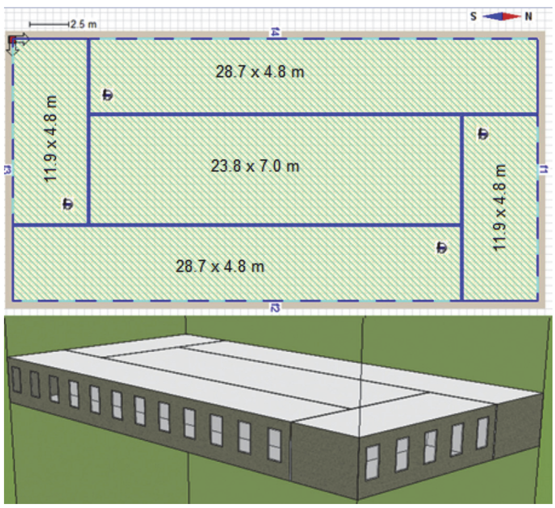

Fig. 1. The generic model of single floor of an office building constructed with 2.4 m room module–plan and 3D view. The locations of workplaces used for control of lighting are marked in the plan.

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

Occupants, W/m^2	5
Equipment, W/m^2	12
Lighting, W/m^2	5
Temperature set point for heating and cooling	+21 and +25 °C
Air flow rate	1.5 l/(s m^2); 35 l/s
Illumination setpoint at locations (x, y, z) = (2.2, 4.0, 0.9), lx	500
Total irradiance on facade above which solar shading is down, W/m^2	200
Frame ratio of windows, %	15
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/(m^3/s)	1.3
Temperature ratio of heat recovery, %	80

The initial data of simulation model is shown in Table 1. Lighting and shading control principles were adopted from [16]. The energy simulations were conducted with well-validated simulation tool IDA ICE 4.5 [17] and the test reference year of Estonia was used [18]. Some simulation were made for comparative purposes with Central European climate data, ASHRAE TRY for Paris was used [19]. The primary energy factor for district heating is 0.9 and for electricity 2.0.

2.2. Minimum window size and the properties of the windows

The criterion of 2% average daylight factor [9] in the daylight zone (up to 4 m from the external wall) was used to calculate minimum window sizes. The open-plan offices were divided into 2.4 m wide modules and office rooms consisting of two modules were used in daylight and cooling load calculations. The bottom edge of all windows was 0.9 m from the floor and the height was 2.2 m. The description of perspective office room is shown in Fig. 2.

The average daylight factor of office rooms is calculated according to the following equation [9]:

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

where, D – average daylight factor, T – scattered light transmittance of glazing (90% of visible transmittance τ), θ – sky angle, 80°, m – clearness of the glazing, 0.9, A – total area of all interior surfaces (incl windows), 109.4 m^2, A_W – total glazed area of windows, m^2, R – mean surface reflectance, 0.5.

The glazing area can be calculated with the following formula:

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

The description of all glazing variants studied is shown in Table 2. The window widths are chosen as small as possible with a step of 50 mm so that average daylight factor would not be below 2%. Variant names are made up so that the first number stands for the number of panes, "C" for clear, highly transparent and "D" for tinted solar protection windows. "e" or "-" describe whether there is external shading or not respectively. For example "2/C/-" stands for a double glazed, clear window without external shading. Initially, 200 mm external wall insulation thickness (U = 0.16) was used with 2 and 3 pane windows and 300 mm insulation thickness (U = 0.11) with 4 and 5 panes. The double, triple and quadruple glazing properties were calculated using window manufacturers' calculation tools. Generally low emissivity coating (ε = 0.03) was used in all gaps between panes (except for glazing with air fillings, only used in Section 3.4). In case of solar protection window cases the outer pane was a solar protection glass with low emissivity also. The quintuple glazing representing not a standard product was calculated with detailed window model of IDA ICE which is based on the method of [20]. It is remarkable that the highly transparent quadruple and quintuple glazing cases have solar heat gain coefficient (g-value) as low as 0.36 and 0.24 respectively, so basically they can also be considered as solar protection glazing. The U-value of frames for double glazed windows was 1.2 W/(m^2 K) and for 3 and higher number of panes it was equal to the U-value of glazing.

2.3. Selection procedure for simulation cases

In first step, it was determined whether highly transparent or tinted solar protection windows allow reaching better energy efficiency. For that purpose, double and triple glazed window cases with minimum window sizes were simulated (results reported in

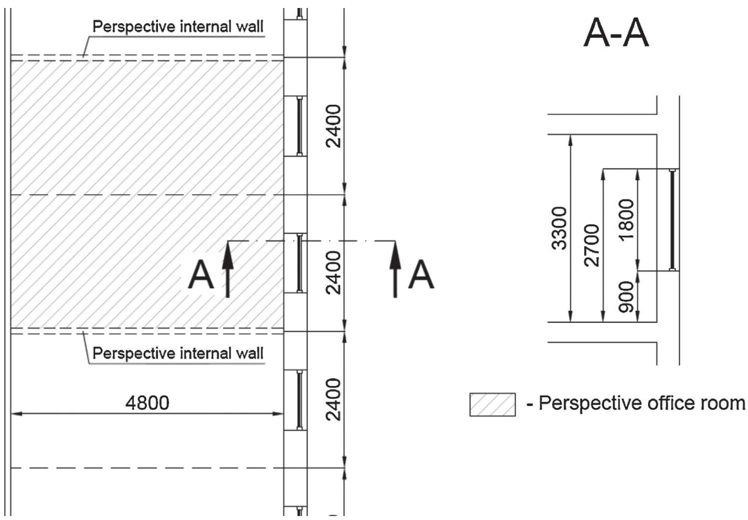

Fig. 2. Floor plan of the open plan office module (2.4 m) and the section showing window and room height.

Table 2
Description of clear and solar protection glazing variants and initial U-value of opaque elements of external walls.

Variant	Glazing				External shading	Initial U-value of external walls, W/(m^2 K)	Gas filling
	No of panes, coatings	U-Value, W/(m^2 K)	g-Value	Visible trans-mittance τ_{vis}			
2/C/-	2 low E	1.1	0.61	0.78	No	0.16	Argon
2/D/-	2 tinted solar	1.0	0.27	0.50	No	0.16	Argon
3/C/-	3	0.54	0.49	0.70	No	0.16	Argon
3/C/e	2 × low E	0.54	0.49	0.70	Yes	0.16	Argon
3/SC/-	3 Clear solar + low E	0.54	0.36	0.60	No	0.16	Argon
3/D/-	3 tinted solar + low E	0.54	0.24	0.45	No	0.16	Argon
4/C/-	4	0.32	0.36	0.63	No	0.11	Krypton
4/C/e	solar + 2xlow E	0.32	0.36	0.63	Yes	0.11	Krypton
5/C/-	5	0.21	0.24	0.56	No	0.11	Krypton
5/C/e	solar + 3 × lowE	0.21	0.24	0.56	Yes	0.11	Krypton

Section 3.2). Larger window sizes were not studied, because these common windows have U-values several times higher than external walls and therefore using highly transparent windows with lowest possible size is in heating dominating climate more energy efficient [21] than using large windows with good solar protection.

In the second step, simulation cases with several WWRs were created to find the optimal size of windows, because with the U-values closer to external wall U-values, the smallest possible window might not be the optimal. As large windows may cause high cooling need, then the influence of external shading was also tested. Simulated cases (results in Section 3.3) covered:

- The range of WWR of 23.9–60% for each façade;
- Glazing from 3 to 5 pane with U-values between 0.54 and 0.21;
- With and without external shading on East, South and West facades.

In the economic analyses, in order to find balance between insulation thicknesses and glazing types, the investment cost of façade element combinations was compared to energy cost and primary energy of each combination as the third step of the analysis (Table 3). The description of studied combinations is shown in Tables 4–6, Fig. 3 and results are reported in Section 3.4. Estonian cost data of windows showed that double windows and triple glazing with air filling cost approximately as much as triple glazing with argon filling. For that reason, optimal WWR analyses were conducted with triple glazing with argon filling or quadruple and quintuple glazing with krypton filling and all insulation thicknesses were studied only for these two glazing types.

The final fourth step was to find out the most energy efficient and cost optimal fenestration design cases for each orientation. The criterion for best energy efficiency was lowest primary energy use and for cost optimality the lowest NPV of investment and energy cost for 20-year period which followed the calculation method of Cost Optimal regulation [11] with discounting interest rate of 1.5%. Simulation cases with double, triple, quadruple and quintuple glazing variants with the best properties and minimum WWRs were created. Furthermore each glazing variant was simulated with and without external shading. The description of simulation cases is given in Table 6 and results are reported in Section 3.5.

Table 3
Cost data of opaque elements of external wall, which were concrete Sandwich elements with mineral wool insulation.

Insulation thickness, mm	U-Value, W/(m^2 K)	Investment cost, €/m^2
150	0.20	131.2
200	0.16	179.5
250	0.13	227.9
300	0.11	276.3
390	0.09	363.4

3. Results

3.1. Daylight calculations

Daylight calculations (Eqs. (1) and (2)) showed that minimum window-to-wall ratio (WWR) of highly transparent windows was between 21% and 29.5%. Minimum WWR increased together with the number of panes as visible transmittance decreases. The minimum WWRs of solar protection windows exceeded 30%. The WWR dependency of visible transmittance of window glazing has been shown in Fig. 4 and the minimum window sizes in 5 (Fig. 5).

3.2. Highly transparent vs. solar protection windows

In all cases room heating dominated the energy use and it was greatly affected by the size of windows as shown in Figs. 6 and 7. Supply air heating and cooling had next largest energy needs followed by lighting. Tinted windows with larger size remarkably increased space heating need. Lighting electricity varied

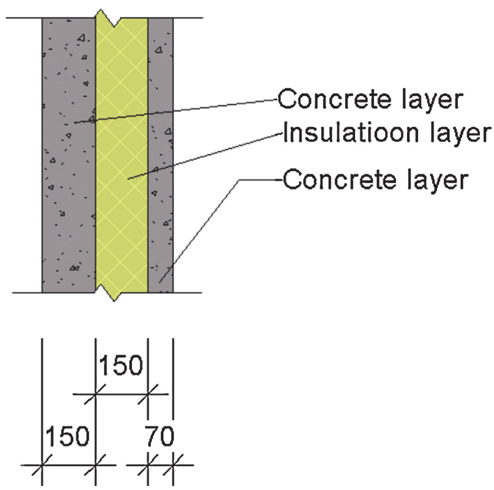

Fig. 3. Section of external wall, the thickness on insulation varies by cases.

Table 4
Cost data of windows, including both glazing units and aluminum profiles with thermal breaks. The window sizes vary for different glazings which affects the development of window cost due to different proportions of frames. Window cost has been more thoroughly described in the companion paper [14].

Variant	Dimen-sions, mm	Gas between panes	*U*-Value, W/(m^2 K)	Solar factor *g*	Visible transmittance τ_{vis}	Investment cost, €/m^2
2/Air	950 × 1800	Air	1.4	0.61	0.78	237.0
2/Arg		90% argon	1.1	0.61	0.78	244.3
3/Air	1050 × 1800	Air	1.1	0.52	0.71	240.0
3/Arg		90% argon	0.54	0.49	0.70	241.9
4/Kry	1150 × 1800	90% krypton	0.32	0.36	0.63	311.6
5/Kry	1300 × 1800	90% krypton	0.21	0.24	0.56	381.3[a]

[a] The cost of quintuple glazing is hypothetical, the cost increase from 3 to 5 panes was taken into account as linear.

Table 5
Investment cost of external wall as a function of insulation thickness and glazing type. All costs in the table are investment costs per m^2 of conditioned floor area, €/m^2.

Insulation thickness, mm	Glazing type and WWR, %					
	2/Air21.6%	2/Arg21.6%	3/Air23.9%	3/Arg23.9%	4/Kry26.1%	5/Kry29.5%
150	91.1	91.9	91.8	92.3	100.8	–
200	94.3	95.0	94.8	95.3	103.8	–
250	–	98.1	97.9	98.4	106.8	–
300	–	–	–	101.5	109.8	121.7
390	–	106.9	107.2	107.6	116.2	127.9

Table 6
Final simulation cases.

Variant	Glazing				Exterior wall *U*-value, W/(m^2 K)	WWR, %	External shading	Window width, m
	No of panes	*U*-Value, W/(m^2 K)	Solar factor *g*	Visible transmittance τ_{vis}				
3/C/Ar/-	3	0.54	0.49	0.70	0.16	23.9/37.5	No	1.05
4/C/Kry/-	4	0.32	0.36	0.63	0.13	26.1/37.5[a] 60.0(N)	No	1.15/1.65[b]
5/C/Kry/-	5	0.21	0.24	0.56	0.09	29.5/37.5(W)/60.0[b]	No	1.30/1.65[a]
3/C/Ar/e	3	0.54	0.49	0.70	0.16	23.9[a]/37.5[a]	Yes	1.05
4/C/Kry/e	4	0.32	0.36	0.63	0.13	26.1[a]/37.5[a]	Yes	1.15
5/C/Kry/e	5	0.21	0.24	0.56	0.09	29.5[a]/37.5[c]60.0(W)	Yes	1.30/1.65[a]

(N) – north façade only, (W) – west façade only.
[a] South, east and west façades only.
[b] South, east and north facades only.
[c] South and east facades only.

by orientations, but was practically the same for each glazing variant as the windows have been sized according to daylight criterion. The space cooling energy need fluctuated several times, however the influence on total energy use was low. Compared to highly transparent glazing, clear solar protection windows showed slightly worse energy use on each façade.

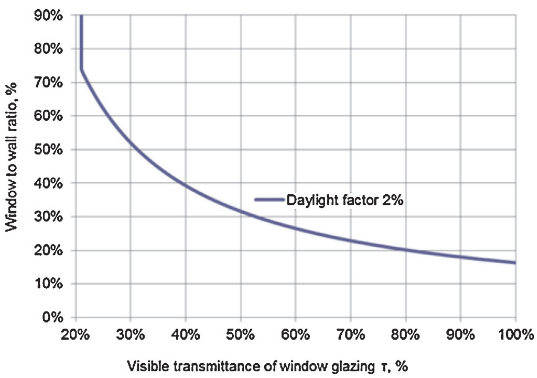

Fig. 4. Minimum window to wall ratio depending on visible transmittance of window glazing.

The comparison of highly transparent and tinted solar protection windows showed that in case of similar *U*-values highly transparent solar protection glazing results in better energy efficiency as can be seen from primary energy shown in Fig. 8.

3.3. Optimal window-to-wall ratio

The simulation cases with fixed insulation thickness resulted in delivered and primary energy shown in Figs. 9 and 10. Generally increasing WWR increased cooling energy use and decreased lighting electricity. Space heating energy use increased with triple windows, fluctuated with quadruple windows and decreased slightly with quintuple windows if WWR was increased as shown in Fig. 9. The use of external shading in all cases increased heating and lighting energy use and decreased cooling energy, whereas it improved primary energy use only in case of larger window sizes. In addition the positive effect of external shading was higher for east and west orientations. For the north façade external shading was not studied. In Figs. 9 and 10 the effect of external shading is shown only for cases where primary energy decreased compared to the case without external shading.

For triple windows the increase of WWR increased delivered energy, which made WWR 24.1% the most energy efficient case. However in the north façade WWR 37.5% gave lower primary energy than 24.1% due to lower lighting electricity despite slight increase in heating and cooling energy.

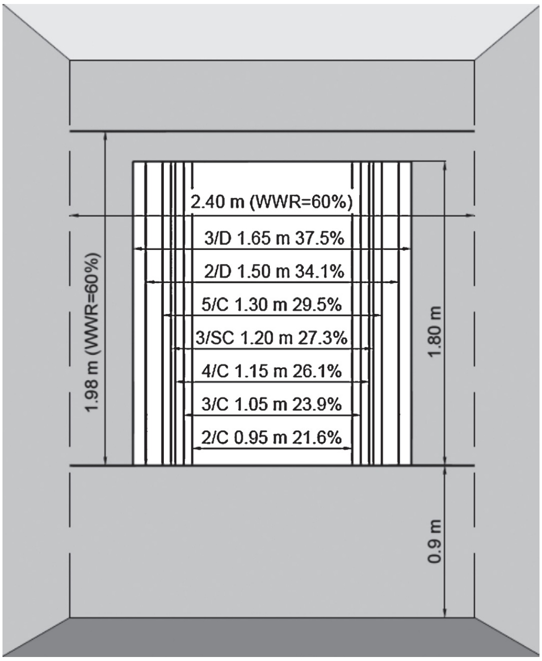

Fig. 5. Window sizes of glazing variants (variant codes correspond to Table 2, e.g. 2/C 0.95 m 21.6% means double, highly transparent window with width of 0.95 m and the window-to-wall ratio 21.6%). 2.4 m is the maximum width of the window providing WWR 60%.

In case of quadruple windows the following results can be seen from Fig. 10:

- In all cases, heating and lighting primary energy decreased when WWR was increased from 26.1% to 37.5%. At 60% WWR, the cooling energy started to dominate on south, east and west facades.
- Most energy efficient south orientated case was with WWR 37.5% and without external shading.
- East and west facades most energy efficient case was with WWR 60% and external shading, whereas without external shading WWR 37.5% provided slightly higher primary energy.
- On the north façade WWR 60% resulted in lowest primary energy because of significant decrease in lighting energy without any important increase in cooling energy.

In case of quintuple windows the following results can be seen from Fig. 10:

- In all cases, heating and lighting primary energy decreased when WWR was increased. At 60% WWR, the cooling energy increased significantly on south, east and west facades.
- Most energy efficient south and north orientated cases were with WWR 60% and without external shading.

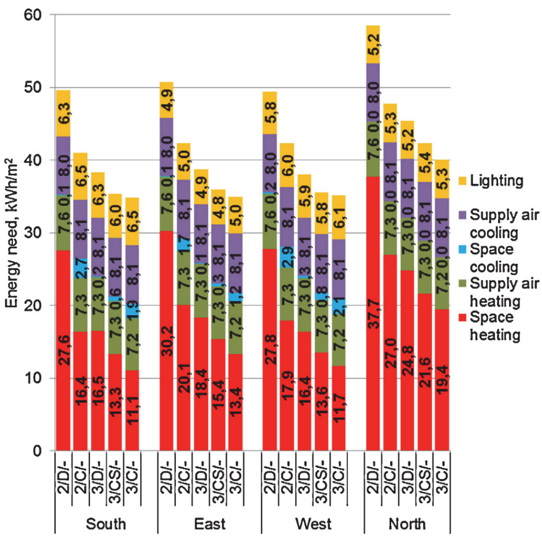

Fig. 6. Energy need in zones with highly transparent and solar protection windows with minimum size according to the daylight criterion of 2%.

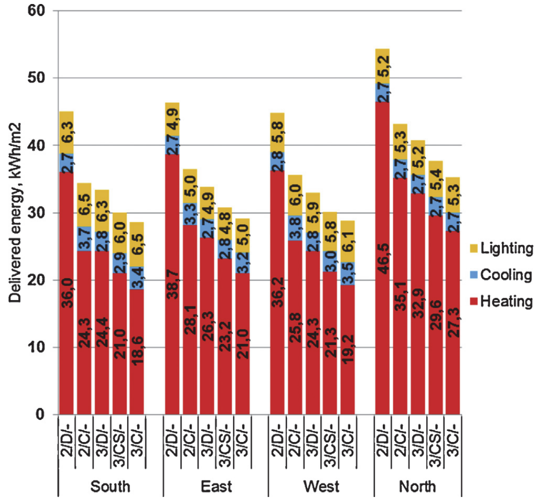

Fig. 7. Delivered energy for the cases of Fig. 5.

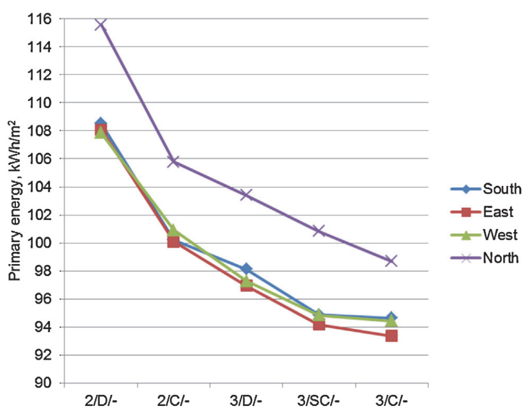

Fig. 8. Primary energy for the cases of Figs. 5 and 6.

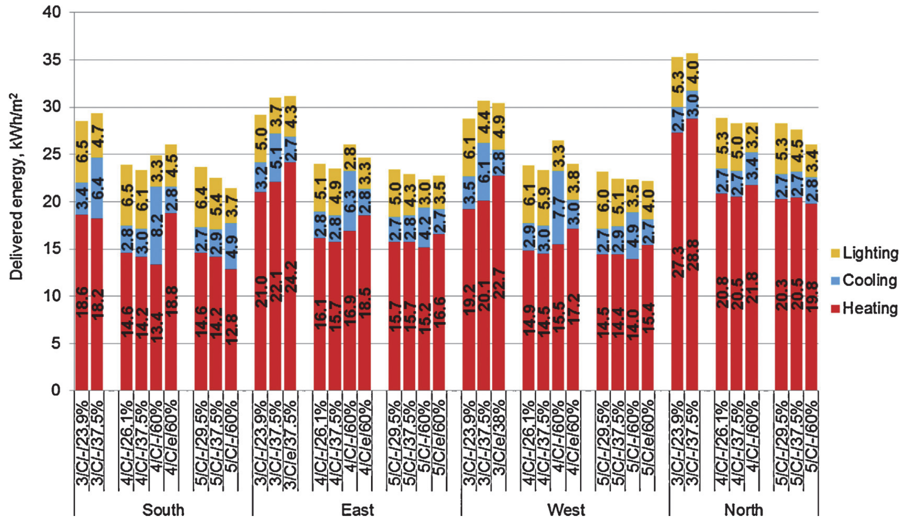

Fig. 9. Delivered energy results of the cases used to determine optimal WWR with initial fixed insulation thickness (200 and 300 mm for 3 and 4 pane respectively). Delivered energy is given in each zone as a function of window type, external shading, orientation and window size. Case codes are described in Table 2, e.g. 3/C/-/23.9% means 3-pane, clear solar protection glass, no external shading and WWR = 23.9%.

- East and west facades most energy efficient case was with WWR 60% and external shading.

3.4. Optimal external wall insulation thickness

The calculations since now have been done with insulation thickness of 200 mm for 3 pane and 300 mm for 4 and 5 pane windows. To determine the most sensible external wall insulation thickness Façade investment cost and net present values for a 20 year period were calculated for glazing variants described in Table 5. Financial analysis is fully reported in a companion article of this paper by Pikas et al. [15]. In the following only the results necessary for creating final simulation cases are reported. The primary energy, investment cost and NPV of all cases are shown in Figs. 11 and 12. The insulation thickness which resulted in lowest NPV was 200 mm for most cases, which was chosen for final analysis for triple glazing variants. However compared to case with quintuple 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 was chosen for final analysis of 4 pane glazing. A similar situation appeared

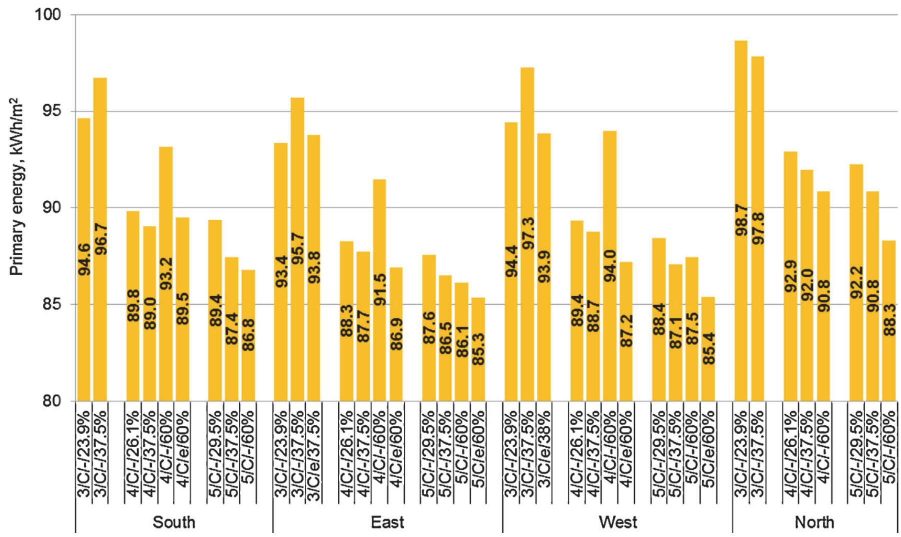

Fig. 10. Primary energy for the cases of Fig. 9.

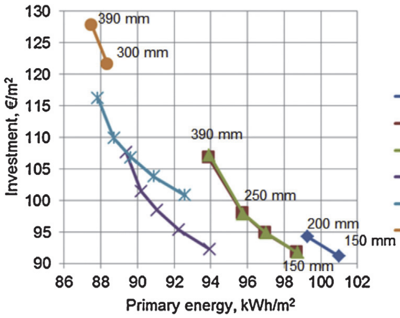

Fig. 11. Investment cost and primary energy of different glazing (all without external shading) and external wall insulation cases. Insulation thicknesses from left to right 150, 200, 250, 300 and 390 mm if not otherwise specified.

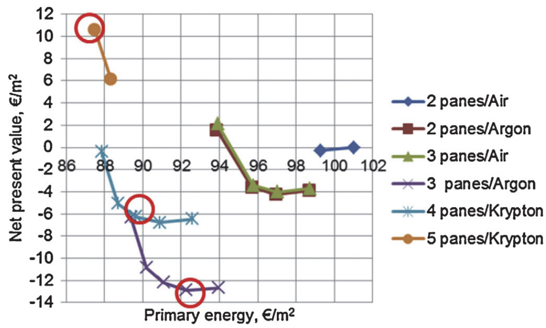

Fig. 12. Net present value and primary energy for the cases of Fig. 11. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

between 4 panes/390 mm insulation and 5 panes/300 mm insulation cases so 390 mm of insulation thickness was chosen for quintuple glazing.

Therefore the following glazing and insulation thickness combinations were selected for final analyses (marked with red circles in Fig. 12):

- Triple glazing with argon filling and 200 mm – the cost optimal.
- Quadruple glazing with krypton filling and 250 mm – the most relevant for 4 pane (in between the cost optimal and the most energy efficient).
- Quintuple glazing with krypton filling and 390 mm – the most energy efficient.

3.5. *Most energy efficient and cost optimal cases*

For the window types and insulation thicknesses selected in Section 3.4 energy simulations and economic analyses were repeated for optimal range of WWR with and without external shading. These results allow to determine optimal solutions refining the results of calculations done in Sections 3.2 and 3.3 with initial, not optimal combinations. Compared to results shown in Section 3.3 the external wall insulation thicknesses of quadruple and quintuple window cases have been changed to 250 and 350 mm respectively (based in Section 3.4 results). Also the energy needs of different systems have been given (see Fig. 13) and in addition the effect of external shading has been shown for all cases except north orientation.

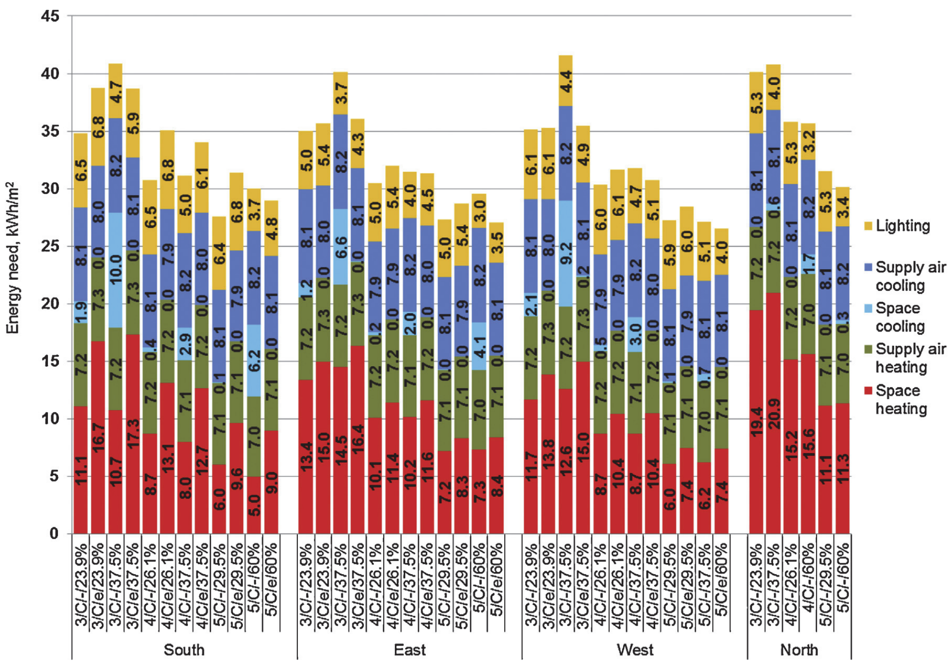

Fig. 13. Energy needs of final simulation cases for all zones. Insulation thicknesses determined in Section 3.4 are used.

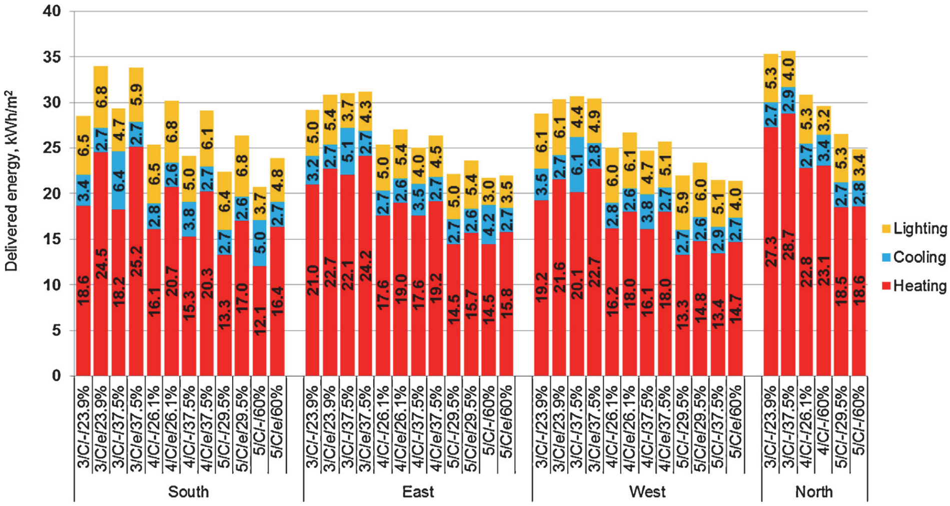

Fig. 14. Delivered energy of final simulation cases.

External blinds increased space heating energy need in all cases, whereas the effect was biggest on the south façade. The largest space cooling needs appeared in case of triple glazing with WWR 37.5% and when windows were sized according to daylight requirements the space cooling needs were rather insignificant. The increase of WWR caused remarkable reduction in lighting energy use, whereas external shading slightly reduced it.

Heating dominates the delivered energy of all cases, Fig. 14. The effect of external shading in case of smaller window sizes on energy use becomes more obvious. Only the cases that have high space cooling needs receive positive effect on energy efficiency from added external blinds.

The most energy efficient cases (lowest primary energy, Fig. 15) were by orientation the following (also marked with red circles in Fig. 15):

- South – 5 panes with no external shading, WWR = 60%, external wall insulation 390 mm.
- East – 5 panes with external shading, WWR = 60%, external wall insulation 390 mm.
- West – 5 panes with external shading, WWR = 60%, external wall insulation 390 mm.
- North – 5 panes with no external shading, WWR = 60%, external wall insulation 390 mm.

In Section 3.3 it was determined whether WWR 37.5% or 60% result in better energy efficiency for each glazing type on each façade and in Fig. 15 only the results of the more energy efficient WWR cases has been shown. For example in case of quadruple glazing the results for WWR 37.5% have been shown for south, east and west and in case of WWR 60% for only north.

The primary energy relationship to investment cost and NPV are shown in Figs. 16 and 17 respectively. The cases shown in the figures have been connected with lines if not otherwise specified in the following order: 3/C/37.5%, 3/C/23.9%, 4/C/26.1%, 4/C/37.5% and 5/C/29.5. Case 5/C/-/37.5% has been added for west facades as it resulted in better primary energy and NPV than similar case with lower WWR.

Financially most feasible cases that had lowest NPV were by orientation the following (also marked with red circles in Fig. 17):

- South – 3 panes with no external shading, WWR = 37.5%, external wall insulation 200 mm.

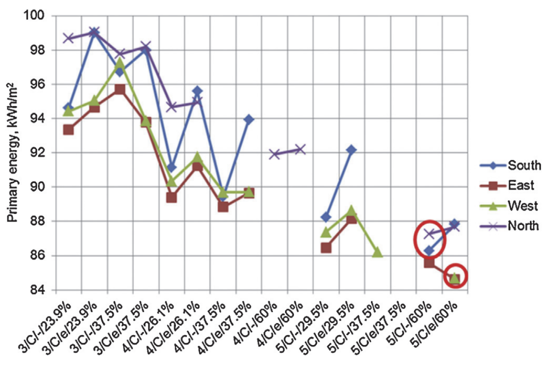

Fig. 15. Primary energy of final simulation cases. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

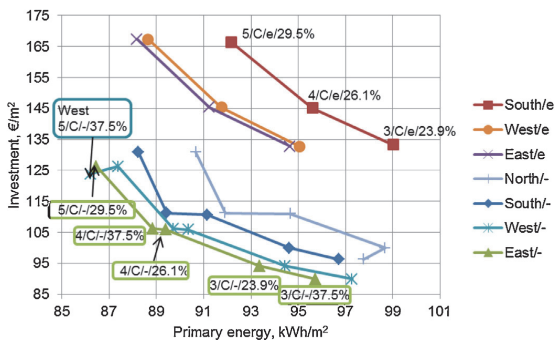

Fig. 16. Investment and primary energy of final simulation cases. Three upper curves are with external shading (marked with *e*) and lower curves with more cases without.

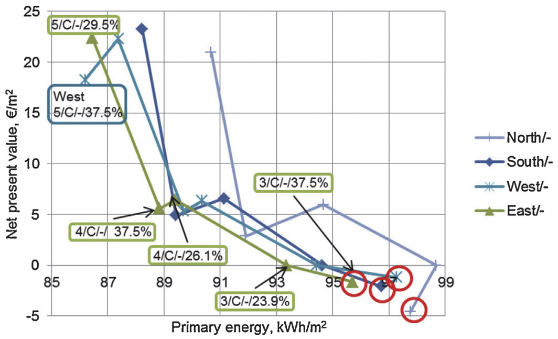

Fig. 17. Net present value and primary energy of final simulation cases without external shading. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

- East – 3 panes with no external shading, WWR = 37.5%, external wall insulation 200 mm.
- West – 3 panes with no external shading, WWR = 37.5%, external wall insulation 200 mm.
- North – 3 panes with no external shading, WWR = 37.5%, external wall insulation 200 mm.

In south, east and west facades with triple glazing and no external shading WWR 37.5% resulted in worse energy performance than 23.9%, however the cost per area for windows was smaller than of external walls and therefore WWR 37.5% was most financially feasible. If triple windows would be more expensive than external wall with insulation thickness 200 mm, then the cost optimal WWR would be 23.9% in south, east and west facades.

3.6. Cooling load with and without external shading

External shading generally did not improve energy performance and if it did, then the investment could be so high that energy saving alone is not enough for the payback (economic analyses of external shading are provided in the companion paper [15]). However external shading has impact on HVAC systems, in the form of reduced capacity of chiller and cooling system. The effect of external shading on sensible cooling capacity of a 4.8 m × 4.8 m room with 2 persons in it is shown in Fig. 18. External shading has helped reaching very low sensible cooling capacities around 20 W/m² and below. Quadruple and quintuple glazing with minimum window sizes allows reaching reasonable cooling capacities around 40 W/m² without external shading, whereas WWR may be increased to 37.5% in case of 5 panes with shading. Small sized double and triple glazing and quadruple windows with WWR of 37.5% resulted in cooling capacities around 50 W/m² and higher. These cases also showed significant rise in room cooling needs compared to other simulation variants (see Fig. 13).

3.7. Extending single floor model to full building model

The maximum allowed annual primary energy use of office buildings in Estonia is 160 kWh/m² and the requirements for low and nearly zero energy buildings are 130 and 100 kWh/m² respectively [22]. The primary energy consumption of most simulated cases shown in Figs. 10 and 14 remain below the nZEB requirement of 100 kWh/m², whereas in Fig. 14 information is shown in zones by orientations and the whole office floor has generally even lower energy consumption than the zones separately.

The generic floor model used in the analysis was very compact because of adiabatic floor and ceiling. The model is relevant for studying façade solutions, but the results may give a misleading impression about the simplicity of meeting nZEB requirements. In order to characterize the fluctuations in delivered energy related to compactness of buildings, external ceiling was added to the generic floor model. Two models were created: one had the most financially feasible solutions for each façade and the other the most energy efficient solutions. The roof *U*-values used for financially optimal and energy efficient cases were 0.10 W/(m² K) and 0.09 W/(m² K) respectively.

Adding roof had expectedly the biggest effect on heating energy increase, decrease of cooling energy was smaller and lighting practically did not change at all. The increase of the delivered and primary energy was about 35% and 20% for both cases, whereas the influence on the energy efficient case was slightly higher as its initial energy use was lower. The fluctuation in the energy use of the simulation models is shown in Figs. 19 and 20. The heating energy increase of the whole building is higher than of any other zone located on the facades, which is caused by heat loss through the ceiling of the zone located in the center of the floor. The influence on cooling energy varies much from orientation to orientation, however the change is higher when initial space cooling energy forms a larger part of total cooling energy. According to the results of these two cases, a safety margin of 20% can be applied for the primary energy calculated with a typical floor model.

With these model simulating a full building, the primary energy use was 103.4 kWh/m² and 110.9 kWh/m² for energy efficient and

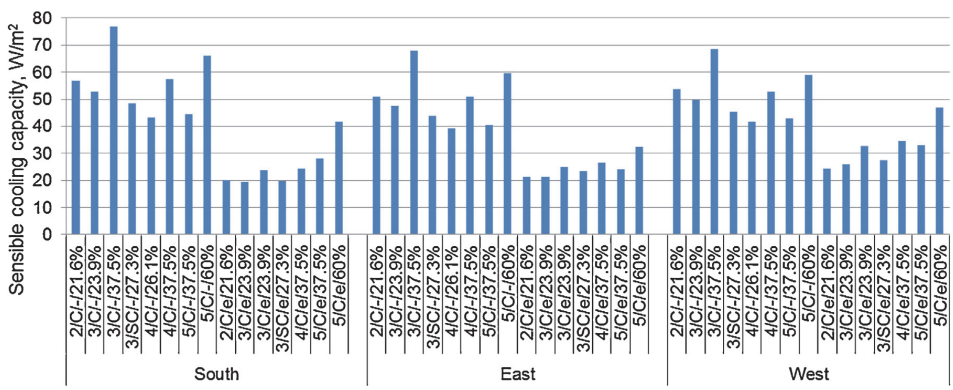

Fig. 18. Office room cooling capacities of final simulation cases.

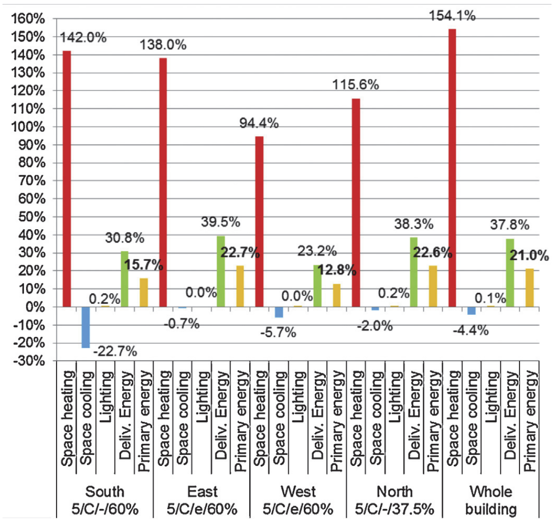

Fig. 19. Energy use fluctuation of the most energy efficient cases.

economically feasible cases respectively which means that they fulfill low energy building requirements instead of nZEB ones. In order to reach nZEB level, on site energy production e.g. PV-panels must be used.

4. Discussion

Results show that the single floor model used for façade analyses was not relevant to describe a full building, because of very high compactness. Normally office buildings are not that compact as they have areas with large glazed areas (e.g. lobbies) and also the shape is less compact. An attempt was made to transfer the results from this model to a full building, by adding external roof to the model. In two calculated cases the delivered energy increased

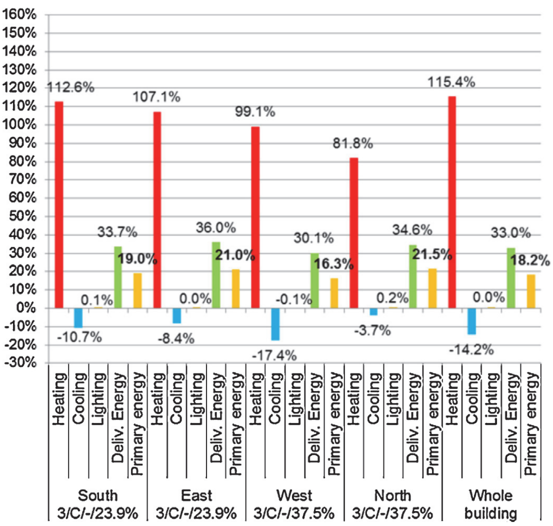

Fig. 20. Energy use fluctuation of the financially most feasible cases.

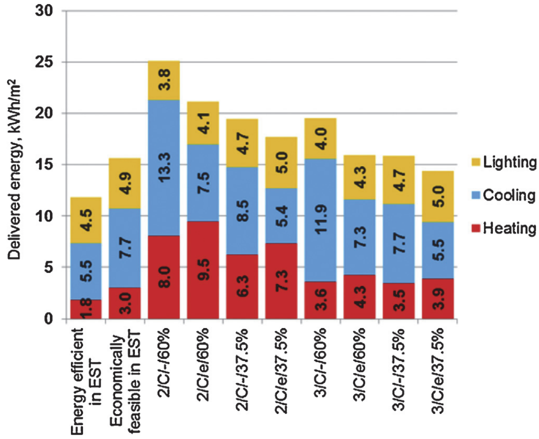

Fig. 21. Delivered energy in Paris. In two first cases the cost effective and most energy efficient façade solutions in Estonian climate are used. In other cases *U*-values were 1.1 for double glazing, 0.6 for triple glazing and 0.2 for external walls.

approximately 35% and primary energy 20%. These values depend on a specific building and were not analyzed further, because the aim of the study was to find optimal façade solutions. Previous experience shows that calculated 20% margin in primary energy could be slightly on the safe side for most of real office buildings, but still can be recommended for the scaling results from single floor model until the final results would be calculated with a full building model.

Usually windows are considered to be more expensive than insulated external wall, however in the current study it was the other way around for triple glazed windows and the NPV of this case was more affected by investment cost than energy use. If less expensive external wall assembly can be found, this will stress the principle of possibly small windows in the case of triple glazing. In any case, the results show the importance of economic calculation to be run in parallel with energy simulations, as cost optimal solution can really change the design.

According to the results, the largest energy use affected by the façade design in office buildings located in a cold climate was the heating energy. 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 (Section 3.5) were run without changes. For other cases similar *U*-values of the Elithis Tower [23] nZEB case study were used (1.1 W/(m^2 K) for windows and 0.3 W/(m^2 K) for external walls). For these cases 1.1 W/(m^2 K) was used for windows, and the less insulated external wall with *U*-value of 0.20 W/(m^2 K) was used. The results showed that the cooling energy starts to dominate and also proportion of lighting energy increased as is shown in Fig. 21. Due to larger cooling energy use the effect of external shading was positive in all the cases. Similarly to the climate of Tallinn, smaller sizes of double and triple windows resulted in better energy performance and there was a remarkable drop in heating energy use caused by triple glazing. However the heating energy still remained higher than that in cases with Estonian insulation. The situation could be different with higher internal gains, but this study used very small internal heat gains suitable for nZEB buildings.

Triple glazing showed significantly better results in primary energy than double glazing as can be seen in Fig. 22. However, the performance of the case with Estonian most energy efficient façade was not achieved. This indicates that even in Central European climate, there is a need for improved façade components. Indeed the

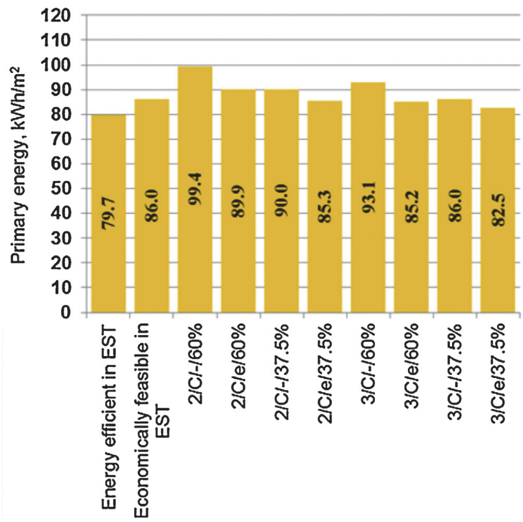

Fig. 22. Primary energy in Paris for the cases of Fig. 21.

solutions feasible in a cold climate could not pay back because of lower heating need.

Double-skin facades were not studied in this paper, however often used in modern office buildings as offering good protection to external climate and allowing to using lighter external blinds between skins. Double-skin facades also provide architects the opportunity to give the impression of a glass building without necessarily having to use large window areas that decrease energy performance. Another benefit is its ability to preheat the air between the building and closed double-skin façade which reduces ventilation heating costs, however the risk of over-heating makes the use of automatically controlled ventilation hatches necessary. On the other hand double-skin facade reduces the efficiency of using daylight and that also increases minimum window-to-wall ratios which finally results in increased space heating energy use as shown in this study. As the investment cost also rises, the feasibility of using double-skin facades becomes completely different question deserving another study to find optimal solutions.

Another aspect of façade solutions that requires more research is the control principles of external shading. External blinds were controlled according to a very simple algorithm in the analysis and that often resulted in reduced energy performance. More advanced control algorithms could be possible to develop in order to reach full effect of active shading.

5. Conclusions

Cost optimal and most energy efficient façade solutions, including window properties, external wall insulation, window-to-wall ratio (WWR) and external shading were determined with energy and daylight simulations in the cold climate of Estonia. These façade parameters were optimized for the lowest life cycle cost and alternatively for the best achievable energy performance to be used as design guidelines for architects and engineers working with facades in low and nearly zero energy buildings.

Heating dominated in the energy balance of office buildings in case of conventional windows and therefore improving the *U*-values of windows by increasing the number of panes and low emissivity coatings also improved energy performance. Optimal window sizes for double and triple glazing were as small as daylight requirements allow, because the *U*-values of these windows are relatively high compared to opaque elements of external walls and larger windows cause high heating and cooling energy use, which were not compensated by decreased electric lighting.

In the comparison of clear low emissivity glasses to tinted solar protection glasses and clear solar protection glasses with high visible transmittance the best energy performance was achieved with clear low emissivity glasses and the second best with clear solar protection glasses that followed the minimum size of windows determined by the daylight requirement. Also the cooling load was possible to keep at reasonable level with minimum size clear low emissivity glazing. Therefore all optimal cases found in this study were with clear glazing, where a low emissivity coating was in each gap between the panes.

In the case of high performance windows with quadruple and quintuple glazing and *U*-values of 0.3–0.2 windows heat losses become similar to opaque elements of external walls and the minimum window-to-wall ratios did not show any more the best energy performance. 4 and 5 panes clear low emissivity glazing provided also naturally good solar protection, because of high number of panes and coatings. Therefore the positive effect of larger windows on electric lighting and in some cases even on heating energy exceeded the negative effect on cooling energy increase. Best energy performance was achieved at 37.5% and 60% WWR in the case of quadruple and quintuple windows respectively.

Adding external shading reasonable window sizes increased primary energy as the initial space cooling needs were quite low and the increase in heating and lighting energy was not compensated, however a relatively simple control principle of shading was used in the current analysis. In the case of large double or triple glazing, external shading was useful as effectively reduced cooling need. Because of high investment cost, external shading was not economic to use, however it decreased cooling capacities significantly that was not accounted in economic analyses.

Based on the results the most energy efficient façade solutions were by orientation the following:

- South – 5 panes without external shading, WWR = 60%, external wall insulation 390 mm.
- East – 5 panes with external shading, WWR = 60%, external wall insulation 390 mm.
- West – 5 panes with external shading, WWR = 60%, external wall insulation 390 mm.
- North – 5 panes without external shading, WWR = 60%, external wall insulation 390 mm.

In cost optimal performance level, based on 20 years net present value calculation, the best energy performance was achieved with façade solutions:

- South – 3 panes without external shading, WWR = 23.9%, external wall insulation 200 mm.
- East – 3 panes without external shading, WWR = 23.9%, external wall insulation 200 mm.
- West – 3 panes without external shading, WWR = 23.9%, external wall insulation 200 mm.
- North – 3 panes without external shading, WWR = 37.5%, external wall insulation 200 mm.

For South, East and West facades the exact cost optimal point was achieved at WWR = 37.5%, which increased primary energy and cooling load but due to lower window cost relative to insulated wall the NPV was slightly decreased. However, because of increased cooling load WWR = 37.5% will need extra investments in room conditioning units or external shading which were not taken into account in cost optimal calculation. Therefore, for practical cost effective design, the conclusion is that WWR about 25% can be recommended for South, East and West facades, when the North façade needs about 40% WWR.

Quadruple windows with about 40% WWR and no external shading provided an interesting alternative in between cost optimal energy performance level with triple glazing and very expensive quintuple glazing. Increase in the net present value was not very high, and energy performance improvement from 4 to 5 panes was already quite marginal.

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 very large windows showed worse results compared to more reasonable sizes. In the case of less effective lighting system, the effect of large windows could be less negative.

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PAPER II

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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 $0.33\,\mathrm{W/(K\,m^2)}$ and district heating at around $140\,\mathrm{kWh/(m^2\,a)}$ 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

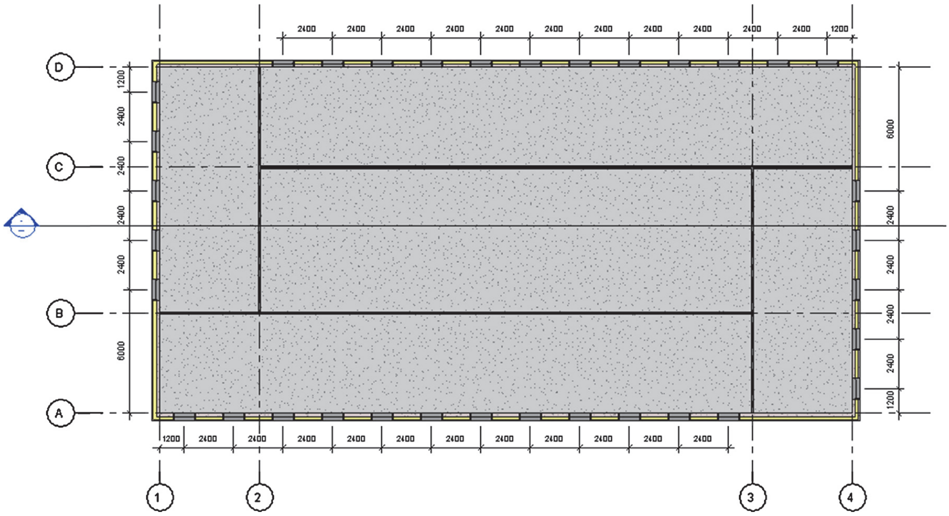


Fig. 1. Perspective view of generic single floor of office building.

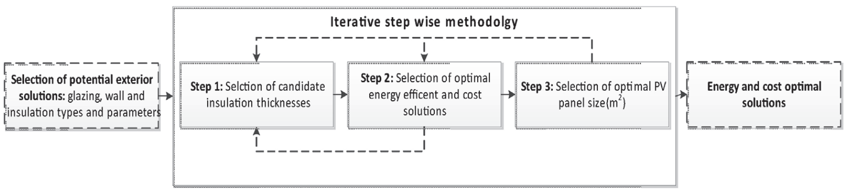


Fig. 2. Research methodology.

Table 1
Glazing investment cost per m^2.

No.	Glazing type	No of panes	Gas between panes	U-value (W/(m^2 K))	Solar factor g	Visible transmittance τvis	Profile type	Investment cost (€/m^2)
1	2/Air	2	Air	1.4	0.61	0.78	Profile system with U value 1.2 W/(m^{2}K)	110.51
2	2/Arg		90% argon	1.1	0.61	0.78		117.51
3	3/Air	3	Air	1.1	0.52	0.71		117.80
4	3/Arg		90% argon	0.54	0.49	0.70		122.00
5	4/Kry	4	90% krypton	0.32	0.36	0.63		190.06
6	5/Kry	5	90% krypton	0.21	0.24	0.56		267.74[a]

[a] The cost of quintuple glazing is hypothetical, while the cost increase from 3 to 5 panes was considered linear.

Table 1. Together with unit prices for glazing, the manufacturer provided a profile system with a U value of 1.2 W/(m^2 K). The unit price of the profile was 20 €/m^2. In general, the cost of windows increases as the quality and number of panes increases. Window unit prices include materials, installation and project management costs (Tables 2 and 3).

Table 2
Insulation thicknesses, U-values and investment costs of external wall.

Insulation thickness (mm)	U-value (W/(m^2 K))	Investment cost (€/m^2)
150	0.20	131.20
200	0.16	179.50
250	0.13	227.90
300	0.11	276.30
390	0.09	363.40

As can be seen, financially the most sensible window type would be either triple glazing with argon filling or quadruple glazing with krypton filling. The reason is that double windows and triple glazing with air filling cost approximately as much as triple glazing with argon filling, but triple glazing is more energy efficient. For the

Table 3
Shading costs depending on the size of the window.

Nr	Glazing type	Window size (mm)	Shading type	Cost per one (€)
1	3/Clear/Ar/016/e	1050 × 1800	Dynamic motorized solar shading	603.00
2	3/Clear/Ar/016/e/37.5%	1600 × 1800		703.00
3	4/Clear/Kry/013/e	1150 × 1800		632.00
4	4/Clear/Kry/013/e/37.5%	1650 × 1800		703,00
5	5/Clear/Kry/009/e	1300 × 1800		643.00
6	5/Clear/Kry/009/e/60%	11900 × 1980		1124.00

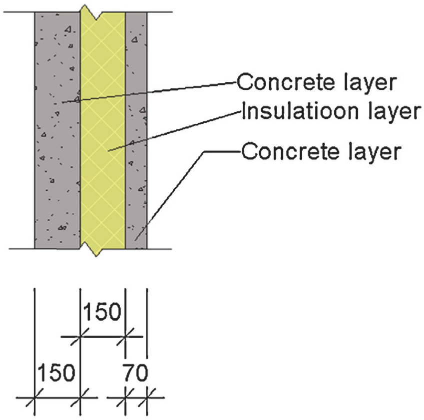


Fig. 3. Gross section of the typical exterior wall.

specification of the exterior wall solution, a local manufacturer provided us with information on unit prices and installation costs. The type of wall selected for the research was the concrete sandwich panel, being one of the most typical solutions found in Estonian office buildings. For quantity extraction, models were prepared in a building information modeling application. The structural layer and outer layer of the selected element type were kept constant, and insulation thickness was made a variable. Discrete insulation thicknesses, not analytical, were selected, since this is how exterior walls are commonly built. The gross section of the typical wall is shown in Fig. 3. Unit prices for the exterior walls include materials, installation and project management costs. Every additional 10 cm of mineral wool insulation costs an extra 9.00 €/m^2.

In the second step, the addition of external shading was also analyzed, except in the case of the north facing facade. Unit costs for motorized shading systems were provided by a local reseller. Front-mounted external venetian blinds with 80 mm flat slats were used. Windows with quintuple glazing and a WWR (window to wall ratio) of 60% required three sets of blinds each. The other windows were each fitted with one properly sized set of blinds. Unit prices for the motorized blinds include materials, installation and project management costs.

In the final stage of this research, unit costs for solar PV panels were provided by a local reseller. The aim of adding solar panels was to make it possible to analyze the cheapest solution for achieving the nZEB level (≤100 kWh/(m^2 a) in Estonia) for the office building in question [11]. For this research, PV poly panels with 10% efficiency and a cost of 276.00 €/m^2 were used. The unit cost of the PV panel system included materials, installation, connection to the power grid, and taxes. As our goal was to study cost and energy efficient office building fenestration design solutions and to achieve the nZEB level, energy efficient HVAC solutions remained fixed. Kurnitski et al. [11] concluded on the basis of their sensitivity analysis for replacement, maintenance and disposal costs that these costs have a minor influence on calculation results. Therefore, to keep the comparison of fenestration design solutions meaningful, they ignored these costs in their study. Furthermore, EN 15459:2007 permits neglecting the objects/components of a building that are not being considered for cost optimality calculations [11]. These costs are also ignored in this study, except in the case of the PV panels in the third step.

Annual energy consumption for different design alternatives were calculated in the paper [11]. Based on these results annual energy costs were calculated. Estonian price levels during the preparation of this study were as follows:

- Electricity 0.1245 €/kWh + VAT (20%).
- District heating 0.0625 €/kWh + VAT (20%) (Tallinn, natural gas boiler).

Connection fees for electricity and heating were as follows:

- Electricity 111.85 € + VAT (20%) per 1 A of main fuse.
- District heating 2500.00 € + VAT (20%).

2.3. PV panel sizing

Primary energy for four cases capable for nZEB performance level was simulated, and the necessary PV-panel area was calculated so that the annual primary energy would be ≤100 kWh/m^2. PV panels selected for this study have 10% efficiency with production of 107 kWh/m^2. These values are kept constants for calculating PV panel size, which is a variable. These cases were simulated with the top floor model of the office building including the roof (instead of the generic single floor model), which was used to describe the whole building. With the top floor model, the delivered and primary energy were increased by factor of about 1.2, which was concluded in [12] to be a slightly safe side estimate when assessing whole building results from generic single floor model (exact values depend on the specific building studied). The U value for the roof varied for different glazing types. For office floors with triple and quadruple glazing, a roof with a U value of 0.10 W/(m^2 K) was used. For office floors with quintuple glazing, a roof with a U value of 0.09 W/(m^2 K) was used. For further details and descriptions, see Section 3.4. Surplus electricity produced would be sold to the main grid. The selling price of electricity was not the same as its cost. The NPV calculations required calculating the proportion of electricity used in the building. The percentage was calculated by comparing hourly consumption to simulated hourly PV production, i.e., hourly load matching calculations were carried out.

2.4. NPV calculations and selection of interest rate

In order to identify cost optimal solutions at every stage, total investment cost and NPV were calculated in [11]. The global incremental energy performance related cost was calculated as a sum of the energy performance related construction cost and discounted energy cost for 20 years, including all electrical and heating energy consumption. The energy performance related construction cost, which does not include the basic cost of construction, was used to compare alternative design solutions that affect the energy performance of buildings. In every step, the global incremental cost for energy performance was calculated relative to the reference solution:

$$C_g = \frac{C_g^{ref}}{A_{floor}} - \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \quad (1)$$

where:

C_g global incremental energy performance related cost included in the calculations, NPV, €/m^2.
C_I energy performance related construction cost included in the calculations, €.
C_a annual energy cost during the starting year, €.
$f_{pv}(n)$ present value factor for the calculation period of n years.
C_g^{ref} reference fenestration design solution's global energy performance related cost, NPV, €/m^2.
A_{floor} heated net floor area, m^2.

Fig. 4. Average interest rates from entrepreneur to entrepreneur (source: Bank of Estonia, www.eestipank.ee).

To calculate the present value factor $f_{pv}(n)$, the real interest rate R_R must be calculated. R_R depends on the market interest rate R and inflation rate R_i [11]:

$$R_R = \frac{R - R_i}{1 + (R_i/100)} \quad (2)$$

The market interest rate of 4.0% (R) used for this analysis is based on the average interest rates reported by the Bank of Estonia for entrepreneurs from entrepreneurs over the last thirteen years, as shown in Fig. 4 (2000–April 2013). An inflation rate of 3.5% (R_i) was used in the calculation of the real interest rate. For energy performance calculations, it is common to consider different values for escalation and inflation rates. To calculate the percent value factor, the escalation rate e must be subtracted from the real interest rate R_R, as described by Abel and Voll [13].

The present value factor $f_{pv}(n)$ for the calculation period of n years is calculated as follows [11]:

$$f_{pv}(n) = \frac{1 - \left(1 + (R_R - e)/100\right)^{-n}}{(R_R - e)/100} \quad (3)$$

where:

R_R the real interest rate,
% e escalation of the energy prices (%).
n the number of years considered, i.e., the length of the calculation period.

3. Results

3.1. Window–wall cost ratio analysis

The study of window costs revealed that from a cost perspective it was preferable to use windows with a larger glazing area, as the cost of profile and energy loss is significant compared to that of glazing. The thick red line in Fig. 5 represents the profile cost per window size, showing that up to a size of 5 m^2 the cost of profile per window is higher than that of glazing itself. Quintuple glazing was not considered in this analysis as it was not available as a standard product.

The cost differences between windows up to triple glazing were marginal but on average a window with four panes was 41% more expensive than a window with three panes, Fig. 6.

A matrix of insulated wall and window combination costs is shown in Table 4. The number of combinations was limited to the cases selected on the basis of the pre-study, which determined potential energy and cost optimal solutions. The cost of combinations was linear up to triple glazing and for all insulations. However, the costs for windows with four and five panes increased significantly. In order to find a balance between insulation thicknesses and glazing types, the investment cost of facade element combinations was compared to the energy cost and primary energy of each combination, as shown in the following sections.

3.2. Step 1: selecting optimal range for insulation thicknesses

A clearer picture of the relationship between initial investment and energy cost per year is provided by Fig. 7, which shows that the more we invest, the better the energy performance we should potentially achieve. However, this is not realistic, as budgets are typically limited, especially from a business point of view. Therefore, further analysis is required to analyze investment efficiency.

The determination of the proper insulation thickness for window types in – 1 is shown in Fig. 8. Double glazing windows in NPV is calculated against reference design solution: 150 mm insulation and double glazing windows.

Fig. 8 are used as a reference case to show cost optimal solutions. The results indicate that triple glazing windows perform better in terms of cost and energy efficiency, while up to triple glazing

Table 4
Investment cost of insulation thickness and glazing type combinations per square meter of heated area (€/m^2).

Insulation thickness (mm)	Glazing type and WWR (%)					
	2/Air 21.6%	2/Arg 21.6%	3/Air 23.9%	3/Arg 23.9%	4/Kry 26.1%	5/Kry 29.5%
150	91.10	91.90	91.80	92.30	100.80	–
200	94.30	95.00	94.80	95.30	103.80	–
250	–	98.10	97.90	98.40	106.80	–
300	–	–	–	101.50	109.80	121.70
390	–	106.90	107.20	107.60	116.20	127.90

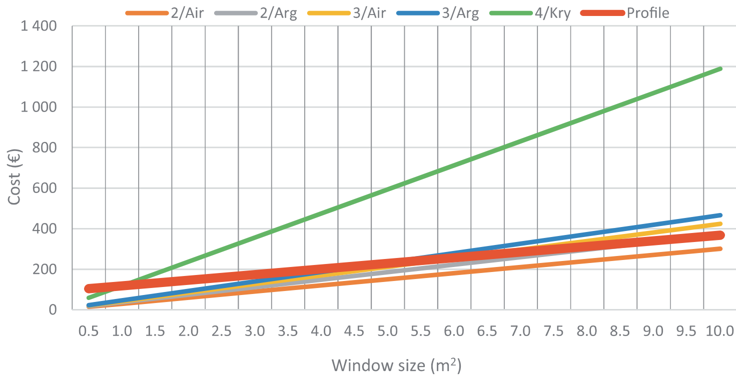


Fig. 5. The cost of window components (profile and glazing) per window size.

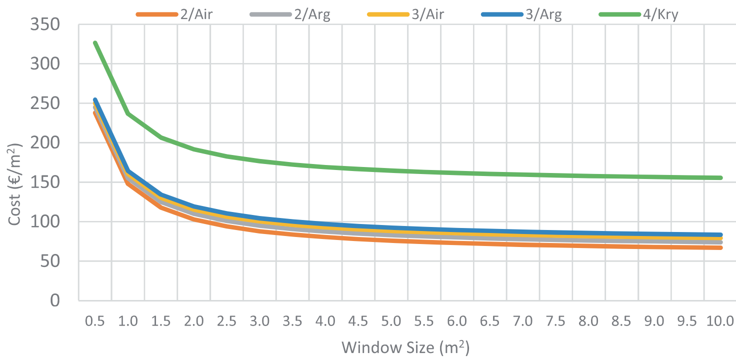


Fig. 6. Specific window cost as a function of window size.

there are no substantial differences between costs. Taking a closer look, we see that triple glazing with argon filling performed better than triple glazing with air filling (both with double low-emissivity coatings), as the cost difference between argon and air filling is only 4.20 €/m^2. The insulation thickness which resulted in the lowest NPV value for triple glazing was 200 mm. Compared with the other solutions, this solution offers the best investment and energy performance ratio. The next sensible solution is a window with four panes and 250 mm thick insulation, as it offers better energy performance than a window with triple glazing and 390 mm thick insulation. Similarly, a window with five panes and 390 mm thick insulation is the next reasonable selection and also the most energy efficient solution. The combinations selected for a more detailed analysis in the following steps are circled red in NPV is calculated against reference design solution: 150 mm insulation and double glazing windows.

- Triple glazing with argon filling and 200 mm thick insulation–cost optimal.

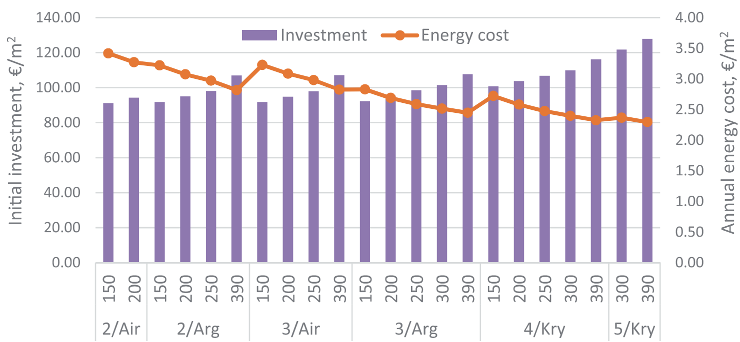


Fig. 7. The interdependency of initial investment and energy cost per year.

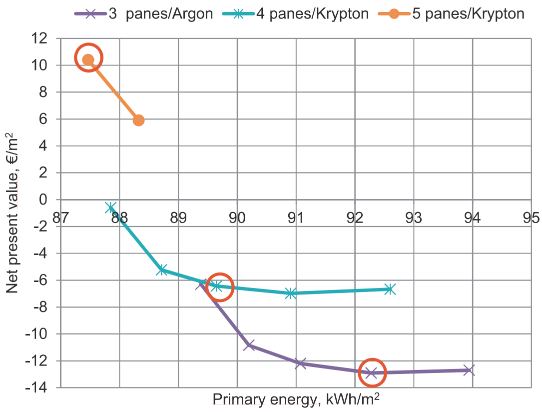


Fig. 8. NPV and Primary Energy performance for selected combinations. Insulation thicknesses from right to left are per sequential points are 150, 200, 250, 300 and 390 for triple and quadruple glazing. Insulation thicknesses from right to left for quintuple glazing are 300 and 390.

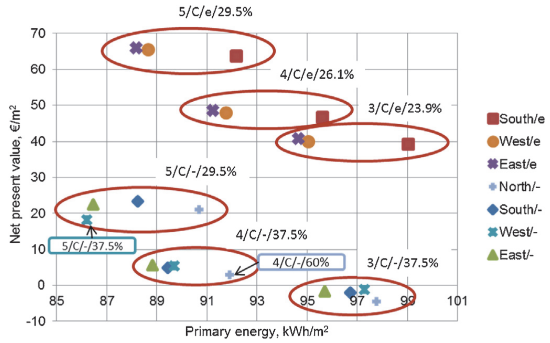


Fig. 10. Net present value and primary energy for the facades.

- Quadruple glazing with krypton filling and 250 mm thick insulation–relevant for four panes glazing (being between the cost optimal and the most energy efficient solution).
- Quintuple glazing with krypton filling and 390 mm thick insulation–the most energy efficient.

NPV is calculated against reference design solution: 150 mm insulation and double glazing windows.

3.3. Step 2: developing cost and energy efficient solutions

In this step, orientation specific simulation cases were conducted based on the results in Section 3.2. For selected cases, energy and cost calculations were repeated over the optimal range of WWR with and without external shading systems with the aim of determining energy and cost optimal solutions. A shading system for the north facing façade was not considered. In Fig. 9, it can be seen how the investment cost increases from left to right and energy cost declines from left to right in every orientation. The peaks in investment cost and energy cost per year represent the added investment cost of shading systems and added energy cost of additional lighting needs. In most cases, it can be seen that adding shading is not economically reasonable, except in the case of the west facing façade, where energy cost decreased when shading was added (data in the figure highlighted with a red rectangle). The question is whether or not this additional cost for the west facing facade is economically justified over a 20 year period.

Adding shading significantly increases the investment required but has a smaller impact on energy performance. According to Fig. 9, there are two cases in the west facing orientation where annual energy cost decreases when shading is added: 3/C/e/37.5% with argon filling and 5/C/e/60% with krypton filling.

The primary energy relationship to NPV is shown in Fig. 10. The figure represents cost optimal and economically feasible solution groups (for each orientation). Grouping is according to glazing type and shading. 3/C/-/37.5% has been added for west and north facing facades, as it resulted in better primary energy and NPV than similar cases with lower WWR. Quadruple glazing with a WWR of 37.5% has been omitted for cases with external shading. Insulation

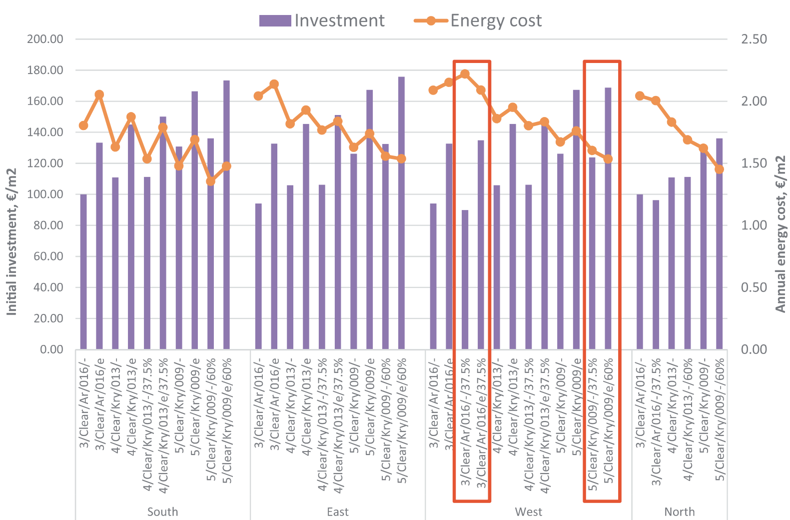


Fig. 9. The interdependency of initial investment and energy cost per year for each facade.

Table 5
Electricity use and generation profile in the nZEB office building.

No.	Façade solution type	Overall electricity used in building (kWh/m^2)	Electricity produced with PV panels (kWh/m^2)	PV generation sold (kWh/m^2)	Delivered electricity (kWh/m^2)	% of PV generation used in the building	% of PV generation used in overall electricity use
1	Cost optimal solution	38.20	5.44	0.83	33.58	84.84	12.09
2	Next sensible alternative solution	37.35	4.56	0.69	33.49	84.87	10.35
3	Next sensible alternative solution	36.95	3.57	0.50	33.88	85.98	8.31
4	Most energy efficient solution	37.04	1.78	0.19	35.46	89.28	4.28

Table 6
Comparison of selected solutions for PV panel calculations.

No.	Solution type	Windows	WWR/Width by orientation	Primary energy (kWh/m^2)	Investment without PV panels (€/m^2)	20 NPV without PV panels (€/m^2)	Investment with PV panels (€/m^2)	Initial annual energy cost without PV panels (€/m^2)	New annual energy cost with PV panels (€/m^2)	20 NPV with PV panels (€/m^2)
1	Cost optimal	3/Clear/Ar/016/	All ori.:37.5%/1.65 m	110.6	92.0	293.2	110.2	8.55	7.85	294.8
2	Next sensible alternative solution	4/Clear/Kry/013/-	S,E and W: 37.5%/1.65 m; N: 60%/11.9 m	109.1	107.8	300.5	123.4	8.19	7.58	301.8
3	Next sensible alternative solution	5/Clear/Kry/009/-	All ori.: 29.5%/1.3 m	107.1	127.7	317.1	140.0	8.05	7.57	318.0
4	Energy efficient	5/Clear/Kry/009/-	All ori.: 60%/11.9 m	103.4	160.5	349.4	166.4	8.03	7.79	349.7

thicknesses for different glazing types were selected in Step 1. Fig. 10 shows that energy efficiency improves with every additional pane. However, with every added pane, NPV increases as well, due to the additional investment need, as in the case of shading.

In conclusion, the cost optimal solution was fenestration with clear argon filled triple glazing and a WWR of 37.5%. For quadruple glazing, the most reasonable solution was clear krypton filled glazing with a WWR of 37.5%, except in the case of the north facing façade, which has a WWR of 60%. This was because the larger window improves lighting during the day without increasing cooling needs. For solutions with five panes, the most economically viable solution was clear krypton filled windows with a WWR of 29.5%, 37.5% in the case of the west facing façade. These solutions assume insulation thicknesses of 200, 250 and 390 mm, respectively. Despite better energy performance in a few cases, adding shading significantly increased the investment cost and therefore, also NPV. This means that from the point of view of cost optimality in the given climate, it was not reasonable to install shading, while

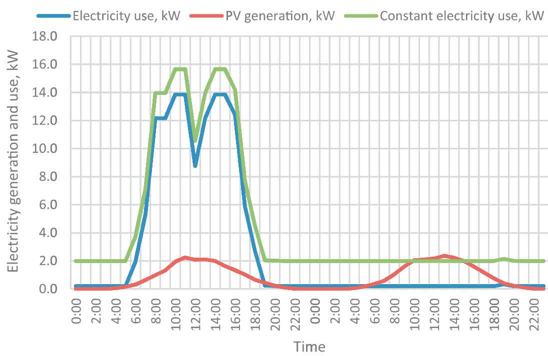


Fig. 11. An example of load matching for a working day, 29 June 2012, and non-working day, 30 June 2012.

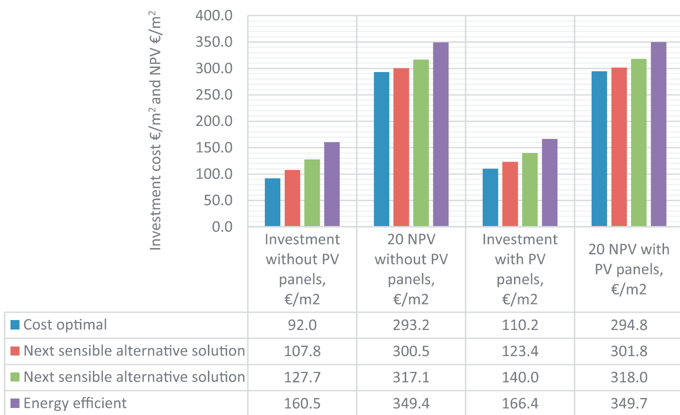


Fig. 12. Comparison of selected cases with and without PV panels.

the energy savings from cooling would not lead to a recovery of the initial investment, and in most cases, it increased lighting needs.

Even though triple clear glazing windows with a WWR of 37.5% were found to be cost optimal, based on the results in the paper [11], it is actually recommended to use triple glazing with a WWR of 23.9%. This is because smaller windows result in significantly smaller cooling loads, which in turn results in better indoor climate. Therefore, within the cost optimal range, the following solutions by facade orientation are recommended:

- south–3 panes with no external shading, WWR = 23.9%, external wall insulation 200 mm.
- east–3 panes with no external shading, WWR = 23.9%, external wall insulation 200 mm.
- west–3 panes with no external shading, WWR = 23.9%, external wall insulation 200 mm.
- north–3 panes with no external shading, WWR = 37.5%, external wall insulation 200 mm.

In all cases, Fig. 10 show that primary energy is less than 100 kWh/m^2. This is due to the fact that a compact office floor model was used for simulations in the first two steps. However, this can be misleading. For Step 3, a top floor with a roof is used, adding an additional exterior element to the office floor. The paper [11] concluded that a factor of 1.2 could be applied to a single floor model to estimate the primary energy of the full building model, but in this study, a supplementary analysis including the top floor was conducted. This resulted in primary energy consumption of 103.4 kWh/m^2 for the most energy efficient solutions and 110.9 kWh/m^2 for the most cost optimal solutions. For further details, see the paper [11]. These solutions fulfill the Estonian low energy building requirement [14]. In Step 3, to achieve the nZEB level, simulations were carried out to calculate PV energy production demand.

3.4. Step 3: achieving nZEB with local energy production

To achieve the nZEB level, on-site renewable electricity generation was required, according to results in Step 2. Kurnitski et al. [15] recommend using PV panels for the office buildings, as other renewable energy sources were considered less efficient in the given climate and for this building type. For four selected cases (from cost optimal to most energy efficient) primary energy was calculated together with hourly energy generation and usage within in the office building. The selected cases are shown in Tables 5 and 6: the cost optimal solution, the two next most reasonable solutions, and the most energy efficient solution. Insulation thicknesses for the selected models were 200, 250, 390 and 390 mm, respectively. In all cases, except in the case of model nr 2, all orientations had the same glazing WWR.

Fig. 11 illustrates two cases of electricity usage in the building: the blue line represents electricity usage without a constant load, while the green line represents usage with a constant load. A constant load in office buildings could represent, for example, the running of computer servers. The red line shows hourly electricity generation. When PV generation (red line) exceeds consumption (green and blue line), due to the load mismatch, then the excess production will be sold to the central power grid. The price for selling electricity is the electricity cost without VAT, taxes and network service cost - all together 0.044 €/kWh. Fig. 11 also illustrates how the constant load will impact efficiency of the solar panel system, meaning that more energy is used within the building. Table 5 summarizes the electricity profile and PV production. Proposed square meters of PV panels are minimal sizes for different design solutions. The last column represents the percentage of PV production consumed compared to overall electricity usage. In general, it can be noted that the more energy efficient the office is, the less PV production is required. However, in more energy efficient cases a higher fraction of the PV production was used in the building.

Based on the electricity consumed, generated and sold, the new total annual energy cost per square meter was calculated. Total annual energy cost includes all energy costs, even the cost of keeping the building systems running, whereas, previously the calculations included only energy requirements for heating, cooling and lighting. This new annual energy cost was used to calculate NPV. In addition, as the life-cycle for PV panels is shorter (15 years in this case) than that for structural elements, the replacement cost for PV panels was also included in the NPV calculation. Fig. 12 shows that the cost optimal façade solution without PV panels was the most cost optimal solution. The same solution with PV panels had slightly higher NPV by 1.6 units but achieves the nZEB level. In effect, it is up to the owner to decide if he is willing to accept the additional investment requirement and if it somehow conforms to project objectives.

Fig. 12 summarizes the difference between cases with and without PV panels. It can be seen in all cases that adding PV panels increases NPV by a few units. Nevertheless, PV panels are not cost efficient if you include maintenance and disposal costs of the PV panels, neither of which were considered in this study.

4. Discussion

Conditions can and are constantly changing, including energy prices, governmental politics, construction prices, etc. This means it is important to study the reliability of solutions and ranges of optimality. This section is divided into four parts: the first focuses on the construction costs of the building façade and their impact on cost optimal solutions; the second studies the impact of energy escalation; the third section considers the impact of selling prices on optimal nZEB levels; and the final section discusses design alternatives from the perspective of achievable building energy classes and costs.

4.1. The impact of window costs on NPV calculations

Quadruple glazing is a standard product, even though it is not yet in wide use. Fig. 6 shows that the cost of windows with quadruple glazing is almost twice that of windows with triple glazing. Even though energy performance is better, the initial additional required investment is not recoverable over a 20 year period, unless it becomes cheaper, as has happened in the case of double and triple glazing. The difference between triple and double glazing is marginal, but their energy performance varies significantly in favor of the former. Quintuple glazing is not considered in this section, as it is not a standard product, and the aim of using it was only to study the potential of future technologies.

In Step 2, a solution with facades with a WWR of 23.9% was recommended, despite the fact that the cost optimal solution was a WWR of 37.5%, due to the window unit price, which was lower than the insulated external wall unit price. By using a reversed calculation of formula (1), as shown in formula (4), fixing the NPV value of the cost optimal solution, the unit price for windows with a WWR of 23.9% can be calculated that make it cost optimal. This does not consider the case of the north facing façade, where the cost optimal solution is triple glazing windows with a WWR of 37.5%, due to reduced artificial lighting needs. While the current unit cost for a WWR of 23.9% is 122.00 €/m^2, to make it cost optimal it would be necessary to reduce it by 19.23 €, which is approximately 15.8%.

$$\mathrm{UP}_{\mathrm{window}} = \frac{(\mathrm{NPV}_{(\mathrm{currently\_optimal})} - C_{\mathrm{a}} \times f_{\mathrm{pv}}(n) \times A_{\mathrm{zone}} - A_{\mathrm{wall}} \times \mathrm{UP}_{\mathrm{wall}} - I_{\mathrm{network}}}{A_{\mathrm{window}}} \quad (4)$$

where:

Table 7
Analysis of the effect of selling price on annual energy cost (AEC) and NPV calculations.

No.	Solution type	Selling price, €/kWh 0.014		0.024		0.034		0.044		0.054		0.064		0.074	
		AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²	AEC, €/m²	NPV, €/m²
1	Cost optimal	7.87	295.35	7.86	295.16	7.85	294.97	7.85	294.78	7.84	294.59	7.83	294.41	7.82	294.22
2	Next sensible alternative solution	7.60	302.30	7.60	302.13	7.59	301.97	7.58	301.81	7.58	301.65	7.57	301.49	7.56	301.33
3	Next sensible alternative solution	7.58	318.39	7.58	318.27	7.57	318.16	7.57	318.04	7.56	317.92	7.56	317.81	7.55	317.69
4	Energy efficient	7.80	349.86	7.80	349.82	7.79	349.78	7.79	349.73	7.79	349.69	7.79	349.65	7.79	349.61

- $UP_{window/wall}$–unit cost for windows/walls, €/m^2.
- $NPV_{(currently\ optimal)}$–current optimal solution, according to the new unit price to be calculated, €/m^2.
- C_a annual energy cost during starting year, €.
- $f_{pv}(n)$ - discount factor for year n.
- A_{zone}–zone area by façade orientation, m^2.
- A_{wall}–wall quantity used for calculating investment, m^2.
- $I_{network}$–one time investment for connection to power grid, €.

The same method can be used to calculate the required unit price for quadruple glazing windows to make them cost optimal. Therefore, we need to reduce the cost of windows with quadruple glazing (krypton filling) compared to triple glazing with the same WWR of 37.5%. While the current unit cost for quadruple glazing is 176.88 €/m^2, to make it cost optimal it must be reduced by 42.58 €, which is approximately 24%.

4.2. Energy escalation in NPV calculations

Energy escalation has an impact on the cost optimality calculations, as the annual energy cost is discounted for a 20 year period. To calculate an escalation rate that makes quadruple glazing cost optimal, we need to create a system of equations for the windows with triple and quadruple glazing in Step 3 based on the equation (1): $C_g(3/Clear/Ar/016/) = C_g(4/Clear/Kry/013/)$. We are looking for a discount factor f_{pv} (n) that makes NPV in both cases equal. By making them equal we can cancel out C_g^{ref}/A_{floor} and A_{floor}. From what remains, the discounting factor 87.78 can be found:

$$C_I + C_a \times f_{pv}(n) = C_I - C_a \times f_{pv}(n) \quad (5)$$

To find the escalation rate required to make quadruple glazing optimal, we need to apply the discounting factor formula (3). Interest rate and inflation rate are constants, which comprise approximately 11.8% of energy escalation in one year. This result is unreasonably high and will probably never happen. Rather a combination of reduced construction costs and energy escalation is required to make quadruple glazing an optimal solution. Further discussion of this solution is beyond the scope of this work.

4.3. Impact of selling price of exported electricity on nZEB NPV calculations

To understand the impact of selling price on NPV value, a simple analysis is summarized in Table 7. Increasing or decreasing selling price in arithmetic progression by 1 cent has a linear impact on the annual energy cost (AEC) and NPV values. The NPV value for the optimal (triple glazing and 200 mm insulation) case with PV panels was calculated to be 294.78 €/m^2 in Step 3 and 293.24 €/m^2 for the cost optimal solution. To make a solution with PV panels cost optimal, the selling price must be increased by 3 cents. Lowering the energy selling cost increases NPV value for cases with PV panels. Therefore, it cannot become cost optimal. However, if the cost of PV panels were less or subsidized by the government, using PV panels could become an optimal solution. In 2013, the Estonian government engaged in a short-term project for residential building owners, where they supported the construction of renewable energy systems. Using the same method as in section 4.1, we can see that if the cost were reduced or subsidized by 14.4%, then it would become a cost optimal solution.

4.4. Guidelines for designers and construction industry clients

Based on these analyses, several recommendations for construction industry clients (who have buildings built for their own purposes) and designers (who help owners to achieve their goals)

Table 8
Summary of fenestration design solutions for a low energy building. Façade layouts are given for a room module 2 × 2.4 m (a partition between every second 2.4 m) and floor to floor height of 3580 mm; WWR permits the application of results to other arrangements.

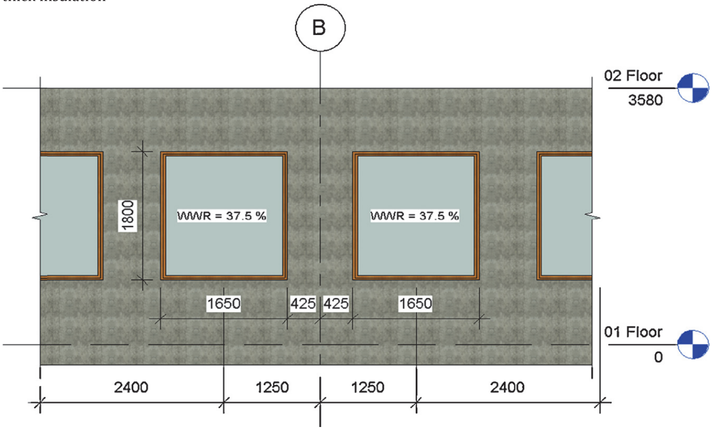
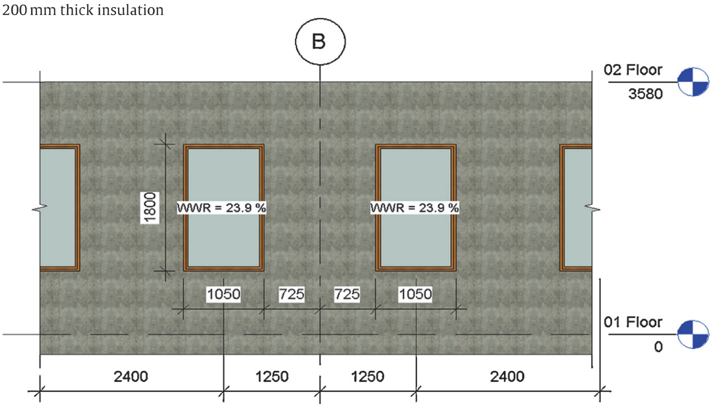
Solution case	Technical details	Key performance indicators
Low Energy Building, ≤130 kWh/m^2		
A. Cost optimal solution but with higher cooling load than recommended solution: triple glazing and 200 mm thick insulation  	Windows: • Triple glazing • WWR: 37.5% • *U* value: 0.54 W/(m^2 K) • Gap filling: 90% argon • Solar factor g: 0.49 • Visible transmittance τ_{vis}: 0.70 • Cost per unit: 104.68 €/m^2 Wall: • Insulation thickness: 200 mm • *U* value: 0.20 W/(m^2 K) • Cost per unit: 179.5 €/m^2	• Investment: 92.0 €/m^2 • Primary energy: 110.6 kWh/m^2 • Total energy cost per year: 8.55 €/m^2 • NPV: 293.2 €/m^2
A.1 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/(m^2 K) • Gap filling: 90% argon • Solar factor g: 0.49 • Visible transmittance τ_{vis}: 0.70 • Cost per unit: 122 €/m^2 Wall: • Insulation thickness: 200 mm • *U* value: 0,20 W/(m^2 K) • Cost per unit: 122.00 €/m^2	• Investment: 95.7 €/m^2 • Primary energy: 109,9 kWh/m^2 • Total energy cost per year: 8.50 €/m^2 • NPV: 295.70 €/m^2
B. Next sensible solution: quadruple glazing and 250 mm thick insulation (see the figure for solution A; north facing façade: see the figure for solution C)	Windows: • Quadruple glazing • WWR: 37.5% and North 60% • *U* value: 0,32 W/(m^2 K) • Gap filling: 90% krypton • Solar factor g: 0.36 • Visible transmittance τ_{vis}: 0.63 • Cost per unit: 176.88 €/m^2 and North 144.68 €/m^2 Wall: • Insulation thickness: 250 mm • *U* value: 0,13 W/(m^2 K) • Cost per unit: 227.9 €/m^2	• Investment: 107.80 €/m^2 • Primary energy: 109.1 kWh/m^2 • Total energy cost per year: 8.19 €/m^2 • NPV: 300.50 €/m^2

Table 8 (*Continued*)

Solution case	Technical details	Key performance indicators
C. The most energy efficient solution: quintuple glazing and 390 mm thick insulation. All orientations have windows with a size of 11600 × 1800 mm (figure below)	Windows: • Quadruple glazing • WWR: 60% (11.6 m) • *U* value: 0,21 W/(m^2 K) • Gap filling: 90% krypton • Solar factor *g*: 0.24 • Visible transmittance τ_{vis}: 0.56 • Cost per unit: 230.95 €/m^2 Wall: • Insulation thickness: 390 mm • *U* value: 0,093 W/(m^2 K) • Cost per unit: 363.4 €/m^2	• Investment: 160.50 €/m^2 • Primary energy: 103,4 kWh/m^2 • Total energy cost per year: 8.03 €/m^2 • NPV: 349.40 €/m^2

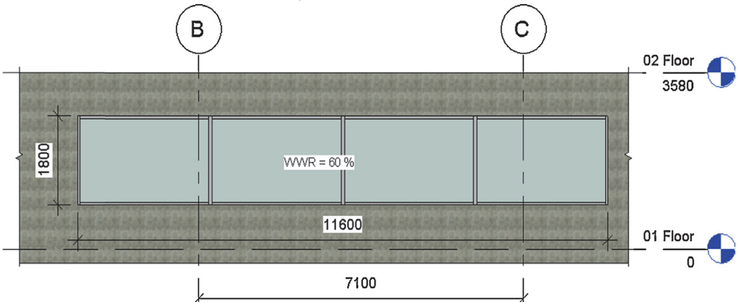


Table 9
Summary of fenestration design solutions for nearly zero energy building.

Solution case	Technical details	Key performance indicators
Economical solution for nZEB: triple glazing, 200 mm thick insulation and PV panels (for window layout, see the figure for solution A)	Windows: • Same as A Wall: • Same as A PV panel: • Efficiency: 10% • PV generation needed per heated area: 5.24 kWh/m^2 • Cost per unit: 276.00 €/m^2	• Investment: 110.2 €/m^2 • Primary energy: 100 kWh/m^2 • Total energy cost per year: 7.85 €/m^2 • NPV: 294.80 €/m^2
Next sensible solution for nZEB: quadruple glazing, 250 mm thick insulation (see the figure for solution B, except the north facing façade: see the figure for solution C) and PV panels	Windows: • Same as B Wall: • Same as B PV panel: • Efficiency: 10% • PV production needed per heated area: 4.53 kWh/m^2 Cost per unit: 276.00 €/m^2	• Investment: 123.4 €/m^2 • Primary energy: 100 kWh/m^2 • Total energy cost per year: 7.58 €/m^2 • NPV: 301.80 €/m^2
The most energy efficient solution for nZEB: quintuple glazing, 390 mm thick insulation and PV panels. All orientations have windows with a size of 11600 × 1800 mm	Windows: • Same as C Wall: • Same As C PV panel: • Efficiency: 10% • PV production needed per heated area: 1.70 kWh/m^2 Cost per unit: 276.00 €/m^2	• Investment: 166.4 €/m^2 • Primary energy: 100 kWh/m^2 • Total energy cost per year: 7.79 €/m^2 • NPV: 349.70 €/m^2

can be offered. In general, every project must start with the end goal in mind, which the owner/client must be sure to articulate clearly to designers. This helps to come up with design solutions that are within budget limits. Obviously, this is not always the case due to various reasons, and often decisions are made with only the short term in mind. That is why building codes set general requirements and rules for the design of buildings, including office buildings. According to Estonian regulation [14], new office buildings must comply with a minimum energy performance requirement of primary energy ≤160 kWh/m^2, if no stricter requirements by the client have been specified, as in the case of a low energy building with primary energy ≤130 kWh/m^2, or an nZEB with primary energy ≤100 kWh/m^2. Tables 8 and 9 summarize the results of this study for a low energy building and nZEB solutions. In the current context, cost optimal solutions lead to low energy buildings; however, achieving nZEB level requires additional costs and therefore, results in higher NPV values. It is up to the owner/client to decide what he/she wants to achieve. The solutions specified in the tables below can be used as guidelines for designers, who are responsible for converting the targets into technical solutions.

Table 9 presents exactly the same solutions as Table 8, except the recommended solution which was omitted for PV calculations. All these cases have technically the same solution, but the PV panels have been added based on the calculations in Step 3. This changes key performance indicators, as shown in the table.

5. Conclusions

Cost optimal and most energy efficient fenestration design solutions were determined for the cold Estonian climate. A three step approach was used to determine cost optimal and economically feasible solutions for low energy building and nZEB levels. Step 1 identified optimal ranges for wall insulation thicknesses. Step 2 analyzed window parameters to determine optimal window sizes and their costs. It was observed, that for the cold Estonian climate, windows with a smaller window to wall ratio, triple glazing and argon filling and walls with 200 mm thick insulation are energy efficient and cost optimal within 20 years.

Energy calculations and their results were mainly obtained from the paper [11]. Additional energy analyses in this study were carried out to calculate daily electricity usage with and without constant loads and PV generation in Step 3. The mismatch between electricity used and generated helped to calculate the amount of energy that can be sold back to the central power grid. However, as can be seen in Fig. 11, maximizing the use of electricity generated in the building lowers the amount of energy delivered. The tangential slope for electricity sold is smaller than for electricity consumed within the building; i.e., one saves more money by buying less energy from outside than selling excess energy, as these prices are different.

According to Estonian regulations [14], new office buildings must comply with a minimum energy performance requirement of primary energy $\leq$160 kWh/m^2, but according to this study, a low energy building ($\leq$130 kWh/m^2) is at a cost optimal level in the given economic environment. nZEB buildings ($\leq$100 kWh/m^2) were not cost optimal. Thus, current regulations, which were prepared several years ago, are not cost optimal anymore, and this change has occurred only over the last couple of years. The sensitivity analysis showed that by a combination of energy escalation and the reduction of construction costs of PV panels and/or windows with four panes, nZEB can become cost optimal in the near future. For designers and construction clients, a set of solution classes have been provided for designing a low energy building and nZEB. Technical and economical key performance indicators are provided for choosing between different fenestration design solutions.

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PAPER III

Thalfeldt, M., Kurnitski, J. External shading optimal control macros for 1- and 2-piece automated blinds in European climates. Building Simulation 8 (2015) 13-25.

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External shading optimal control macros for 1- and 2-piece automated blinds in European climates

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Research Article

Abstract

Dynamic external shading is considered an effective measure for improving energy performance and decreasing cooling loads. Optimal control principle is needed to minimize energy use and maximize occupants' satisfaction. We developed and described in detail optimal control macros in software IDA ICE 4.5 and simulated office building energy performances with varying facade solutions and climates over Europe. Primary energy savings between 1 and 32 kWh/m^2 were reached. Shading control to avoid glare during office hours and overheating outside work time was recommended in Tallinn and Paris. In addition shading adjustment according to room temperature during work time was necessary in Athens to minimize energy use. Also suntracking could be used in Tallinn and Paris, but PI-controllers for slat angle control were needed in Athens. Cooling load comparison of internal and external shading showed significant reduction in space cooling capacities ranging between 40% and 70%, whereas design date selection influenced cooling system design considerably besides facade solutions and orientations. Developed control macros are proposed for testing in other studies in order to find optimal control principles satisfying office workers which then could be generally implemented in design guidelines and manuals.

Keywords

solar shading,
control algorithm,
energy efficiency,
cooling load,
facades,
offices

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1 Introduction

External shading is considered an effective measure for improving indoor climate and energy performance of buildings. Cooling needs and summertime indoor temperatures are decreased by blocking direct sunlight and another benefit is that glare is avoided; on the other hand, heating and lighting energy increases due to any kind of external shading. The energy performance of buildings under design is being evaluated more and more often with energy simulations. However any kind of dynamic shading requires a proper control principle to increase the reliability of calculations and minimize future energy costs.

Dynamic shading may be adjusted either manually by building users or automatically with a control system. Besides the different nature of position adjustment of automated and manual blinds, there is no clear understanding how people operate the shades, which makes predicting the effect of shading difficult. Mahdavi et al. (2008) studied the behavior of occupants in 3 Austrian office buildings and stated that the manner of controlling shades may differ significantly building by building. Several other studies have pointed out that the position of motorized shading is changed more frequently than that of manual blinds, whereas when not controlled automatically a significant proportion of people formulate their decisions about blind position over a period of weeks or months, and not days or hours as was concluded by Van Den Wymelenberg (2012). Yao (2014b) studied the energy performance of manually controlled solar shades and concluded that using ideal control principle in energy simulations might result in overestimating energy savings by 16%–30%. This suggests that if energy and indoor climate are considered, automated blinds prove to be a better solution than manually controlled ones. Colaco et al. (2008) referred to a common belief that the use of "artificial intelligence" for building automation can elevate energy saving besides optimizing visual and thermal comfort. Lee et al. (2013) reported significant reductions in cooling loads

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Building Thermal, Lighting, and Acoustics Modeling after studying the effect of window opening and blind operation, whereas one of the influences pointed out was choosing operating hours and proper cavity control. Similarly, Shen and Hong (2009) reported possible savings up to 43% as a result of integrated electric lighting, window transmission and HVAC control. Yao (2014a) combined field measurements with energy and indoor climate simulations and reported that movable solar shades offer reaching substantial improvements in both energy efficiency and indoor environment quality.

In a cold climate it is essential to utilize as much of sun radiation during heating period as possible; however in low or nearly zero energy office buildings, the heating need depends remarkably on the office use and internal gains (Thalfeldt et al. 2013a). The possible energy penalty caused by external shading in the climate of Scotland was reported by Littlefair (2010). Therefore simple control principles of automated blinds depending only on external conditions may not be optimal and might even increase energy consumption (Thalfeldt et al. 2013b). The importance of proper control strategy especially in the case of balanced heating and cooling has been also stressed by da Silva (2012). One of the crucial aspects of automated dynamic solar shading is choosing the control parameters. In their study, Daum and Morel (2010) emphazise that at least two parameters should be used and the importance of internal temperature stands out. Controlling shades based on solar radiation is often used; however illuminance threshold might be a more appropriate solution (Tzempelikos and Shen 2013). According to recent studies, the control principle of shading is essential, which makes a need for studies regarding blind control algorithms evident.

The purpose of this study was to determine an optimal control principle for external shading on different facades. An effective control principle for a cold climate suggested by Thalfeldt and Kurnitski (2014) was developed further and in addition the facade performance in the climates of Paris and Athens was studied. The key criterion for assessing shading control principles was energy use; however the duration of unobstructed view from windows and the simplicity of the shading system was also considered. Detailed shading control macros were developed in the simulation software IDA ICE (IDA–ICE 2013). A generic office floor was analyzed and the proportion of cooling in total energy use varied in the cases selected. The numbers of window panes, window-to-wall ratios (WWR) and external wall U-values ranged from 3 to 5, 25% to 60% and 0.09 to 0.16 W/(m^2·K), respectively.

2 Methods

We simulated the performance of external automatically controlled dynamic venetian blinds to develop optimal control algorithms. The study was conducted by simulating four different generic office floors with varying facade properties—window sizes, number of panes and external wall insulation thickness. The most efficient control principles were chosen based on the energy performance, simplicity and the duration of unobstructed view. In addition the cooling capacities of zones were calculated to assess the effect of the shading principle on the sizing of cooling units.

2.1 Office floor simulation model

We conducted energy simulations on the basis of a generic open-plan office single floor model shown in Fig. 1. The floor model was divided into five zones—four orientated to south, west, east and north respectively and in addition one in the middle of the building . The longer zones consisted of twelve room modules of 2.4 m and shorter ones of five 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 had heat recovery. The working hours were

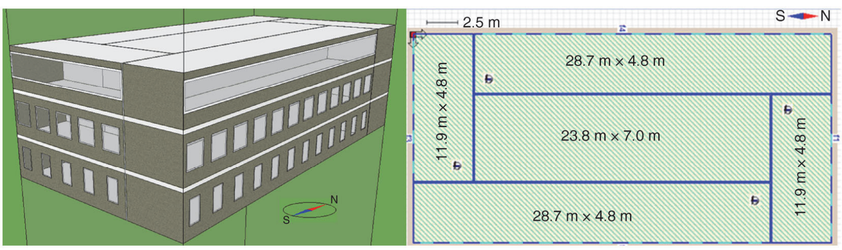

Fig. 1 Description of simulation models' geometry. Office floor models with triple, quadruple and quintuple windows (from bottom to top in the 3D figure left) were simulated in separate models

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 average in each zone. The initial data of the simulation model is shown in Table 1. The energy simulations were conducted with the well-validated simulation tool IDA ICE and the test reference year of Estonia was used (Kalamees and Kurnitski 2006) and the climate files of Paris and Athens were downloaded from www.equa.se. The monthly average outdoor temperatures and monthly solar radiation on horizontal surfaces have been described in Fig. 2. The primary energy factor for district heating is 0.9 and for electricity 2.0. The usage profile, primary energy factors and other indices were taken from Estonian regulations for calculating energy performance of buildings (Estonian Government Ordinance No. 68 2012).

The office floor facade solutions were chosen such that the balance of heating and cooling energy need would vary, which is achieved with differing thermal properties of windows and external walls and also window-to-wall ratios as can be seen in Table 2 and Fig. 1. The case names used in cold climate simulations (3-23.9%, 4-37.5%, etc.) were derived from the number of window panes and WWR used in the specific case. Additional cases were created to analyze the shading performance in the climates of Paris and Athens, whereas in the Tallinn case 4-37.5% was used in the comparison of different locations. Detailed window models were used, which means that the thermal resistance of glazing depended on the temperature difference between internal and external conditions. Cooling capacities of all cases were simulated besides the energy use. Four dates were simulated for each case—21.06., 21.07., 21.08. and 21.09. and the diurnal design outdoor temperatures for each location and date are given in Table 3. The maximum outdoor temperatures of each month in the climate files were used as outdoor temperatures at midday. To calculate the minimum diurnal outdoor temperature, three days of each month with highest average outdoor temperature were selected and the average temperature amplitude of those days was subtracted from the maximum monthly temperature. Also the internal gain usage factor of 55% was used for the open-plan offices.

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

Occupants (W/m^2)	5
Equipment (W/m^2)	12
Installed lighting (W/m^2)	5
Temperature setpoint for heating and cooling (℃)	+21/+25
Airflow rate (L/(s·m^2))	1.5
Illumination setpoint (average over zone floor) (lx)	500
Frame ratio of windows (%)	15
Heating system (radiators) efficiency	0.97
Heat source (district heating) efficiency	1.0
Cooling system losses (% of cooling energy need)	10
Mechanical cooling application SEER	3.5
Temperature ratio of heat recovery (%)	80

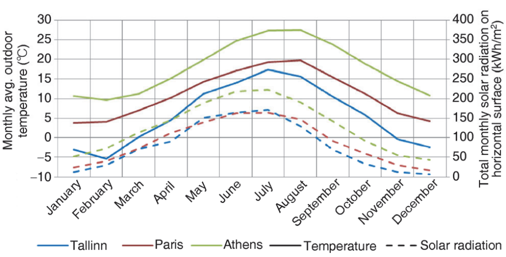

Fig. 2 Description of the climates of Tallinn, Paris and Athens used in the study

The venetian blinds were constructed of opaque slats with 80 mm width and 70 mm distance between them. The upper and lower layers of slats had reflectances 0.7 and 0.4 respectively for total shortwave and visible radiation and longwave reflectance for both sides was 0.9.

2.2 External blinds and lighting control

Automated shading combined with an automatically controlled lighting system gives the best result in achieving low energy need. Figure 3 depicts such a solution where motorized venetian blinds (marked with 1) are installed outside the window that are controlled using a multi-sensor on the ceiling (2) to detect occupancy and measure illuminance levels on the desktop and the room user can choose the control parameters from the control panel on the wall (3), where room temperature is also measured. The slat angle of venetian blinds may be adjusted evenly over the entire shade or it can be divided into two parts to block direct radiation on the workplace with the lower part but allow access of daylight from the upper part, whereas 2-piece blinds also need an additional actuator. The primary goal of occupancy monitoring is to prevent unnecessary electric lighting when nobody is present; however it can be effectively used for blind control also to determine whether avoiding glare is necessary. Besides the elements shown in Fig. 3 sensors for measuring vertical irradiance on facades may also be installed for effective blind control and measuring wind is also necessary to detect conditions that might harm the blinds.

Table 2 Description of simulation cases

Case code	Glazing						Window-to-wall ratio (%)	U-value of external walls (W/(m^2·K))
	No. of panes[a]	U-value[b] (W/(m^2·K))	g-value	Visible transmittance τ_{vis}	Gas filling	Gap width between panes (mm)		
3-23.9%	3	0.55	0.45	0.71	Argon	18	23.9	0.16
4-37.5%	4	0.32	0.34	0.63	Krypton	12	37.5	0.13
5-37.5%	5	0.21	0.25	0.56	Krypton	12	37.5	0.09
5-60%	5	0.21	0.25	0.56	Krypton	12	60.0	0.09
Paris	3	0.55	0.45	0.71	Argon	18	37.5	0.20
Athens	2	1.14	0.58	0.80	Argon	18	37.5	0.33

[a] One is a simple highly transparent pane, the other panes have low emissivity coating (ε=0.03).

[b] Given according to calculations of ISO 15099: 2003/E (ISO 2003) at internal and external temperature difference of 20℃.

Table 3 Design outdoor temperatures for cooling capacity calculations. The maximum value is the highest monthly temperature of the climate file. The average temperature amplitude of three warmest days of each month was subtracted from the maximum temperature to calculate minimum values

Date	Design outdoor temperature (max/min) (℃)		
	Tallinn	Paris	Athens
June 21	24.7/13.8	28.0/17.9	35.8/24.8
July 21	27.3/15.8	30.0/18.5	35.0/23.9
August 21	27.2/15.1	30.0/16.8	37.2/28.1
September 21	22.4/11.7	24.3/18.0	33.6/24.9

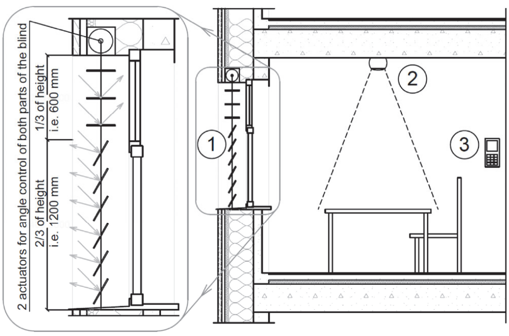

Fig. 3 Cross-section of an office room. 1: motorized external venetian blind with two actuators for changing position and slat angle, 2: multisensor for detecting occupancy and measuring illuminance at desktop, 3: control panel with built in temperature sensor

2.3 Shading control principles

The study of Thalfeldt and Kurnitski (2014) confirms that in a cold climate external shading should be controlled according to internal temperature and desktop illuminance. While drawn shading decreases cooling needs, it increases heating and especially lighting energy use, furthermore the view is obstructed. The question of which is more important—maximizing daylight utilization or minimizing cooling needs—remained unanswered. The main goal of this study was to develop a simple control algorithm for minimization of total energy use.

We developed control algorithms that have different rules about permitting shading position changes according to either room temperature or desktop illuminance (Table 4). The table provides information about the blind types (1- or 2-piece), when shading is permitted to be drawn due to too high room temperatures or desktop illuminance values respectively and how or with what slat angle is controlled. The strategies 1–4 were used in all climates—Tallinn, Paris and Athens. Additional control principles—5–7 for Tallinn and 8–10 for Paris and Athens—were developed in work process based on control principles 1–4. In addition case 0 with internal venetian blinds was created to assess the benefits of dynamic external shading compared to internal shading. Control principles 5–7 focus on 2-piece blinds in Tallinn climate. Control principle 8 did not prove to be effective in Tallinn climate (Thalfeldt and Kurnitski 2014) and is therefore tested only in the cases of Paris and Athens. Algorithm 9 was mainly tested for the climate of Athens, which differs significantly from the other two. In Paris and Athens only one control algorithm for 2-piece blinds was simulated.

We created shading control macros in IDA ICE for each algorithm and the components of all macros are shown in Fig. 4 and Fig. 5. Table 5 presents the components of each control principle macro with their description. The control parameter setpoints given as examples were used in the current study, developed in (Thalfeldt and Kurnitski 2014). The figures show a large number of macro elements, but no control strategy contains all of them. In order to create a control macro, the elements indicated in Table 5 were connected in similar manner as shown in Fig. 4 and Fig. 5, while leaving out the unnecessary components. The optimal control principle macros for the climates of Estonia, Paris (Fig. 8) and Athens (Fig. 12) are given in Sections 3.1 and 3.2 respectively to increase the clarity how the macros were created in IDA ICE.

Table 4 Blind types, shading position and slat angle control rules of studied control principles. Abbreviations: OW—outside working hours, DW—during working hours, UP—upper part, LP—lower part

No.	Blind type	Shading position control		Slat angle control
		Temperature	Illuminance	
0	Internal	Drawn when vertical irradiance on facade exceeds 200 W/m^2		Constantly 45°
1	1-piece	At all times	DW	PI-controller
2	1-piece	OW	DW	PI-controller
3	1-piece	OW & when illuminance is not too low DW	DW	PI-controller
4	1-piece	OW (same as 2)[a]	DW	Suntracking
5	2-piece	At all times (same as 1)	DW	UP PI-controller according to illuminance LP suntracking
6	2-piece	OW (same as 2)	DW	UP PI-controller according to illuminance LP suntracking
7	2-piece	OW (same as 2)	DW	UP 0° DW; suntracking OW LP suntracking
8	1-piece	Drawn when vertical irradiance on facade exceeds 200 W/m^2		Suntracking
9	1-piece	OW & vertical irradiance on facade exceeds 200 W/m^2 DW	DW	PI-controller
10	2-piece	OW & when illuminance is not too low DW (same as 3)	DW	UP illuminance DW & temperature OW with PI-controller LP PI-controller

[a] In the case of Athens, room temperature based shading position control was also allowed when illuminance was not too low.

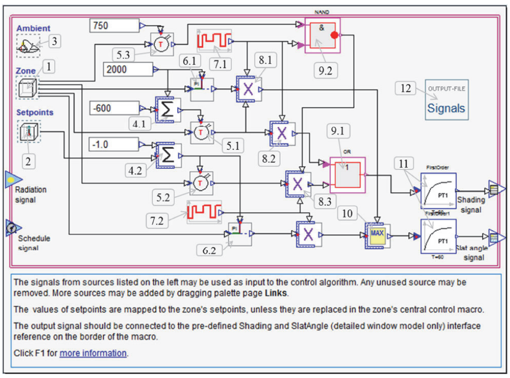

Fig. 4 Macro for shading control in strategies 1–7 composed in IDA ICE. The description of elements is shown in Table 5. The components used for control strategies 1–7 are shown in the figure, whereas none of the strategies contain all elements

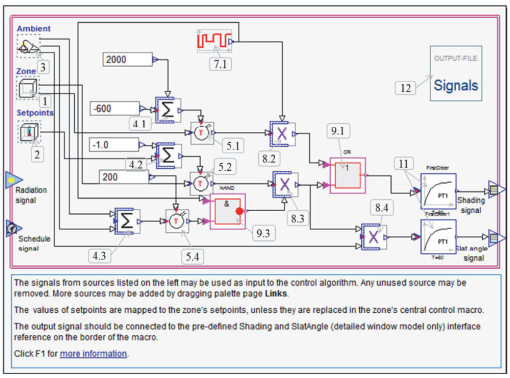

Fig. 5 Macro for shading control in strategies 8–10 composed in IDA ICE. The description of elements is shown in Table 5. The components necessary to describe control strategies 8–10 are shown in the figure. Some of the macro components are also shown if Fig. 4 and their labels are the same

3 Results

The results section of this article presents the primary energy use of all cases to compare the influence of control principles on energy performance. The energy uses of all cases from which the primary energy was calculated from have been given in Appendix. To compare the control principles, besides energy use, the quality of view was used, which was assessed by the amount of hours while the blinds were down during working hours. The simplicity of the control principle/macro was used as the criterion to choose the optimal algorithm, if the energy performance and view quality of control principles did not differ significantly.

Table 5 Description of control macro elements shown in Fig. 4 and Fig. 5

No.	Element	Control principle used in 1	2	3	4	5[a]	7[a]	8	9	10[a]	Description
1	Zone	•	•	•	•	•	•		•	•	Measures needed values from zone
2	Setpoint	•	•	•	•	•	•		•	•	Setpoints for zone climate control
3	Ambient				•	•	•	•	•		Information about ambient condition
4.1	Adder	•	•	•	•	•	•		•	•	Adds a constant (e.g. −600) to desired desktop illuminance (e.g. 2000)
4.2	Adder	•	•	•	•	•	•		•	•	Adds a constant (e.g. −1.0) to zone temperature setpoint for cooling
4.3	Adder							•	•		Adds diffuse and direct irradiance on the facade to get total irradiance
5.1	Thermostat	•	•	•	•	•	•		•	•	Draws shading if illuminance in zone is too high (e.g. 2000−600=1400 lx, deadband is −1000, i.e. ±500 lx)
5.2	Thermostat	•	•	•	•	•	•		•	•	Draws shading if temperature in zone is too high (e.g. +25−1=+24 ℃, deadband is −1, i.e. ±0.5 ℃)
5.3	Thermostat			•						•	Permits drawing shading during working hours only when illuminance is high enough (e.g. 750 lx, deadband is 300 lx, i.e. ±150 lx)
5.4	Thermostat							•	•		Permits drawing shading when total irradiance is too low (e.g. 200 W/m^2, deadband 10 W/m^2, i.e. ±5 W/m^2)
6.1	PI-controller	•	•	•		•			•	•	Controlles slat angle so that desired illuminance (e.g. 2000 lx) is achieved; min. value=0, max value=90
6.2	PI-controller	•	•	•					•	•	Controlles slat angle so that desired temperature (e.g. +24 ℃) is achieved; min. value=0, max value=90
7.1	Schedule	•	•	•	•	•	•		•	•	Determines occupancy/work time; value=1 during work time, value=0 outside work time
7.2	Schedule		•		•	•	•		•	•	Determines vacancy/time outside work time; value=0 during work time, value=1 outside work time
8.1	Multiplier	•	•	•		•			•	•	Determines that slat angle is controlled only if it is work time (7.1) and there is excessive daylight available (4.1)
8.2	Multiplier	•	•	•	•	•	•		•	•	Determines that shading can be drawn due to excessive daylight (4.1) only during work time (7.1)
8.3	Multiplier		•	•	•		•		•	•	Determines that shading can be drawn due to too high temperature (4.2) only outside work time (7.2)
8.4	Multiplier					•	•			•	Determines that slat angle is equal to sun angle only when shading is drawn only due to high temperature, otherwise slat angle is 0°
9.1	Or	•	•	•	•	•	•		•	•	Draws shading if it is required either by thermostat 4.1 or 4.2
9.2	Not + And			•						•	Denies drawing shading due to high temperature if it is work time and illuminance is too low
9.3	Not + And								•		Denies drawing shading due to high temperature during work time if total irradiance of facade is too low
10	Max	•	•	•		•			•	•	Chooses maximum required slat angle value required by PI-controllers 5.1 and 5.2
11	Timers	•	•	•	•	•	•	•	•	•	Timers for avoiding numerical problems and shortening simulation time (delay e.g. 60 seconds)
12	Output file	•	•	•	•	•	•	•	•	•	Output file for recording shade positions and illuminance level, gathers signals from zone and multipliers 8.2 and 8.3

[a] Only the elements of control algorithm of upper part of a 2-piece blind are given. The lower parts of the 2-piece blinds are controlled similarly to another control algorithm that is specified in Fig. 4.

3.1 Optimal control principle in a cold climate

The results in Fig. 6 show that generally external blinds noticeably improved energy efficiency compared to internal ones, whereas the effect was larger in case of larger glazing areas and higher *g*-values. The primary energy of the whole floor decreased between 0.3 and 2.8 kWh/m^2 and improvements were between 1.2 and 6.2 kWh/m^2 on the west facade. When only the cases of external shading were compared, which was the main purpose of the study, then the greatest difference between annual primary energy use of the analyzed control principles was 1.3 kWh/m^2, i.e. only

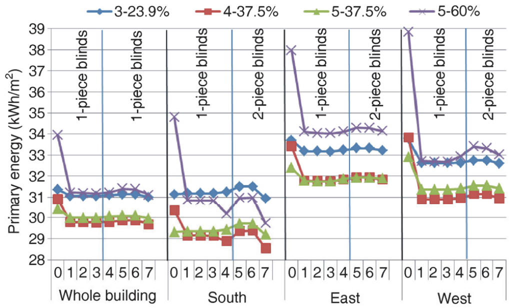

Fig. 6 The primary energy use of control principles 1–7 in the climate of Tallinn. Case 0 stands for internal venetian blinds

3% of heating, cooling and lighting energy which is insignificant. The largest fluctuations in the energy use appeared in the case of 5-pane windows with WWR 60% followed by 4-pane windows with WWR 37.5%. The variations in the annual primary energy use remained within 0.6 kWh/m^2 in the case of 3-pane windows with WWR 23.9% and 5-pane windows with WWR 37.5%. The variations in the primary energy use of cases with external blinds were up to 4.2%, 2.2% and 0.8% in south, west and east facades respectively, making south the most sensible orientation. No significant improvement was found in the energy performance if 2-piece blinds were used instead of 1-piece blinds, whereas 2-piece blinds could slightly even increase energy use. Therefore in the cold climate of Tallinn using 2-piece blinds are not recommended. Controlling slat angle according to the sun angle i.e. using suntracking can be recommended as it did not increase energy use and is by its nature a more simple method than using PI-controllers.

The small impact of studied control methods on the energy use can be explained with the information provided in Fig. 7, where the reasons for drawing shading during work time have been given in case of control principle 1. Control principle 1 means that shading could be drawn due to too high room temperatures at all times and due to high illuminance values during work time. The largest need for drawing blinds appeared in the south facade where blinds were drawn for 27%–36% of total 2860 working hours. South was followed west and east with the obstructed view duration of 15%–25% and 14%–18% respectively. The duration of drawn blinds at different facade solutions increased as follows: 5-37.5%, 3-23.9%, 4-37.5% and 5-60%. The need for drawing shades occurred prevailingly due to too high illuminance values. Therefore controlling shading according to only illuminance during working hours did not result in higher energy use compared to other strategies.

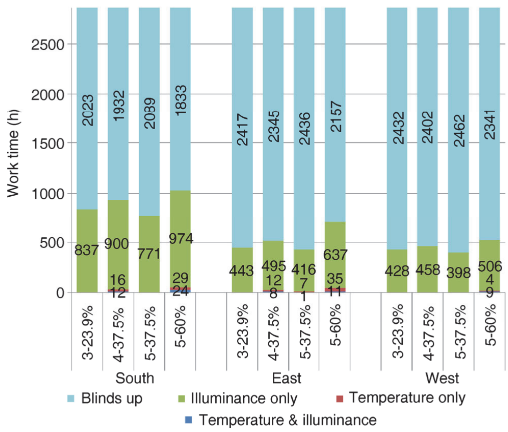

Fig. 7 The illustration of shading need on different facades in the climate of Tallinn in the case of control principle no. 1

As varying control strategies and using 2-piece blinds practically had no effect on the energy use, the simplest control principle i.e. strategy 4 was chosen as the optimal one. The external blinds should be controlled according to desktop illuminance during working time (occupancy), room temperature outside working hours and suntracking should be used for slat angle adjustment. The control macro of the principle is presented in Fig. 8, whereas in case of actual installation the information about working time should be provided from occupancy sensor instead of time schedules (elements 7.1 and 7.2 in Fig. 8).

3.2 Comparison of different climates

The simulation results in Fig. 9 show that similarly to the climate of Tallinn external shading improved energy efficiency significantly, whereas the range of primary energy reduction in Paris was on average of 1–2 kWh/m^2 which is slightly larger than in Tallinn. However, in Athens the overall

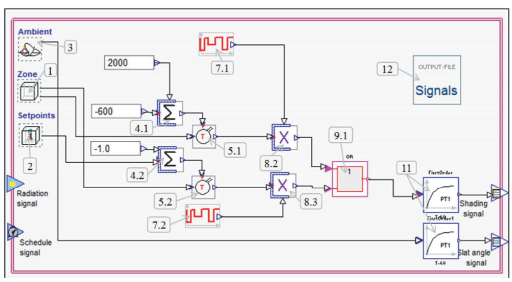

Fig. 8 The macro of optimal control principle in Tallinn and Paris (control principle no. 4 in Table 4 and Table 5)

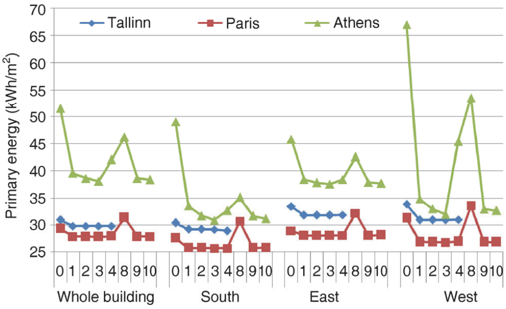

Fig. 9 The primary energy use of control principles 1–4 and 8–10 in the climates of Tallinn, Paris and Athens. Control principles 8–10 were not simulated in the case of Tallinn

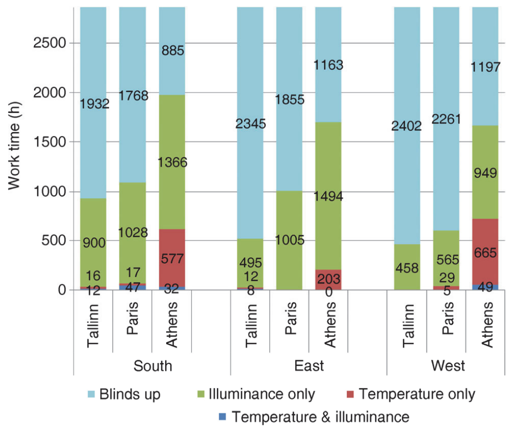

Fig. 10 The illustration of shading need on different facades in all climates in the case of control principle no. 1

reduction in the primary energy of the whole floor was 11.9 kWh/m² and as high as 32.1 kWh/m² in the west facade. The control principles had a significantly larger effect on the energy use in the warm climate of Athens compared to Tallinn and Paris. Out of control principles 8–10 simulated only with the climates of Paris and Athens, 8 proved to be clearly the least energy efficient in all cases with external shading. The algorithm used only total irradiance on the facade for shading position control and similar results were obtained with the climate of Tallinn in (Thalfeldt and Kurnitski 2014). Athens was the only climate where principle 8 did not cause higher energy consumption than case 0 with internal blinds. When other control principles were considered, the fluctuations of primary energy remained within 0.2 kWh/m² in Tallinn and Paris, but in Athens the difference in the primary energy depending on the control principle was as high as 13.5 kWh/m².

Disabling room temperature based shading position control during occupancy in the Paris climate did not affect primary energy noticeably similarly to Tallinn. However in Athens allowing drawing shades due to too high temperatures when the illuminance levels were high enough during working hours, had a significant positive effect on the energy performance of all zones. Suntracking increased the energy use in Athens significantly unlike Tallinn and Athens. The most sensible orientation to the choice of the control principle in Paris and Athens was the west, whereas in Tallinn it was the south. A similarity for all climates was that controlling shading based on indoor conditions provided the lowest energy use and using 2-piece blinds did not improve energy efficiency significantly.

Relatively larger impact of studied control methods on the energy use in Athens can be explained with the information provided in Fig. 10, where the reasons for drawing shading during work time have been given in the case of control principle 1. While the duration of drawn shading in Paris was higher than in Tallinn, the nature of the reasons for drawing the shading was similar. However in Athens the necessity to prevent overheating became evident even when there was no excessive daylight. That explains why a slightly more complicated control algorithm is needed in the hot climate of Athens, which at certain conditions also allows adjusting shading position according to room temperature during occupancy.

Figure 11 demonstrates that in Tallinn and Paris the duration of drawn blinds did not depend much on whether shading was controlled according to room temperature during occupancy besides illuminance levels or not. However in the case of Athens there were substantial differences between control principles 1–3. Naturally, adjustment of blinds only according to illuminance during occupancy resulted in the shortest time of drawn shading. In addition to Fig. 10, Fig. 11 also shows the differences in the need for shading depending on the climate and location. In Tallinn and Paris the duration of blinds being in down position did not exceed 40% during occupancy for any case, whereas in Athens the duration could be as high as 70% of working time. The south facade may receive direct sunlight for most part of a working day, while east and west have it either in the beginning or the end of the work day respectively. Therefore the duration of drawn blinds is also the longest in the south orientation, especially in Tallinn where in the middle of winter the sun has not yet risen when the work day begins and has already set when the work day ends and that reduces the need for shading in east and west orientations.

Another aspect that appeared was that in east and west orientations of buildings located in Tallinn and Athens, the duration of drawn blinds did not differ much. However, in

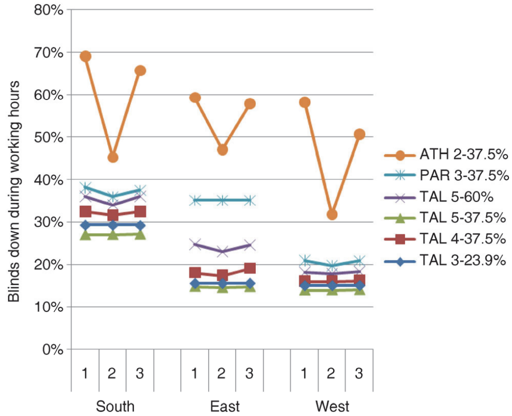

Fig. 11 The effect of control principle, facade solution, orientation and climate on the time that blinds are down during working hours

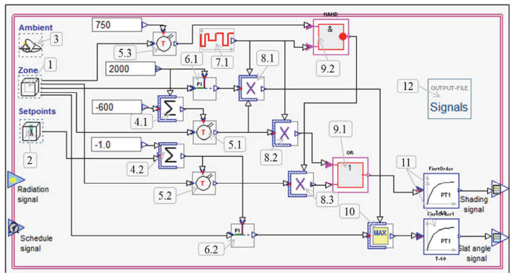

Fig. 12 The macro of optimal control principle in Athens (control principle no. 3 in Table 4 and Table 5)

Paris drawn shading was required for a significantly longer time period in the east facade than the west. While Tallinn and Athens are located at east longitudes 24.8° and 27.3° respectively which correspond well to their Eastern-Europe timezone, Paris is located near the Greenwich meridian, but its timezone is Central-European. Due to that in Paris the sun azimuth is further north when work time begins in Paris and the east facade receives more sunlight during the beginning of a work day than it does in Tallinn and Athens. The same effect does not appear on the west facade because generally the sun has not set yet when work days end in all of the studied locations.

The results of the analysis for the climate of Paris were alike to Tallinn and therefore similarly the most simple control principle i.e. strategy 4 was chosen as the optimal one. The control macro can be found at the end of Section 3.1 in Fig. 8. In the case of Athens using 2-piece blinds or control methods based on external conditions also did not achieve better energy efficiency than algorithms based on room temperature and illuminance. However, allowing drawing shades according to room temperature when illuminance was not too low during working hours i.e. control principle 3 resulted in lowest primary energy use. Although control principle 2 assured longer periods of unobstructed view, it also had high cooling needs. Low energy need and better thermal comfort usually are connected and therefore control principle 3 was chosen as the optimal one and occupants could always manually redraw the blinds if they prefer view over thermal comfort. The control macro of the principle 3 is presented in Fig. 12, whereas in the case of actual installation the information about the working time should be provided from occupancy sensor instead of the time schedule (element 7.1 in Fig. 12).

4 Discussion

It was concluded in (Thalfeldt 2013b) that installing external shading in the cold climate of Estonia mainly due to high investment cost is unreasonable. However a simple control principle not fully utlilizing the potential of external shading was used in the study. Optimizing the control principles increased the energy savings achieved with external blinds; however we believe that it is insufficient to assure the financial feasibility if only energy use is taken into account. The reduction in cooling system investment cost resulting from the decreased cooling capacities may become the crucial aspect when the feasibility of external blinds is considered in the early stages of building design.

It is important to know if and how different control principles affect the design cooling capacities illustrated in Fig. 13 and Fig. 14. Using external blinds decreased sensible cooling capacities by 19–49 W/m^2 i.e. 47%–75%, which allows reducing investment on the cooling equipment significantly while increasing its efficiency as it becomes more easy to utilize free cooling sources. Using PI-controllers for slat angle control assured cooling capacities around 15–20 W/m^2, whereas suntracking resulted in slightly larger cooling capacities between 20–30 W/m^2. Sensible cooling of 15 W/m^2 can be assured by supplying 1.5 L/(s·m^2) of +17℃ fresh air into a +25℃ room. Simulated situation applies for average use in an open plan offices as the internal gains usage factor of 55% was applied. In cooling design of smaller offices a usage factor close to 100% should be used and therefore it cannot be said that supplying cool air only is enough for assuring +25℃ throughout the year. In addition, a very efficient lighting system was used and in case of a common lighting system internal heat gains might prove to be also too high for eliminating room conditioning units. As cooling capacities are affected by several building parameters, the values shown in this section are not universal, but they indicate external blinds' effectiveness of reducing solar gains instead.

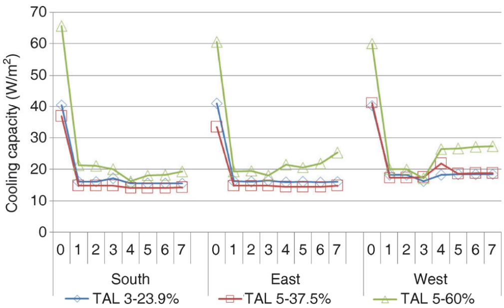

Fig. 13 The cooling capacities of different control principles in Tallinn cases with triple and quintuple windows. The case quadruple glazing is shown in Fig. 14

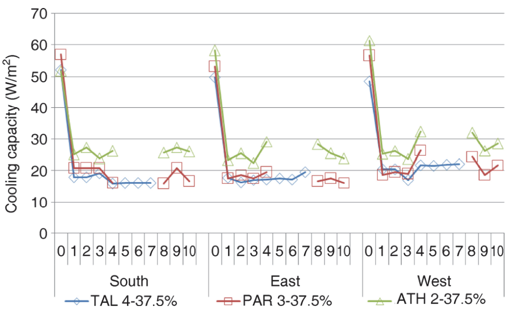

Fig. 14 The cooling capacities of different control principles in different climates

Currently it is common practice to size room cooling units by simulating only one design date for the whole building; however sun angles differ significantly throughout the year. In cold climates the temperature differences between indoor and outdoor conditions during summer are not large and solar gains have a much larger effect on cooling capacities compared to external temperature. Figure 15 describes how sensible cooling capacities depend on the sun angles on different dates. Clear sky conditions were used and the solar radiation was calculated by IDA ICE. It can be seen that the highest solar gains in the south facade appear in spring and autumn of all locations when the sun angle is lower in midday. In the east and west the critical time is the summer in Tallinn and Paris; however in Athens 21st of August could be appropriate for designing the capacity of space cooling. The results of cooling capacity calculations characterize the complexity of the issue as the highest heat gains due to solar radiation might appear in the cooler seasons if there are no surrounding objects blocking the sunlight. Thus the design dates must be carefully chosen to design the cooling units on different facades and the chiller of the whole building. Design periods for calculating cooling capacities should be developed for different months to also take into account the cooling or heating effect of diurnal outdoor conditions.

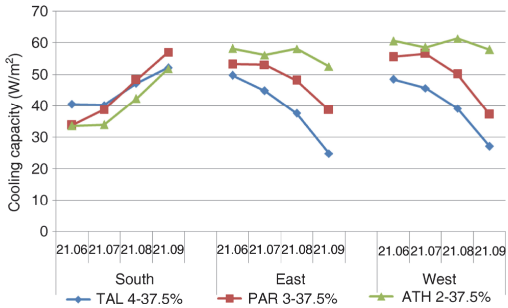

Fig. 15 The cooling capacities in different climates depending on the design day

The properties of heating, ventilation, cooling and lighting system and the parameters of the venetian blinds remained the same throughout the study. At the same time, the results may be sensible for changing any of these parameters. Aspects for further analysis are the control setpoints and deadbands, especially when considering workplace illuminance levels. The small deadband for drawing shading due to glare might cause redrawing the shading shortly after it was drawn and too frequent position changes reduce the life span of actuators and might also disturb the office worker. In addition conflicts might occur if there are workers present near the window that need glare protection and also at the back wall needing daylighting. Therefore, we propose the developed control macros for testing in other studies in order to find optimal control principles satisfying office workers which then could be generally implemented in design guidelines and manuals.

5 Conclusions

We simulated the performance of external automatically controlled dynamic venetian blinds to develop optimal control algorithms. Four different generic office floors with varying facade properties—window sizes, number of panes and external wall insulation thickness—were simulated. The most efficient control principles were chosen for the climates of Tallinn, Paris and Athens based on the total energy performance, simplicity and the duration of unobstructed view. In addition the cooling capacities of zones were calculated to assess the effect of the shading principle on the sizing of space cooling. We developed the control macros in the simulation software IDA ICE 4.5 and described them in detail.

The results of the study were similar for Tallinn and Paris where the analysis showed that the reduction in the calculated primary energy use was up to 3 kWh/m² for the whole floor and 6 kWh/m² on the west facade when external blinds were used instead of internal ones. These results applied for optimally selected relatively small windows and glazing unit's properties, in other cases the differences could be higher. Different control principles using room temperature and desktop illuminance as control parameters did not cause significant fluctuations in energy use and the duration of unobstructed view. The reason was that during working hours a need for external shading appeared mostly to avoid glare and not because of too high temperatures.

In Athens the initial cooling needs were higher and the potential saving of external shading was 12 kWh/m^2 on average and as high as 32 kWh/m^2 on the west facade. Also the control algorithms had a significantly larger effect on the energy use compared to Tallinn and Paris. A need for drawing shading due to high temperatures appeared on working hours and at absence of any glare problems. Therefore, shading control according to the room temperature was also necessary to minimize energy use.

The proposed control algorithm had the following principles:

- During working hours shading should be drawn when illuminance levels on desktop are too high in all locations. In Athens shading should also be drawn in case of too high temperatures if it does not cause the need for artificial lighting.
- Outside working hours shading should be drawn when the room temperature is approximately 1℃ below the cooling setpoint.
- In Tallinn and Paris sun tracking should be used, i.e. the slat angle should be equal to the sun angle at any given time; however PI-controllers should be used in Athens.

Cooling load analysis showed that external shading is an effective method for reducing cooling capacities and thereby saving on the investment cost of the cooling system. Calculated cooling load decreases of 40%–70% offers opportunities to reduce cooling investment cost while increasing the systems efficiency. Our results showed that cooling capacities with external blinds using different control algorithms varied up to 15 W/m^2, whereas using suntracking caused higher cooling load when compared to using PI-controllers for slat angle control. Although suntracking did not increase energy use in Tallinn and Paris, investing in PI-controllers for slat angle adjustment might prove to be cost effective when it allows using simpler and cheaper cooling solutions. It also appeared that solar gains depend remarkably on the time of the year in all climates, especially on the south facade where low sun angles during spring and autumn cause higher cooling loads. On the other hand outdoor temperatures are lower in autumn than in summer and therefore careful consideration of the design date for cooling design is essential.

Acknowledgements

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Appendix

Table A1 The energy needs of simulated cases in the climate of Tallinn

	Control principle	Space heating (kWh/m^2)				Supply air heating (kWh/m^2)				Space cooling (kWh/m^2)				Supply air cooling (kWh/m^2)				Lighting (kWh/m^2)			
		3-23.9%	4-37.5%	5-37.5%	5-60%	3-23.9%	4-37.5%	5-37.5%	5-60%	3-23.9%	4-37.5%	5-37.5%	5-60%	3-23.9%	4-37.5%	5-37.5%	5-60%	3-23.9%	4-37.5%	5-37.5%	5-60%
Whole building	0	13.6	12.5	12.1	14.1	3.9	3.8	3.9	3.9	1.0	3.0	1.5	6.2	7.7	7.7	7.7	7.7	5.1	4.8	5.2	4.5
	1	14.1	13.2	12.7	15.2	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.1	7.6	7.7	7.6	7.7	5.1	4.8	5.2	4.5
	2	14.1	13.2	12.7	15.2	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.1	7.6	7.7	7.6	7.7	5.1	4.8	5.2	4.5
	3	14.1	13.2	12.7	15.2	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.1	7.6	7.7	7.6	7.7	5.1	4.8	5.2	4.5
	4	14.1	13.2	12.8	15.1	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.3	7.6	7.7	7.6	7.7	5.0	4.8	5.2	4.5
	5	14.2	13.3	12.8	15.3	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.3	7.6	7.6	7.6	7.7	5.1	4.8	5.2	4.5
	6	14.2	13.3	12.8	15.3	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.3	7.6	7.7	7.6	7.7	5.1	4.8	5.2	4.5
	7	14.0	13.1	12.7	15.0	3.9	3.9	3.9	4.0	0.0	0.1	0.0	0.3	7.6	7.7	7.6	7.7	5.0	4.8	5.2	4.5
South	0	15.9	13.4	13.3	14.5	3.9	3.8	3.9	3.9	1.6	5.6	2.5	12.1	7.7	7.7	7.7	7.7	3.7	3.3	3.8	2.9
	1	17.7	16.0	15.5	18.4	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
	2	17.7	16.0	15.5	18.4	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
	3	17.7	16.0	15.5	18.4	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
	4	17.8	15.8	15.6	17.8	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
	5	18.1	16.3	15.9	18.6	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.6	7.6	7.7	3.4	3.2	3.5	2.9
	6	18.1	16.3	15.9	18.6	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
	7	17.5	15.4	15.4	17.3	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.4	3.2	3.5	2.9
East	0	19.3	18.1	17.3	20.7	3.9	3.8	3.9	3.9	1.2	3.7	1.7	8.1	7.7	7.7	7.7	7.7	3.6	3.2	3.7	2.9
	1	19.6	18.8	17.8	21.9	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
	2	19.6	18.8	17.8	21.9	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
	3	19.6	18.8	17.8	21.9	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.0	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
	4	19.7	18.9	18.0	21.9	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
	5	19.8	19.0	18.0	22.1	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.6	7.6	7.7	3.5	3.2	3.7	2.9
	6	19.8	19.0	18.0	22.1	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.1	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
	7	19.7	18.9	18.0	21.9	3.9	3.9	3.9	4.0	0.0	0.0	0.0	0.2	7.6	7.7	7.6	7.7	3.5	3.2	3.7	2.9
West	0	17.2	15.8	15.2	18.1	3.9	3.8	3.9	3.9	2.2	5.9	3.3	11.9	7.7	7.7	7.7	7.7	4.3	3.8	4.5	3.3
	1	17.5	16.5	15.7	19.2	3.9	3.9	3.9	4.0	0.1	0.2	0.2	0.4	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3
	2	17.5	16.5	15.7	19.2	3.9	3.9	3.9	4.0	0.1	0.2	0.2	0.4	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3
	3	17.4	16.5	15.7	19.2	3.9	3.9	3.9	4.0	0.1	0.2	0.2	0.4	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3
	4	17.5	16.5	15.8	19.1	3.9	3.9	3.9	4.0	0.1	0.3	0.1	1.0	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3
	5	17.6	16.7	15.9	19.4	3.9	3.9	3.9	4.0	0.1	0.4	0.2	1.0	7.6	7.6	7.6	7.7	4.2	3.8	4.4	3.4
	6	17.6	16.7	15.9	19.4	3.9	3.9	3.9	4.0	0.1	0.4	0.2	1.1	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3
	7	17.5	16.5	15.8	19.1	3.9	3.9	3.9	4.0	0.1	0.4	0.2	1.1	7.6	7.7	7.6	7.7	4.2	3.8	4.4	3.3

Table A2 The energy needs of simulated cases in the climates of Paris and Athens

	Control principle	Space heating (kWh/m²)		Supply air heating (kWh/m²)		Space cooling (kWh/m²)		Supply air cooling (kWh/m²)		Lighting (kWh/m²)	
		Paris	Athens	Paris	Athens	Paris	Athens	Paris	Athens	Paris	Athens
Whole building	0	10.5	3.4	0.3	0.0	2.5	17.7	16.9	49.1	4.0	4.6
	1	10.7	4.8	0.3	0.0	0.0	0.4	16.7	47.9	4.0	3.7
	2	10.7	4.8	0.3	0.0	0.0	1.0	16.7	48.4	4.0	2.9
	3	10.7	4.8	0.3	0.0	0.0	0.5	16.7	48.1	4.0	2.9
	4	10.8	4.4	0.3	0.0	0.1	6.9	16.7	48.8	4.0	2.9
	8	12.8	5.7	0.3	0.0	0.0	8.5	16.4	48.6	4.9	3.9
	9	10.7	4.8	0.3	0.0	0.0	1.0	16.7	48.4	4.0	2.9
	10	10.8	4.9	0.3	0.0	0.0	0.8	16.7	48.2	4.0	2.9
South	0	13.4	0.2	0.3	0.0	0.7	22.1	16.9	49.1	2.4	3.4
	1	12.0	1.8	0.3	0.0	0.1	0.3	16.7	47.9	2.4	2.1
	2	12.0	1.8	0.3	0.0	0.1	1.4	16.7	48.4	2.4	0.7
	3	12.0	1.9	0.3	0.0	0.1	0.4	16.7	48.1	2.4	0.7
	4	12.0	1.6	0.3	0.0	0.0	3.0	16.7	48.8	2.4	0.7
	8	15.6	3.0	0.3	0.0	0.0	2.9	16.4	48.6	3.3	1.4
	9	12.0	1.8	0.3	0.0	0.1	1.4	16.7	48.4	2.4	0.7
	10	12.0	1.9	0.3	0.0	0.1	0.6	16.7	48.2	2.4	0.7
East	0	14.8	7.3	0.3	0.0	1.8	8.1	16.9	49.1	2.1	2.9
	1	15.2	9.1	0.3	0.0	0.0	0.0	16.7	47.9	2.1	1.3
	2	15.2	9.2	0.3	0.0	0.0	0.1	16.7	48.4	2.1	0.8
	3	15.2	9.2	0.3	0.0	0.0	0.0	16.7	48.1	2.1	0.8
	4	15.3	9.3	0.3	0.0	0.0	0.7	16.7	48.8	2.1	0.8
	8	18.1	12.5	0.3	0.0	0.0	0.8	16.4	48.6	2.9	1.4
	9	15.2	9.1	0.3	0.0	0.0	0.1	16.7	48.4	2.1	0.8
	10	15.2	9.2	0.3	0.0	0.0	0.0	16.7	48.2	2.1	0.8
West	0	11.7	0.2	0.3	0.0	8.1	51.2	16.9	49.1	2.7	3.3
	1	12.5	1.5	0.3	0.0	0.1	1.5	16.7	47.9	2.7	2.6
	2	12.5	1.8	0.3	0.0	0.2	3.1	16.7	48.4	2.7	0.8
	3	12.5	1.8	0.3	0.0	0.1	1.8	16.7	48.1	2.7	0.8
	4	12.5	0.6	0.3	0.0	0.4	24.4	16.7	48.8	2.7	0.8
	8	14.6	0.4	0.3	0.0	0.1	30.6	16.4	48.6	5.1	3.1
	9	12.5	1.8	0.3	0.0	0.1	3.0	16.7	48.4	2.7	0.9
	10	12.5	1.8	0.3	0.0	0.1	2.8	16.7	48.2	2.7	0.8

PAPER IV

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Comparison of simplified and detailed window models in office building energy simulations

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Abstract

The aim of this study is to quantify the gap between the simulated energy need of an office building with simplified and detailed glazing models. We studied triple, quadruple and quintuple windows and concluded that differences in energy need of similar cases with different glazing models reached 1.9 and 6.4 kWh/m^2 in space heating and cooling needs respectively. Significant relative differences in heating and cooling were up to 14% and 40% respectively. Largest differences appeared with triple glazing and smallest with quadruple glazing. Compared to detailed window models standard triple and quadruple glazing models resulted in lower heating and higher cooling needs, whereas in case of quintuple windows the results were the opposite.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Energy simulations; windows; glazing; façade design

1. Introduction

Energy simulations of building are a wide-spread method for assessing new buildings energy performance. Simulations are conducted to analyze different building solutions' effect on energy efficiency and indoor climate. However, calculated and measured energy uses rarely match and amongst the causes of the differences are the inaccuracy of simulation models used.

Numerous façade analyses have been conducted in recent years that have used both simplified and more detailed methodologies. Poirazis et al. [1] used simulation software IDA ICE 3.0 to show that increasing glazed of office building facades also increases energy use. Grynning et al. [2] calculated the U- and g-values of glazing, which

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assure the positive effect of window area on the energy use of a building. They compared three methods in their investigation and concluded that results depended on the method used. Petersen [3] calculated the heating energy of a building using a constant declared U-value of glazing and a more accurate dynamic U-value that varied for each hour of the climate year. Constant U-value could lead to significant under estimation of heating energy in cold climates and Petersen suggested using the described dynamic method for energy calculations. Arıcı et al. [4] carried out a numerical study of the properties of double, triple and quadruple glazing and pointed out that the nature of energy balance of glazing depends on external conditions.

Generally energy specialists use standard window models with constant U-values in energy simulations, however the thermal resistance of glazing varies depending on the outdoor temperature, wind speed and direction. The purpose of our study is to quantify the gap between the calculated energy need of an office building model with simplified and detailed glazing models. Similar work was also done in [5] using a model of a single-family building. We composed a generic open-plan office floor model in IDA ICE 4.6 [6] with triple, quadruple and quintuple windows with varying sizes. All cases were created with both standard glazing and detailed glazing models of which the latter took into account the changing external and internal conditions while simulating the energy balance of glazing. The results presented in this article are the bases for further work regarding the effect of window model on the outcome of façade analysis.

2. Methods

2.1. Generic office floor model

Energy simulations were conducted on the basis of a generic open-plan office single floor model similar to the ones we used in [7] The floor model was divided into 5 zones - 4 orientated to south, west, east and north respectively and in addition one in the middle of the building. 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. In all cases ideal heaters and coolers were used and mechanical supply and exhaust ventilation with heat recovery was used. Total of 34 occupants were in the perimeter zones i.e. 2 persons per module and installed power of plug loads and lighting was 12 and 7 W/m^2 respectively. 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 air flow rate was 2 l/s per floor m^2 and the air handling unit worked from 6:00 to 19:00 on weekdays with constant supply air temperature 18 °C. The energy simulations were conducted with well-validated simulation tool IDA ICE 4.6 [6] using the Estonian methodology for energy calculations [8] and the test reference year of Estonia[9].

2.2. Studied facade cases

We studied the behavior of triple, quadruple and quintuple glazing with varying window sizes. Each office module had one window with height of 1.8 meters and the bottom edge was 0.9 meters from the floor. The minimum window size was chosen so that the average daylight factor in the control zone was 2% as required in [10]

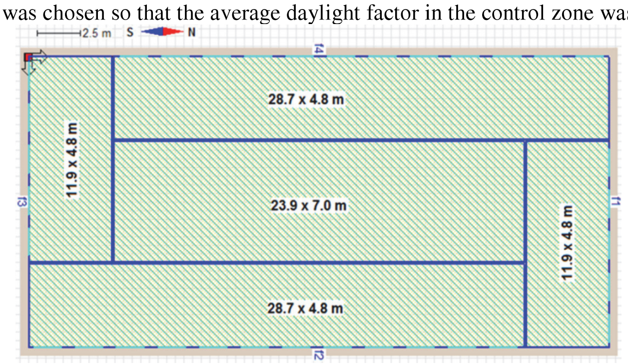

Fig. 1. The generic model of the open-plan office floor. Light blue lines at the perimeter mark the position of windows.

Table 1. Glass pane properties of detailed window models.

Pane	Thermal conductivity, W/(mK)	Total shortwave transmittance, -	Outside		Inside	
			Total shortwave reflectance, -	Longwave emissivity, -	Total shortwave reflectance, -	Longwave emissivity, -
Low-e	1.0	0.62	0.23	0.89	0.27	0.03
Clear	1.0	0.85	0.08	0.89	0.08	0.89

Table 2. The properties of studied window types and the U-value of external wall used with respective window types.

No of panes	Glazing U-value[a], $W/(m^2K)$	Gas filling	Gap width, mm	Glazing g-value	Frame U-value, $W/(m^2K)$	Window U-value, $W/(m^2K)$	External wall U-value, $W/(m^2K)$
3	0.55	90% Ar	18	0.45	0.8	0.59	0.16
4	0.29	95% Kry	15	0.34	0.32	0.29	0.13
5	0.21	95% Kry	15	0.25	0.21	0.21	0.09

[a] - The U-value of standard windows remained constant during simulations and is given according to calculations of ISO 15099:2003/E at internal and external temperature difference of 20 °C. The U-value was dynamic during simulations in case of detailed windows and was calculated also according to ISO 15099:2003/E.

and the calculations are described in our previous work [7]. Quadruple and quintuple glazing are not economically reasonable, however they might be one possible solution to design and build nearly zero energy buildings in the future. It is reasonable to increase the external wall insulation thickness while improving windows. Based on our previous work we chose appropriate external wall U-values for each window type [11] and they are also provided in table 2. The window width was increased with a step of 0.3 meters up to width of 2.4 meters. The investigated window sizes for different glazing types were:

- 3 pane window widths 1.05, 1.2, 1.5, … 2.4 meters; window-to-wall ratio 24% … 55%
- 4 pane window widths 1.15, 1.2, 1.5, … 2.4 meters; window-to-wall ratio 26% … 55%
- 5 pane window widths 1.3, 1.5, … 2.4 meters; window-to-wall ratio 30% … 55%

We created detailed window models in IDA ICE and glazing consisted of highly transparent panes, which had a low-emissivity coating on a pane in each gap. Table 1 describes the parameters of panes, whereas each glazing had one clear pane and other panes had low-emissivity coatings. Table 2 describes the parameters of windows at standard conditions determined in ISO 15009 [12] i.e. at temperature difference of 20 ° C. The simulation software used the methodology of ISO 15009 for calculating the energy balance of detailed glazing models and constant window parameters given in table 2 were used for calculations with standard glazing models. Another important difference is that standard glazing models use and an angle dependence to calculate the solar transmittance and absorptance of glazing, while the energy balance of detailed window models is calculated based on physical formulas. Each pane and their interactions of detailed glazing are taken into account with detailed window models.

3. Results

The analysis show that similarly to detached houses [5] using standard triple and quadruple window models result in lower heating needs and higher cooling needs. However in case of 5 pane windows, the results are the opposite – standard quintuple glazing results in higher heating need and lower cooling need. Figure 2 presents space heating and cooling energy needs with standard and detailed glazing models in case of south, east, west and north oriented zones respectively. The proportions of heating and cooling vary depending on the façade orientation and window type. Therefore simulated total energy need could be higher with either glazing model type in comparison to the other.

Total energy need with triple windows was generally higher with standard glazing models in south, east and west facades due to relatively large proportions of cooling energy. In south the difference ranged between 0.8-4.9 kWh/m^2, in east between 0.1-1.1 kWh/m^2, in west between 0.0-1.6 kWh/m^2, whereas total energy need was slightly lower with standard glazing in east and west orientated zones with small triple windows. The results were the opposite in the north façade as heating need dominated. Triple standard glazing in north façade resulted in lower total energy need by 0.9-1.1 kWh/m^2. In case of quadruple glazing, the only orientation where detailed models provided lower total energy need was the south, where the difference was between 0.2-1.2 kWh/m^2. In east detailed glazing resulted in higher energy need by 0.3-0.5 kWh/m^2, in west by 0.4-0.8 kWh/m^2 and in north by 0.1-0.2 kWh/m^2. In the north façade, smaller standard 5 pane windows resulted in total energy need higher by up to 0.2 kWh/m^2 and in case of larger standard windows the energy need was smaller by up to 0.4 kWh/m^2.

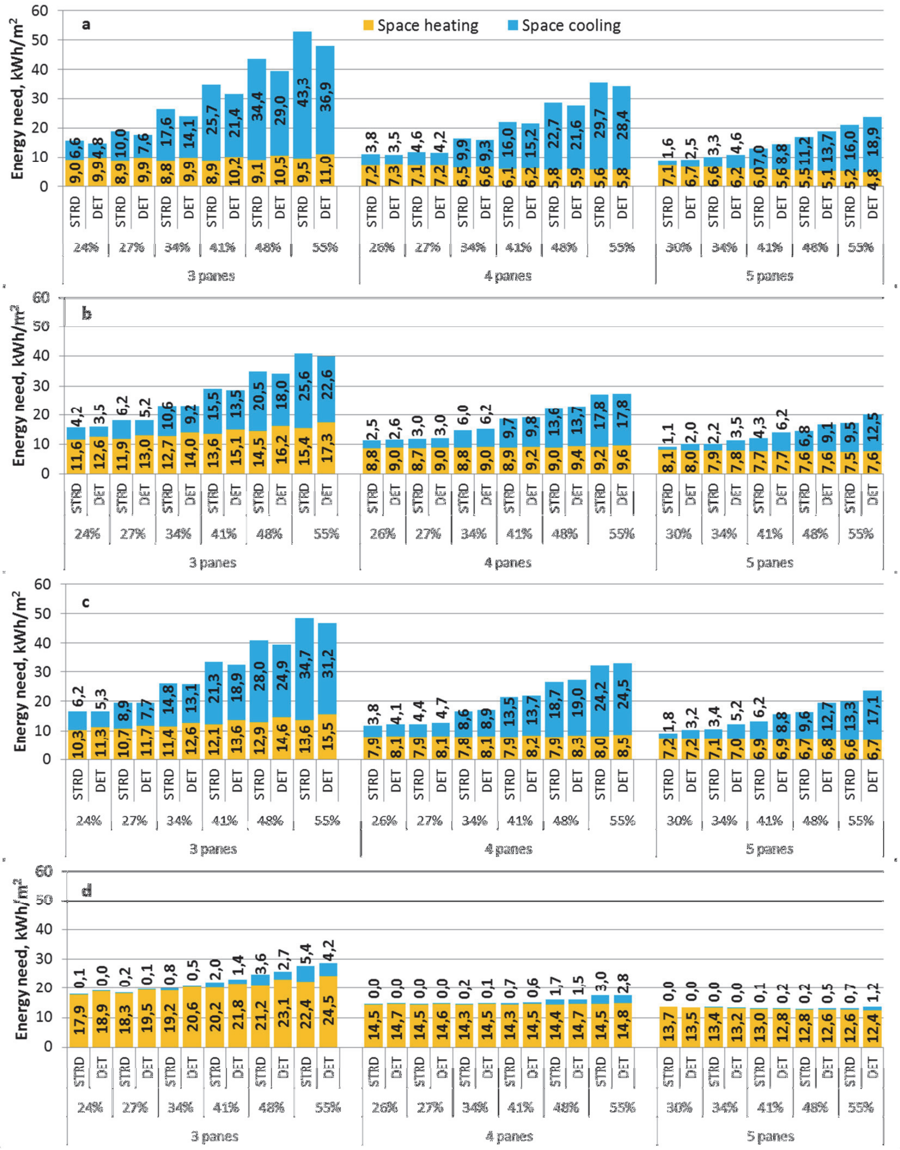

Fig. 2. Space heating and cooling needs in the (a) south, (b) east, (c) west and (d) north oriented zones in case of standard and detailed window models. Code: STRD – standard window model, DET – detailed window model; 24% means window-to-wall ratio 24%.

Analysis of heating and cooling need demonstrated that differences in heating are smaller than in cooling. Figure 3 presents the simulated energy need difference of detailed window models from respective standard window models. Values over 50% are not presented in figure 3b, because the absolute difference was under 0.4 kWh/m^2 in all such cases and increasing the range of vertical axis would have made the figure harder to read. Largest differences in heating energy appeared with triple glazing and the increase with detailed glazing ranged between 0.9-1.9 kWh/m^2 i.e. 9.3-13.8%. In case of 4 and 5 pane windows the differences in heating need remained within 0.5 kWh/m^2 i.e. 0.1-8.2%. Detailed windows resulted in lower cooling need by up to 6.4 kWh/m^2 in case of large south oriented triple windows and in higher cooling need by up to 3.8 kWh/m^2 in case of large quintuple windows in the west façade. Cooling energy difference with quadruple glazing remained below 1.3 kWh/m^2. Relative differences in cooling energy were higher with smaller windows and thereby also cooling needs. Therefore bringing out the largest differences in cooling energy is not reasonable, but if absolute difference in cooling energy was higher than 1 kWh/m^2, then the relative differences up to 40% occurred.

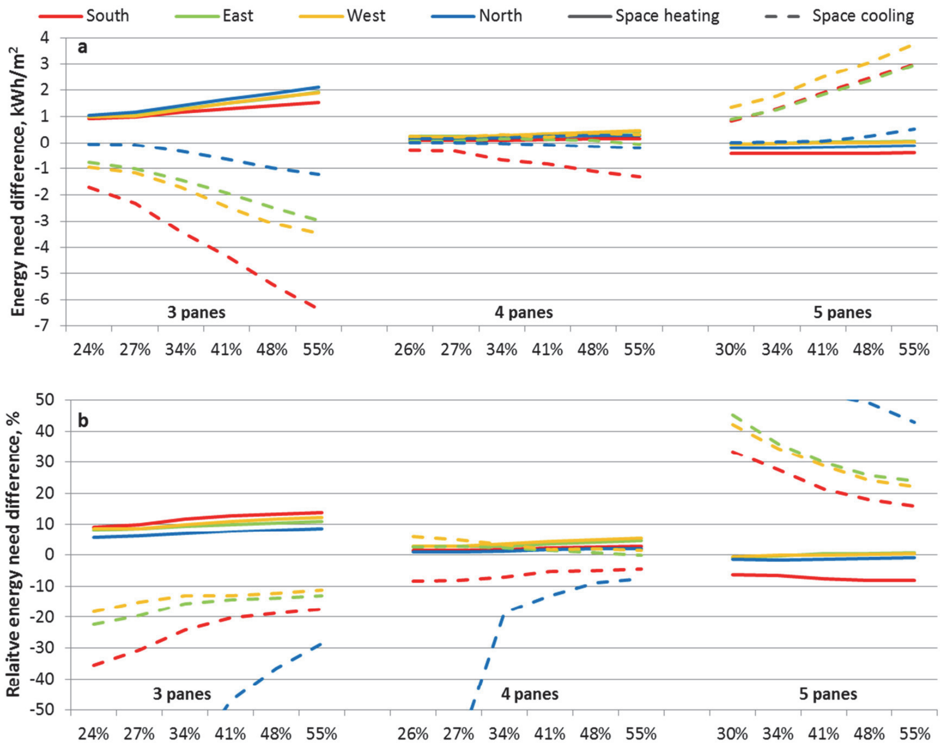

Fig. 3 Detailed window models space heating and cooling need difference from standard window models in zones with different orientations and window types. (a) energy need of detailed window models has been deducted from standard window models respective value; (b) value shows how much the energy need with detailed glazing differs from standard glazing. Code: 24% means window-to-wall ratio 24%.

4. Discussion and conclusions

In this paper we brought attention to the differences in the results of office building energy simulations if simplified standard glazing models of more accurate detailed glazing models are used. We conducted simulations using the cold climate of Estonia and highly transparent 3, 4 and 5 pane windows. The differences in energy needs were highest in case of both heating and cooling with triple glazing and with quintuple glazing in cooling energy needs. The largest difference in heating need was 1.9 kWh/m^2 i.e. 13.8% and 6.4 kWh/m^2 in cooling need, whereas highest relative differences in cooling were around 40%, when the absolute difference was above 1 kWh/m^2. Larger relative differences in cooling energy also occurred, but the absolute difference was small in those cases. Largest differences appeared with triple glazing and smallest with quadruple glazing. Compared to detailed window models standard triple and quadruple glazing models resulted in lower heating and higher cooling needs, whereas in case of quintuple windows the results were the opposite. The sum of space and cooling heating need could be higher in both glazing model cases depending on the number of panes and the size of the windows. Therefore it is difficult to suggest any correction factors for the parameters of standard glazing models as was done in [5].

We have identified the differences in the simulated energy need however it is unknown if the differences have significant effect on the outcome of office building façade analysis. The choice of heat and cooling sources affects the differences in delivered energy and also energy cost. In [7] and [11] we presented financially feasible solutions office building façade design, however standard window models were used. The outcome of this study revealed that in would be reasonable to repeat previous studies with detailed window models and compare the results to determine the importance of simulation models in façade analysis. Also our current work needs to be supplemented with similar analysis considering various solar shading solutions.

Right now it can be recommended to use detailed window models for design decision making typically being based on analyses with single floor models. For energy performance compliance assessment typically done with full building models the accuracy of standard window model may be seen satisfactory in office buildings in cold climates.

Acknowledgements

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PAPER V

Thalfeldt, M., Pikas, E., Kurnitski, J., Voll, H. Window model and price data sensitivity to cost optimal façade solutions. Journal of Building Performance Simulation (submitted 18.01.2016).

Window model and price data sensitivity to cost optimal façade solutions

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Abstract
This study provides information about current cost-effective facade solutions and illustrates the importance of different variables such as accuracy of window models, construction costs, energy prices, interest rate and inflation. The cost-effective South, East and West facade solutions were triple windows with window-to-wall ratio 25-40% and external wall mineral wool insulation thickness 200 mm, whereas larger windows could be used in the North facade. The economic variables and construction price changes compared to 2013 had the largest influence on the cost-effective facade solutions. Lowest energy use was achieved with large quadruple windows and automated external venetian blinds with an advanced control algorithm. Wider market uptake of efficient window solutions could allow more architectural freedom from the point of view of energy-efficient and financially feasible facade design. Using detailed window models instead of standard windows did not influence the suggested facade solutions, but had effects on energy needs in both directions.

Keywords: Energy simulations; cost-effectiveness; net present value; windows; glazing; façade design; energy efficiency

Highlights
- Window models did not affect cost-optimal solutions despite differences in energy use
- Triple windows with WWR 25-40% were cost optimal in South, East and West facades
- North facade tolerated larger triple windows with WWR 40-60 % .
- The economic situation and construction cost influenced cost-optimal solutions most
- Lowest energy use was achieved with quadruple glazing and automated external blinds

1 Introduction
Several countries in the European Union require making energy simulations to prove new buildings compliance with energy performance minimum requirements. It is reasonable to use the energy model of a building under design to optimize architectural and technical solutions. Simulation-based analysis helps to minimize energy use or reach a certain level of energy efficiency at lower cost. However energy and financial calculation results always include a certain degree of error due to simplifications made in the methodology and simulation models and in addition aspects that we cannot predict very accurately such as the occupancy profile or the economic situation. Some of these errors may affect the choice of solutions to be used in the building and it is important to identify the factors that need to be focused on more thoroughly during the early stage design analysis.

The Energy Performance of Buildings Directive (EPBD) 2010 (European Parliament and Council 2010) recast stipulates that member states of the EU should set requirements for energy performance of building at a cost-optimal level in 20 and 30 year perspectives in case of non-residential and residential buildings respectively. Kurnitski et al. were amongst the first ones to calculate cost-optimality levels for residential buildings in the Member states of the EU using Estonia as the location, which were reported in (Kurnitski et al. 2011) and (Kurnitski et al. 2013). Hamdy et al. presented the cost-optimality level for Finnish residential houses in (Hamdy, Hasan, and Siren 2013). Ferrara et al. (Ferrara et al. 2014) did similar work using TRNSYS and a generic building optimization program GenOpt in case of a French detached house. Ganic and Yilmaz (Ganiç and Yılmaz 2014) used two Turkish climates to determine the cost-optimal levels for an office building. In addition to cost-optimal levels Becchio et al. (Becchio et al. 2015) investigated solutions to reach net zero energy building level and calculated the extra costs of a detached house located in Turin, Italy. Zaca et al. (Zacà et al. 2015) also conducted cost-optimality analysis of multi-residential buildings in a Mediterranean climate. Baglivo et al. (Baglivo et al. 2015) studied the cost-optimal solutions of a mono-residential building in a warm climate and in addition did some sensitivity analysis regarding discount rate and its development, which did not affect the optimal solutions. Pikas et al. (Pikas et al. 2015) introduced a methodology to determine the cheapest solutions to reach cost-optimal, low or nearly zero energy building level based on examples of two apartment buildings. They also showed that compared to (Kurnitski et al. 2013) the cost optimal primary energy level had shifted from 140-150 kWh/m^2 to 110 kWh/m^2 during 2-3 years. In addition to studies on new buildings, similar analysis has been conducted for apartment building renovation projects in Estonia by Kurnitski et al. (Kurnitski et al. 2014) and Kuusk et al. (Kuusk, Kalamees, and Maivel 2014) and by Paiho et al. (Paiho, Abdurafikov, and Hoang 2015) for the location of Moscow. Stocker et al. (Stocker, Tschurtschenthaler, and Schrott 2015) studied a school building and in addition to defining the cost-optimal primary energy level concluded that energy prices and interest rates most influenced the results.

Besides numerous studies on the cost-effectiveness in the building level, several analyses have also focused on the facade solutions. Poirazis et al. (Poirazis, Blomsterberg, and Wall 2008) studied office building window-to-wall ratios (WWR) between 30% and 100% and pointed out that buildings with lower WWR consume less energy. Motuziene and Joudis (Motuziene and Juodis 2010) came to similar conclusion that optimal WWR is 20-40%, however they showed concern about daylight availability. Susorova et al. (Susorova et al. 2013) simulated office buildings in seven different climates and the results showed that lower WWR assures better energy efficiency in cold climates. Grynning et al. (Grynning et al. 2013) studied windows with extremely low U-values and concluded that solar heat gain coefficient 0.4 optimized energy use. Tzempelikos (Tzempelikos, Athienitis, and Karava 2007) came to conclusions that optimum combination of glazing, shading and electric lighting systems resulted in remarkable energy savings. Johnson (Johnson et al. 1984) also stressed the importance of automatically controlled efficient lighting in reaching energy saving in addition to other aspects of facade design. Jin and Overend (Jin and Overend 2014) developed a whole-life value optimization tool for façade design and reduced the life-cycle cost and carbon emissions of an office building significantly by analyzing numerous glazing types. Nguyen and Reiter (Nguyen and Reiter 2014) combined 18 design parameters and 6 ventilation strategies of low-cost housing using EnergyPlus and GenOpt and the developed optimization method proved to be efficient for the minimizing construction costs and reaching indoor climate target values.

All the previously mentioned studies have not paid much attention to the results' sensitivity to economic or other factors. Kurnitski et al. (Kurnitski et al. 2011) showed that changes in discount rates and escalation have an effect on the choice of cost-optimal solutions. Basinska et al. (Basinska, Koczyk, and Szczechowiak 2015) analyzed the effect of building shape, heat source, inflation, investment costs and energy prices on the optimal residential building solutions in Polish conditions and concluded that changes in all parameters lead to changes in energy efficiency requirements in time. In addition to economic parameters, there are other aspects that calculated energy use and cost-optimal solutions might be sensitive to e.g. accuracy of different calculation methodologies. Petersen (Petersen 2014) calculated the heating energy of a building using a constant declared U-value of glazing and a more accurate dynamic U-value that varied for each hour of the climate year. Constant U-value could lead to significant under estimation of heating energy in cold climates and Petersen suggested using the described dynamic method for energy calculations. Kokogiannakis et al. (Kokogiannakis, Strachan, and Clarke 2008) calculated the energy use of an office building using monthly quasi-state and simplified hourly methods, ESP-r and EnergyPlus and the comparison of results showed that energy performance rating did not differ by not more than one class compared to the monthly method. In (Thalfeldt, Kurnitski, and Voll [submitted]) we showed that using either simplified or detailed window models in detached house facade analysis lead to differences in calculated energy use and optimal window sizes. We recommended using detailed glazing models, but also suggested a correction factor of 1.15 for standard triple glazing model, when calculating the heating energy only. Hilliaho et al. (Hilliaho, Lahdensivu, and Vinha 2015) measured air temperatures in glazed and unglazed balconies and compared them with simulated ones, which were obtained by using IDA-ICE 4.6. The correlation was good and highest modelling accuracy was reached by using detailed window and zone climate models. In (Thalfeldt, Kurnitski, and Voll 2015) we modelled energy use of an office building with standard and detailed window models and detected differences up to 14% and 40% in space heating and cooling respectively. We also suggested doing additional analysis to determine whether the differences in calculated energy use also affect optimal office building facade solutions.

During years 2012-2013 we analyzed numerous facade solutions and concluded that financially most feasible was to use triple highly transparent glazing with WWR 25% in South, East, and West and 40% in the North (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014). An interesting solution to improve energy efficiency was quadruple glazing with WWR 40%. Automated external venetian blinds were not a feasible solution in a 20 year perspective due to high cost. Cost-optimal external wall insulation thickness was 200 mm and we suggested using 250 mm insulation with quadruple windows. However a simple control algorithm for shading control was used, which in cases with smaller windows could even increase calculated energy use. Therefore we developed a new control principle for external venetian blind, which used internal temperature and desktop illuminance as control parameters (Thalfeldt and Kurnitski 2015). Still the control algorithm requires validating and development in full-scale tests.

The main purpose of this study was to study the effect of window models in simulations, construction costs, energy prices, interest rate and inflation on the outcome of office building façade cost-optimality analysis. We developed cost optimal facade solutions similar to our previous studies (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014), however several significant changes were made, which included energy simulations with both standard and detailed window models and also advanced shading control algorithms, and in addition updating energy prices, construction costs, interest and inflation rates. As a result we identified the most important variables in facade design. Novelty of this study is conducting façade cost-optimality analysis with both simplified and detailed window models and assessing their effect on cost-effective façade solutions. The net present value (NPV) of a 20 year period was calculated for each studied facade solution to assess financial feasibility. Triple and quadruple windows with varying sizes, with and without external shading in South, East, West and

North orientations were studied. In addition we investigated external walls with insulation thicknesses 150, 200 and 350 mm.

2 Methods

The main method used in this study was the cost-effectiveness simulation procedure and results were compared to cost-effective solutions from 2013. Based on this, initial variants of our study were selected and the investigation was done in the following steps:

1. Whole office floor simulations with insulation thicknesses 150, 200 and 250 mm to determine the cost-effective insulation thickness in the current situation
2. Energy simulations with the following variables:
    a. Triple and quadruple windows
    b. Window-to-wall ratio in the range of 25-60%
    c. Internal shades and automated external venetian blinds
    d. Standard and detailed window models
3. Assessing financial feasibility of the cases by calculating 20 year net present value with the following variables:
    a. Construction costs from 2013 and 2015
    b. Energy prices from 2013 and 2015
    c. Interest rates from 2013 and 2015
    d. Inflation rates from 2013 and 2015
    e. Energy price rates from 2013 and 2015
4. Comparing the NPVs of studied cases

2.1 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 one in the middle of the building as shown in Figure 1. Similar model was also used in (Thalfeldt et al. 2013). 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. 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 average over floor area. The general data of simulation model is shown in Table 1. The energy simulations were conducted with well-validated simulation tool IDA-ICE 4.7 (IDA-ICE 2014) and the test reference year of Estonia was used (Kalamees and Kurnitski 2006). The primary energy factor for district heating is 0.9 and for electricity 2.0.

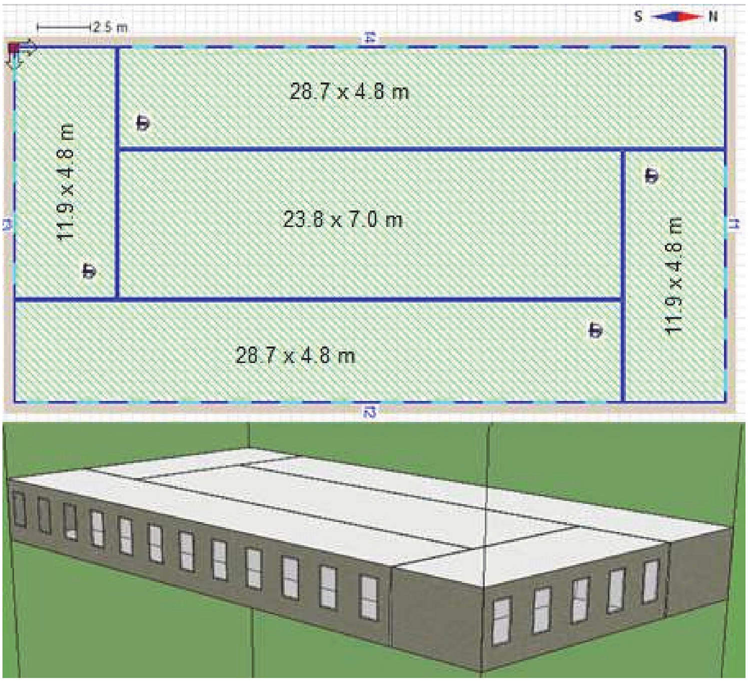

Figure 1 The generic model of single floor of an office building constructed with 2.4 m room module – plan and 3D view. The same floor plan was used in (Thalfeldt et al. 2013).

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

Occupants, W/m^2	5
Equipment, W/m^2	12
Lighting, W/m^2	5
Temperature set point for heating and cooling	+21 and+25 °C
Air flow rate	1.5 l/(s·m^2); 35 l/s
Illumination setpoint, lx	500
Frame ratio of windows, %	15
Heating system (radiators) efficiency, -	0.97
Heat source (district heating) efficiency, -	1.0
Cooling system losses, % of cooling energy need	10
Mechanical cooling SEER, -	3.5
Ventilation SFP, kW/(m^3/s)	1.3
Temperature ratio of heat recovery, %	80

Compared to previous cost-optimality studies (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014) we did several changes to the office floor model. The main changes concerned windows, however two changes also influenced the ventilation system. The changes were:

1. Detailed window models were used in addition to standard window models
2. More realistic solar heat gain coefficient (SHGC or g-value) and solar transmittance multipliers that depict the effect of shading on the standard window properties were used (see Section 2.3)

3. Advanced control algorithm developed in (Thalfeldt and Kurnitski 2015) was used to control external blinds
4. Minimum exhaust air temperature after the heat recovery unit was decreased from +1 °C to -5 °C
5. Ventilation rate outside working hours was decreased from 0.30 l/(s·m^2) to 0.15 l/(s·m^2)

The nature of the changes regarding windows has been described more thoroughly in the following sections.

2.2 Standard and detailed window models

IDA-ICE allows making simulations with both standard and detailed window models. The main difference is that standard windows are modelled as a single layer with constant parameters such as U-value, SHGC, solar and visible transmittance and internal/external emissivities, which have been defined in ASHRAE Fundamentals (Handbook 2005). Detailed windows are modelled according to the methodology of ISO 15099 ("ISO Standard 15099. Thermal performance of windows, doors and shading devices - Detailed calculations." 2003) pane by pane, cavity by cavity and the influence of shading on the energy balance of room zones is modelled according to physical formulas as shown in Figure 2. In (Thalfeldt [accepted]; Thalfeldt, Kurnitski, and Voll [submitted]) we showed that different window models result in different calculated energy uses and also varying optimal WWRs in case of detached houses. The gap in the results is first of all caused by the fact that the glazing properties of standard glazing are given at standard conditions of ISO 15099 i.e. at temperature difference of 20 °C ("ISO Standard 15099. Thermal performance of windows, doors and shading devices - Detailed calculations." 2003), however the U-value of glazing depends on temperature difference across glazing, which detailed window models take into account. Also standard glazing models use an angle dependence to calculate the solar transmittance and absorbance of glazing, while the energy balance of detailed window models is calculated based on physical formulas as stated before.

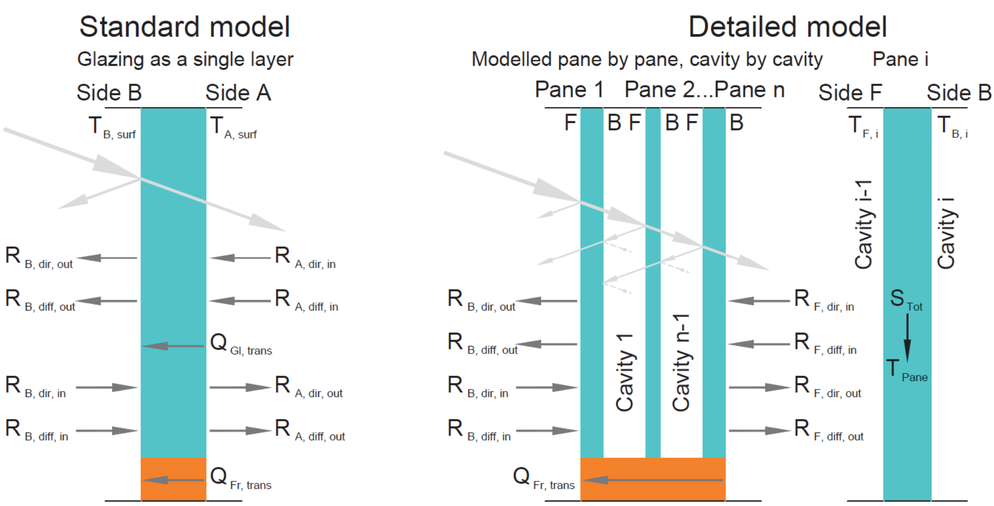

Figure 2 The calculated variables of standard and detailed glazing models in IDA-ICE. Code: T – temperature of a surface or pane; R – diffuse/direct radiation in/out of a pane/glazing; Q – heat transmission of glazing/frame from surface to surface; S – total absorption heat flux.

2.3 Window types

We analyzed highly transparent triple and quadruple glazing that had two and three low emissivity panes respectively. Figure 3 displays the analyzed glazing types and the positioning of low-emissivity coatings. In IDA-ICE we created detailed window models as is described in Table 2 with pane properties shown in Table 3 and shading slat material properties given in Table 4. Both internal and external venetian blinds had slats with width 80 mm and distance between slats was 70 mm. The window properties shown in Table 2 were used as constant values in standard window models.

In (Thalfeldt et al. 2013) we used multipliers for SHGC and solar transmittance with default values determined in the simulation software to depict the effect of shading on the properties of glazing. For internal and external blinds the multipliers for SHGC was 0.65 and 0.14 respectively and for solar transmittance 0.16 and 0.09 respectively. In Table 2 we can see that the relationship between SHGC with and without internal shading is 0.86-0.91 (previously 0.65), which shows that in our previous work we had overestimated the shading effect of internal blinds. The situation was similar with external blinds as the respective relationship used in this study is 0.28 (previously 0.16).

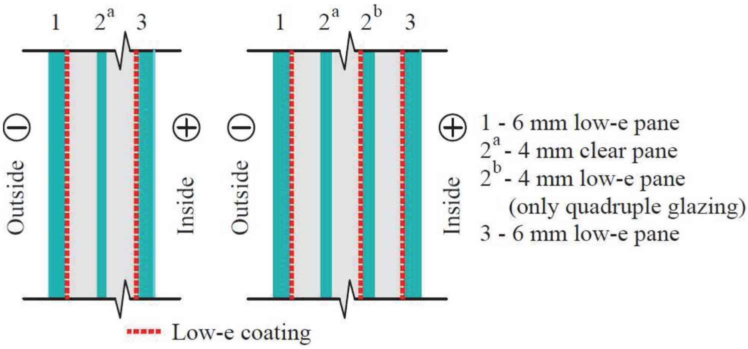

Figure 3 The construction of triple and quadruple glazing and positioning of low-emissivity layers. The same glazing types were also studied in (Thalfeldt, Kurnitski, and Voll [submitted]).

Table 2 The properties of studied window types. All the window parameters are given according to calculations of ISO 15099:2003/E. The parameters of detailed windows were dynamic and simulated according to ISO 15099:2003/E.

	Triple glazing	Quadruple glazing
Glazing U-valuea, W/($m^2\cdot K$)	0.58	0.32
Glazing SHGC without shading, -	0.46	0.37
Glazing SHGC with internal shading, -	0.39	0.34
Glazing SHGC with external shading, -	0.12	0.10
Gap between panes, mm	18	12
Gas filling	90% argon	95% krypton
Frame U-value, W/($m^2\cdot K$)	0.8	0.32
Frame fraction of window area, %	15	15
Total window U-value, W/($m^2\cdot K$)	0.61	0.32
Studied window-to-wall ratios, %[a]	23.9, 37.5, 60.0	26.1, 37.5, 60.0
External wall U-value, W/($m^2\cdot K$)	0.20	0.16

[a] – Smallest window-to-wall ratios assure average daylight factor 2% in an office consisting on two 2.4 m wide modules (Thalfeldt et al. 2013).

Table 3 Glass pane properties of detailed window models.

	Low-e	Clear
Thermal conductivity, W/(mK)	1.0	1.0
Total shortwave transmittance, -	0.62	0.85
Total visible transmittance, -	0.88	0.90
Outside total shortwave reflectance, -	0.23	0.08
Outside visible reflectance, -	0.06	0.08
Outside longwave emissivity, -	0.89	0.89
Inside total shortwave reflectance, -	0.27	0.08
Inside visible reflectance, -	0.05	0.08
Inside longwave emissivity, -	0.03	0.89

Table 4 Slat material properties of detailed window models.

Shortwave, longwave and visible transmittance, -	0.0
Upper side reflectance, -	0.7
Lower side reflectance, -	0.4
Emissivity, -	0.9
Slat thickness, mm	0.6
Heat conductivity, W/(m·K)	160

2.4 Shading control algorithms

In the current study we assumed that external venetian blinds were automated, whereas internal blinds were controlled manually. The same control principle was used with internal blinds as in our previous work i.e. internal blinds were drawn if solar irradiance on the facade exceeded 200 W/m^2 and the slat angle was 45° (Thalfeldt et al. 2013).

In case of external blinds we used a more advanced control algorithm, which we developed in (Thalfeldt and Kurnitski 2015). The algorithm observed room daylight level during occupancy and internal temperature outside working hours. During occupancy the blinds were drawn if room daylight level exceeded 1900 lux and redrawn when daylight level dropped below 900 lux. Outside working hours the temperature setpoint for external blinds was 24±0.5 °C i.e. 1 °C below cooling setpoint. The slat angle of the venetian blinds equaled the solar altitude at the given time.

2.5 NPV calculations

In order to identify cost optimal solutions at every stage, total investment cost and NPV were calculated (EN 15459: 2007) the same way as in (Pikas, Thalfeldt, and Kurnitski 2014). The global incremental energy performance related cost was calculated as a sum of the energy performance related construction cost and discounted energy cost for 20 years, including all electrical and heating energy consumption. The energy performance related construction cost, which does not include the basic cost of construction, was used to compare alternative design solutions that affect the energy performance of buildings. In every step, the global incremental cost for energy performance was calculated relative to the reference solution:

$$C_g = \frac{C_g^{ref}}{A_{floor}} - \frac{C_I + C_a \cdot f_{pv}(n)}{A_{floor}} \tag{1}$$

where:

C_g global incremental energy performance related cost included in the calculations, NPV, €/m^2

C_I energy performance related construction cost included in the calculations, €

C_a annual energy cost during the starting year, €

$f_{pv}(n)$ present value factor for the calculation period of n years, -

C_g^{ref} reference fenestration design solution's global energy performance related cost, NPV, €/m^2

A_{floor} heated net floor area, m^2

To calculate the present value factor $f_{pv}(n)$, the real interest rate R_R must be calculated. R_R depends on the market interest rate R and inflation rate R_i (EN 15459: 2007 2007):

$$R_R = \frac{R - R_i}{1 + R_i/100} \qquad (2)$$

To calculate the present value factor, the escalation rate e must be subtracted from the real interest rate R_R, as described by Abel and Voll (Enno Abel and Elmroth 2007).

The present value factor $f_{pv}(n)$ for the calculation period of n years is calculated as follows [16]:

$$f_{pv}(n) = \frac{1 - (1 + (R_R - e)/100)^{-n}}{(R_R - e)/100} \qquad (3)$$

where:

R_R the real interest rate, %

e escalation of the energy prices, %

n the number of years considered i.e. the length of the calculation period, 20 years

2.6 Interest rates, inflation, energy prices and construction costs

The market interest rate of 2.7 % (R) and inflation rate of 1.7 % (R_i) used for this analysis is based on the rates reported by the Bank of Estonia. Energy price escalation of 0 % (e) was obtained from the Statistics Estonia agency. Since 2013, the economic situation has changed remarkably, -money has become cheaper, interest and energy escalation rates have decreased. In addition, electricity prices have slightly increased and heat prices decreased. The previously used (Pikas, Thalfeldt, and Kurnitski 2014) and updated 2015 data has been presented in Table 5. The construction costs of 2013 and 2015 shown in Table 6 illustrate that insulation and quadruple window cost has increased, while triple windows and external venetian blinds have become cheaper.

Table 5 Economic parameters and energy prices in 2013 and 2015. All costs include value added tax 20%.

	2013	2015
Interest rate R, %	4.0	2.7
Inflation rate R_i, %	3.5	1.7
Energy price escalation e, %	2.0	0.0
Electricity price, €/MWh	149.4	156.2
District heat price, €/MWh	75	72

Table 6 Facade analysis related construction costs in 2013 and 2015. All costs include value added tax 20%.

	2013	2015
External wall, insulation thickness 150 mm, €/m^2	131.2	144.3
External wall, insulation thickness 200 mm, €/m^2	136.0	149.6
External wall, insulation thickness 250 mm, €/m^2	140.8	154.9
Triple window, size 1050x1800 mm (WWR=23.9%), €/m^2	122.0	109.8
Triple window, size 1600x1800 mm (WWR=37.5%), €/m^2	104.7	94.2
Triple window, size 11900x1980 mm (WWR=60.0%), €/m^2	78.6	70.7
Quadruple window, size 1150x1800 mm (WWR=26.1%), €/m^2	190.1	209.1
Quadruple window, size 1600x1800 mm (WWR=37.5%), €/m^2	176.9	194.6
Quadruple window, size 11900x1980 mm (WWR=60.0%), €/m^2	150.8	165.9
External venetian blinds, size 1050x1800 mm, €/pcs	603.0	542.7
External venetian blinds, size 1150x1800 mm, €/pcs	618.0	556.2
External venetian blinds, size 1600x1800 mm, €/pcs	703.0	632.7
External venetian blinds, size 11900x1980 mm, €/pcs	8132.0	7318.8

3 Results

3.1 External wall insulation levels

2013 study results (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014) showed that cost-effective external wall mineral wool thickness was 200 mm and that it was reasonable to use 250 mm insulation layer in case of quadruple windows. The cost-effective insulation thickness has decreased to 150 mm due to changes in the economic situation, construction and energy prices. Figure 4 illustrates the primary energy and facade cost of a whole office floor in case of different facade solutions and Figure 5 describes 20 year NPV instead of facade cost. Lowest NPV was reached with insulation thickness 150 mm with all facade solutions, which made it the financially feasible solution. However if we used 150 mm insulation thickness with quadruple windows, then a more energy efficient and also cheaper solution could be reached with triple windows and larger insulation thickness e.g. case 3/24/i with 250 mm insulation layer. Therefore it is reasonable to use 200 mm mineral wool layer in external wall with quadruple windows. All the subsequent facade analyses of this article were done with insulation thicknesses 150 mm and 200 mm with triple and quadruple windows respectively. The respective external wall U-values were 0.20 and 0.16 W/(m$^2\cdot$K).

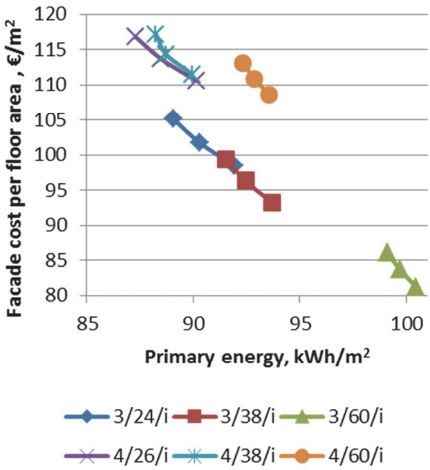

Figure 4 The facade cost and primary energy depending on the external wall mineral wool thickness. The points of each facade represent 150, 200 and 250 mm from right to left respectively. The case codes illustrate window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading.

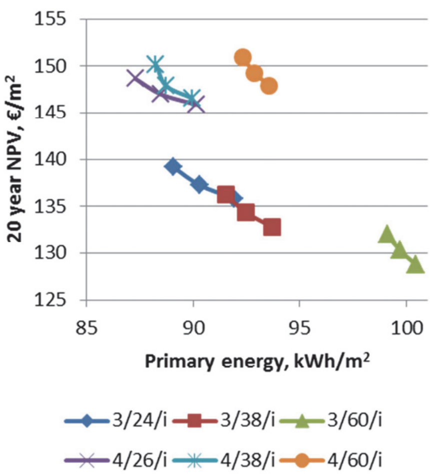

Figure 5 The 20 year NPV and primary energy depending on the external wall mineral wool thickness. The points of each facade represent 150, 200 and 250 mm from right to left respectively. The case codes illustrate window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading.

3.2 Energy simulation results

The results given in Figure 6 show that space heating dominated the energy need of most cases except for ones with large window and internal shading in South, East and West orientations, which had large cooling needs. Lighting energy need did not dominate in any of the cases. Overall the results are similar to (Thalfeldt et al. 2013), however in the previous study external shading increased lighting need, but in the current study using a more advanced control algorithm utilized daylight more efficiently and therefore automated blinds decreased lighting energy need compared to respective cases with internal blinds. The decrease in lighting energy was largest in the South orientation ranging between 24-35% i.e. 0.7 and 1.7 kWh/m^2, followed by East and West facades with 11-22% i.e. 0.3-1.0 kWh/m^2. In the North orientation the effect on lighting energy did not exceed 0.1 kWh/m^2.

Figure 7 presents the primary energy of all studied cases and it shows that increasing the sizes of windows equipped with internal shades also increases primary energy use except for the North orientation with quadruple windows, where primary energy decreased slightly. Compared to (Thalfeldt et al. 2013) the most remarkable change is that previously lowest primary energy with quadruple windows and internal blinds was achieved with WWR 37.5%, while now in South, East and West facades smallest four pane windows assured lowest primary energy. In (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014) we stated that external shading increased the energy use of some cases, however no such case appeared in the current analysis. Finally the primary energy in the current study was slightly lower caused by increased efficiency of ventilation heat recovery, however this did not remarkably affect the choice of facade solutions.

Also the size of a window with external venetian blinds had a significantly smaller effect on primary energy than the size of a window with internal blinds. Increasing the WWR of windows with internal blinds could increase primary energy by up to 7.1-16.1 kWh/m^2 in South, East and West orientations depending on the window type e.g. the gap in primary energy of South orientated cases with triple window WWRs of 24% and 60% was 16.1 kWh/m^2. However, if windows were equipped with external blinds then increasing the WWR could increase primary energy by up to 2.4 kWh/m^2 (triple windows in East facade) or decrease it by up to 4.8 kWh/m^2 (quadruple windows in South facade). This shows that if the designers of an office building in a Nordic climate decide to use automated external shading with an efficient control algorithm, then the architects could have more freedom in dimensioning windows.

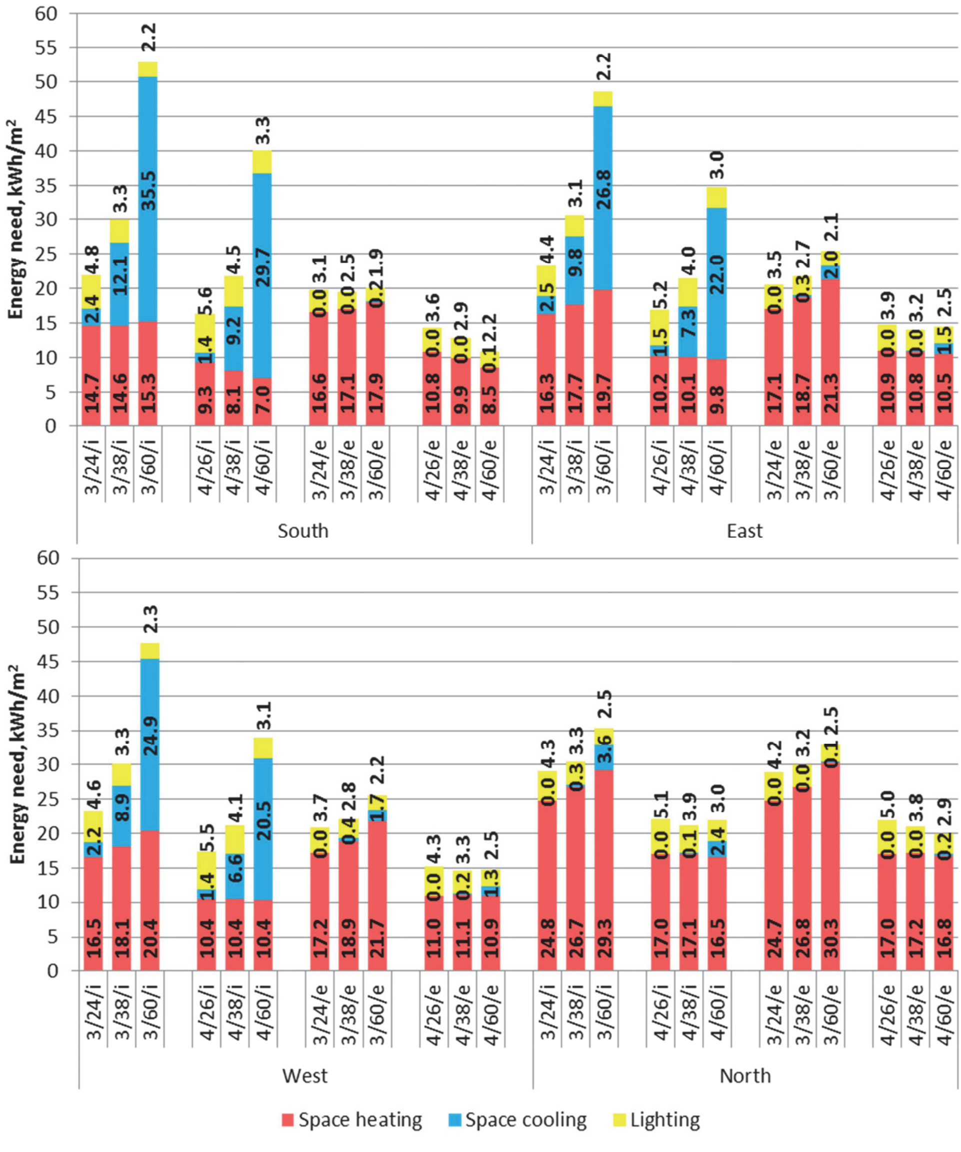

Figure 6 Energy needs of all studied cases. External wall insulation thicknesses 150 and 200 mm were used with triple and quadruple windows respectively. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e" means external shading.

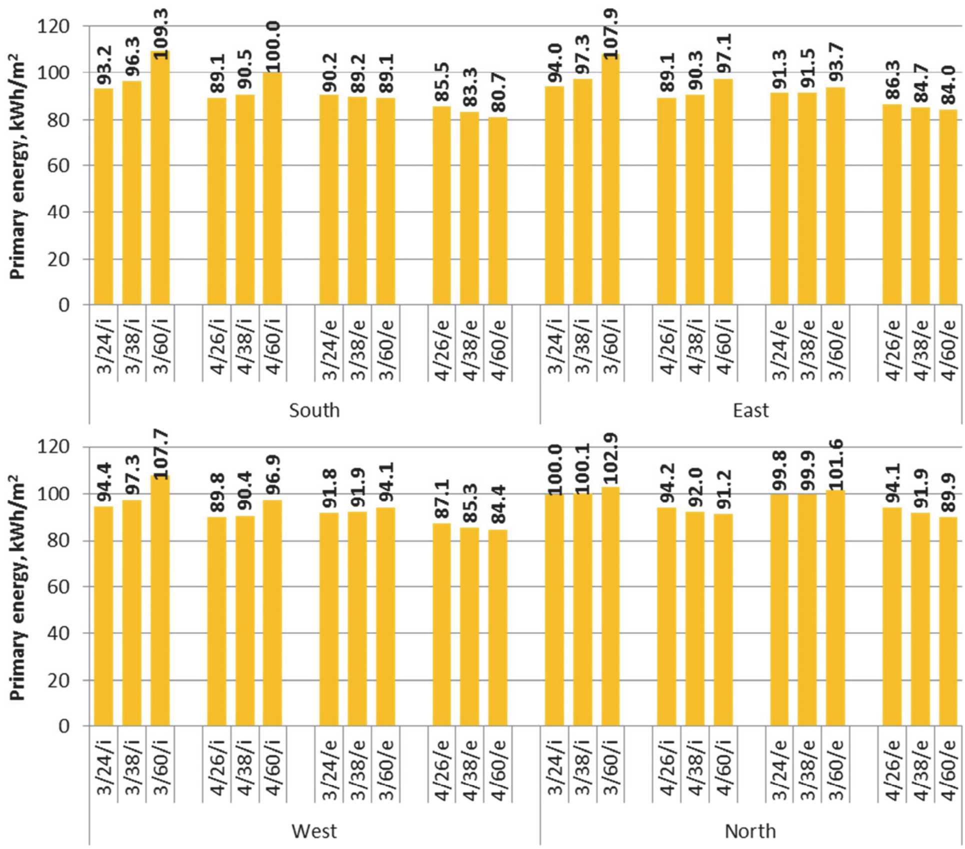

Figure 7 Primary of all studied cases. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e“ means external shading.

3.3 Economic calculation results

Figure 8 presents the results of the NPVs of all studied cases with detailed window models and current economic situation, energy and construction prices. External wall insulation thicknesses 150 and 200 mm were used with triple and quadruple windows respectively. The cost-effective façade solution i.e. with lowest NPV was triple windows without external shading and the optimal WWR was 37.5% in the South orientation and 60% in East, West and North. The NPV was formed by the construction costs of external walls, windows, shading and energy costs including space heating, cooling and electric lighting, which were multiplied by discount factor of 18.0. The construction costs made up the majority of the NPV in all cases and the proportion decreased when WWR increased. The largest proportion of construction cost was formed by external walls and the proportions of other components varied. Windows made up the smallest part if triple glazing was used and external shading cost was significant when used. The relatively low cost of triple windows compared to external wall was the reason why larger windows resulted in lowest NPV despite increased energy costs.

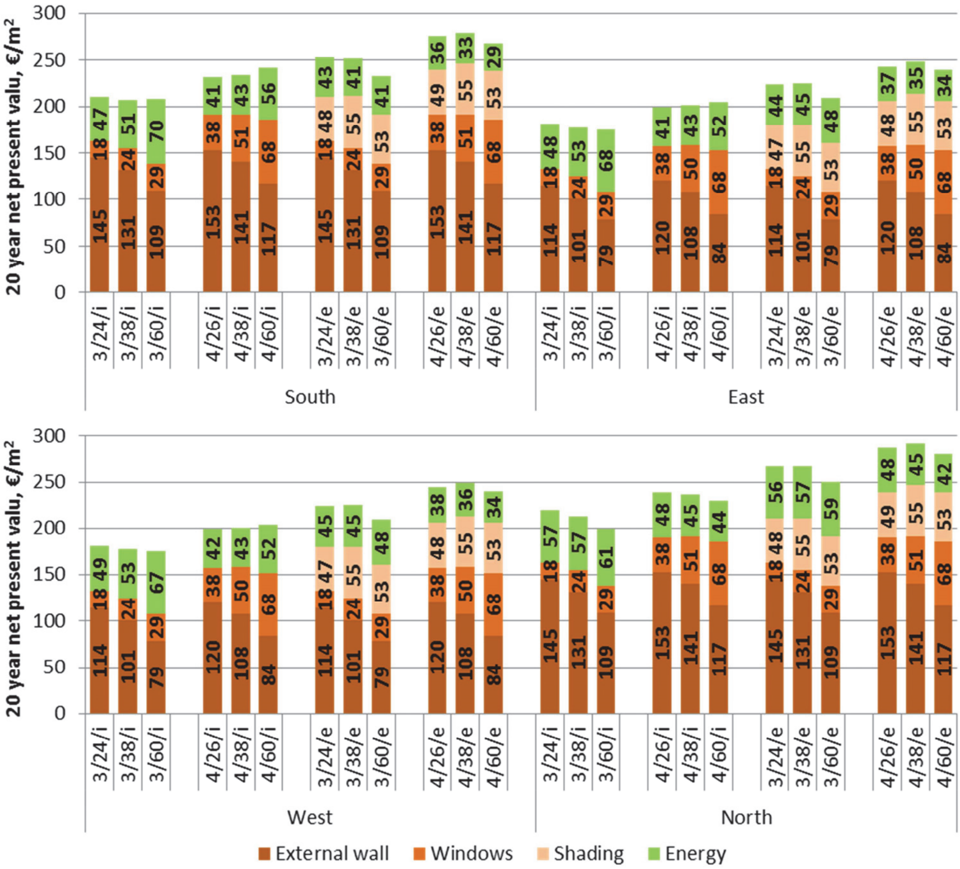

Figure 8 Net present value of all studied cases per floor area of respective zones. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e" means external shading.

3.4 Calculated energy use differences between standard and detailed window models

The energy needs calculated with standard and detailed windows differed by up to 4.0 kWh/m^2, whereas largest gaps appeared in cooling and smallest in lighting as is seen in Figure 9. Generally heating need with detailed windows was higher reaching 1.6 kWh/m^2 and largest differences appeared with triple windows. The only cases with detailed window models resulting in lower heating energy were South oriented externally shaded triple and quadruple windows with WWR 37.5% and 60%. Detailed window models generally resulted in smaller cooling needs by up to 4.0 kWh/m^2, whereas largest differences appeared in case of large internally shaded South and East orientated windows. Standard window models resulted in smaller cooling needs only in case of externally shaded East and West orientated windows with the gaps reaching 0.5 kWh/m^2. The lighting energy need was generally smaller with detailed window models. The largest differences in lighting reached 0.9 kWh/m^2 and standard windows only resulted in smaller lighting need in case of small internally shaded quadruple windows in South, East and West facades.

Generally lower primary energy was achieved with detailed window models compared to standard window models. The difference increased if window sizes were increase in all cases of the South facade and in case of internally shaded quadruple windows in East and West orientations. The case of South oriented internally shaded quadruple window with WWR 60% resulted in the largest primary energy difference of 2.7 kWh/m^2, followed by South facade triple windows with WWR 60% with internal and external shading which had differences of 1.9 kWh/m^2. All these cases resulted in lower primary energy with detailed window models. Usually detailed window models resulted in higher primary energy use in case of large externally shaded windows in East and West facades.

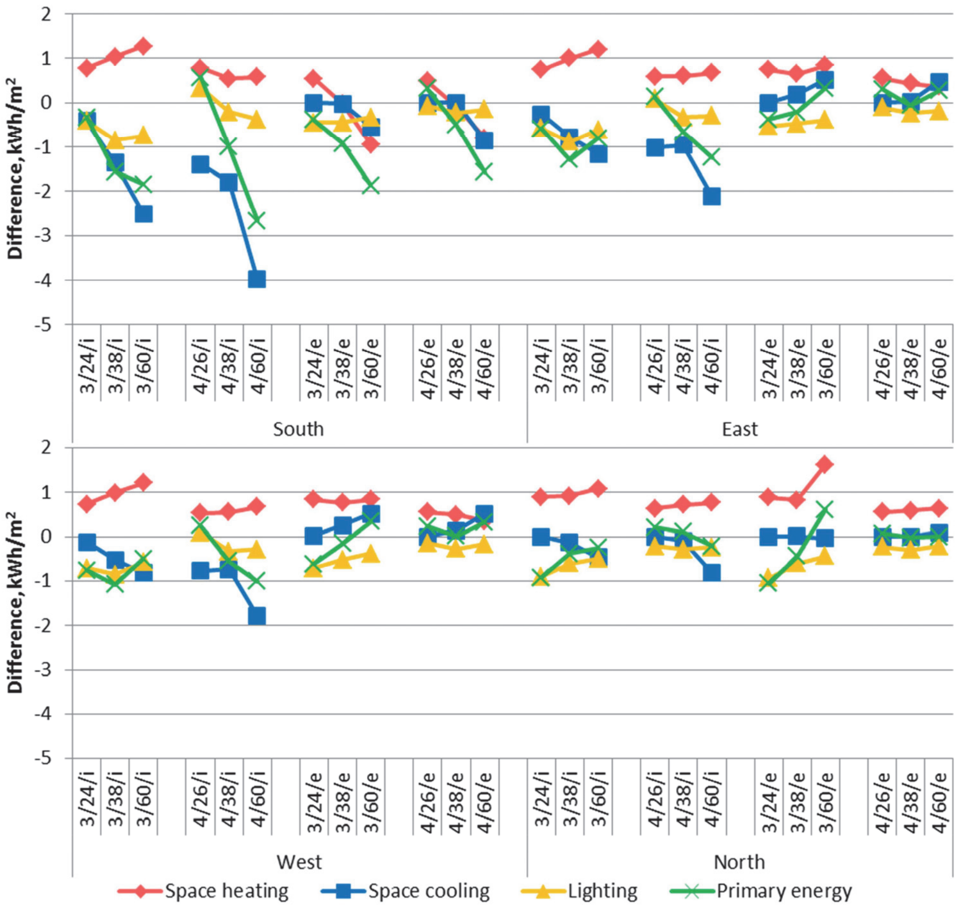

Figure 9 The difference of energy simulation results obtained with standard window models compared to simulations with detailed window models. The results are given as a function of window type, WWR and type of shading e.g. 3/24/i means a case with triple windows, WWR 24% and internal shading. „e“ means external shading.

3.5 Comparison of NPVs

Table 7 presents façade solutions with three lowest NPVs. The cases are given facade by facade in the order of the most financially feasible cases i.e. with the lowest NPV. The base case NPVs were calculated with detailed window models and updated energy prices, interest rate, inflation, energy price escalation and construction prices. The cases included:

1. Model with detailed window models and data from 2015 (Base)
2. The results from the previous study (Thalfeldt et al. 2013; Pikas, Thalfeldt, and Kurnitski 2014) (2013)
3. Standard window models were used instead of detailed models, other data from 2015 (StaW)
4. The energy prices of 2013 were used, other data from 2015 (Energy)
5. The interest rate, inflation and energy price escalation from 2013 were used, other data from 2015 (Economy)
6. The construction prices of 2013 were used, other data from 2015 (Construction)
7. The energy simulation model results of the base case model were used in combination with all other information from 2013 (2013+DetW)

The NPVs of the most cost-effective façade solution are given as absolute values and the difference of NPV from the best case in the row are given for the second and third best solutions. The façade solutions in the table are marked with colors. Green means that changing the respective variable did not affect the outcome of the three most cost-effective façade solutions compared to the base case. Orange indicates that the respective variable affected the cost-effective façade solution.

Compared to the previous study the cost-effective solution remained the same in the South facade, but the optimal window size increased in the other orientations. The triple window case with WWR 60% was not presented in the figures of previous study, because it was neither the most financially feasible nor energy efficient case. Using standard window models instead of detailed models did not affect the optimal solution in any orientation and thus had the smallest effect on the ranking of the cases despite the differences in simulated energy use. Also using the previous energy prices did not have any influence on the ranking order of the facade solutions. However the 2013 economic variables and construction prices both decreased the optimal window size in South, East and West facades. When we used energy prices, economic variables and construction costs combined with the energy simulations of the base case, the optimal facade solution was altered most.

Triple windows with WWR 37.5% and without external shading was ranked first in the South façade for most cases and similar solution with WWR 23.9% was prevailing as the second best choice, while the NPV difference between 1st and 2nd choice remained below 2 €/m^2. The 3rd choices generally had larger increases in the NPV especially with WWR of 60% and therefore triple windows with WWR in the range of 25% and 40% should be used in the South façade.

In the East and West orientations triple windows with WWR 37.5% and 60% without external shading were mostly represented in the columns with two lowest NPVs. Only energy simulations with detailed windows and a few years old price data and economic situation resulted in the lowest WWR of 23.9% as the cost-effective solution, whereas this façade solution dominated the column with 3rd lowest NPVs. Therefore larger windows could be used in East and West orientations compared to the South if only NPVs presented in this table is considered.

The North façade was least influenced by changing of variables and the dominating solution was triple windows with WWR 60% and without external shading. The NPVs increased remarkably if the window sized decreased in the orientation. Therefore the North façade tolerates the largest glazed areas.

Table 7 The façade solution with three lowest NPVs of all orientations in case of updated energy prices, economic parameters and construction costs (Base case). The table also includes cases from the previous study (Previous), and when the standard window model (StaW), old energy prices (Energy), interest rate, inflation and energy price escalation (Economy), construction prices (Construction) were changed. The case 2013+DetW includes all old variables, but the energy simulations were conducted with detailed window model.

		1st choice		2nd choice		3rd choice	
		Solution	NPV, €/m²	Solution	ΔNPV, €/m²	Solution	ΔNPV, €/m²
South	Base	3/38/i	206.6	3/60/i	1.0	3/24/i	3.0
	2013	3/38/i	200.1	3/24/i	0.2	-	-
	StaW	3/38/i	208.8	3/24/i	1.3	3/60/i	1.4
	Energy	3/38/i	206.5	3/60/i	0.3	3/24/i	3.2
	Economy	3/38/i	222.2	3/24/i	1.7	3/60/i	6.6
	Construction	3/38/i	196.9	3/24/i	1.0	3/60/i	3.6
	2013+DetW	3/24/i	212.1	3/38/i	0.0	3/60/i	8.3
East	Base	3/60/i	175.4	3/38/i	2.4	3/24/i	5.0
	2013	3/38/i	169.7	3/24/i	2.1	-	-
	StaW	3/60/i	176.5	3/38/i	3.0	3/24/i	4.7
	Energy	3/60/i	175.1	3/38/i	2.8	3/24/i	5.5
	Economy	3/38/i	193.8	3/24/i	1.2	3/60/i	2.2
	Construction	3/38/i	170.9	3/60/i	0.3	3/24/i	0.6
	2013+DetW	3/24/i	186.3	3/38/i	0.7	3/60/i	5.0
West	Base	3/60/i	175.2	3/38/i	2.6	3/24/i	5.8
	2013	3/38/i	171.8	3/24/i	1.4	-	-
	StaW	3/60/i	175.8	3/38/i	3.4	3/24/i	6.1
	Energy	3/60/i	174.9	3/38/i	3.0	3/24/i	6.1
	Economy	3/38/i	193.8	3/60/i	1.9	3/24/i	1.9
	Construction	3/38/i	170.8	3/60/i	0.0	3/24/i	1.2
	2013+DetW	3/24/i	187.0	3/38/i	0.1	3/60/i	4.1
North	Base	3/60/i	199.1	3/38/i	13.4	3/24/i	20.5
	2013	3/38/i	205.3	3/24/i	13.0	-	-
	StaW	3/60/i	199.4	3/38/i	13.6	3/24/i	21.5
	Energy	3/60/i	200.1	3/38/i	13.3	3/24/i	20.2
	Economy	3/60/i	217.6	3/38/i	12.2	3/24/i	19.2
	Construction	3/60/i	191.9	3/38/i	10.8	3/24/i	15.9
	2013+DetW	3/60/i	208.6	3/38/i	10.0	4/60/i	15.3

The façade solution is the same as the Base case after changing the variable

The façade solution changed compared to the Base case after changing the variable

4 Discussion

The results of this study indicated that the financially most feasible solutions change in time and therefore cost-optimality calculations should be updated every few years. The largest influences were caused by changes in the economic situation and construction prices. It is natural that new technical solutions increase their market share and thus become more affordable, which we believe is the main reason why cost optimal solutions change in time. Triple windows are a good example, which have become remarkably cheaper due to being the primary solution used in new building in Estonia. It is essential for building designers to keep themselves informed with the costs of different technical solutions to more accurately assess the financial feasibility of various facade solutions especially if interest rates remain low.

The NPV calculations showed that optimal window sizes have increased, however they are also less energy-efficient. Based on the results we advise that currently WWRs in the range 25-40% should be used in the South orientation. East and West orientations resulted in facades with larger windows as the cost-efficient solution, however the calculations did not take into account larger cooling capacities, which damages indoor climate and increases the cost of mechanical cooling system. Therefore we advise that similar façade solution should be used in the East and West facades as in the South. Larger windows could be used in the North façade since there is no danger of large cooling capacities, so the WWR should be within 40% and 60%. Such suggestion apply for triple windows without external shading, however we can see that some technical solutions such as external venetian blinds are becoming more affordable and such solutions would give architects more freedom in choosing the window size. Also larger market uptake of quadruple glazing or windows with similar parameters would increase architectural freedom, if energy use, thermal comfort and cost-optimality are considered in facade design. The cost-efficient external wall mineral wool insulation thickness had dropped from 200 mm to 150 mm in the current economic situation. However, if the energy prices should start rising, then the optimal insulation thickness also increases and adding insulation to external wall is difficult. Therefore we advise that 200 mm of insulation should be used in office building external walls in a Nordic climate.

We showed that automated external shading decreased or even diminished the energy penalty of increasing windows. However it is essential to remember that we used an energy-efficient control algorithm. Therefore besides installing external shades an effort has to be made to control them in an efficient way, which in addition would not disturb the office workers. The algorithm we used has to be developed further to utilize it in real projects and further studies have to be made regarding this aspect.

During the study we simulated the energy use with both simplified standard window models and more accurate detailed window models. The choice of the window model did not affect the cost-effectiveness ranking of facade solutions, therefore an energy efficiency specialist could use both of them in early design facade analysis. However their results had a gap in simulated primary energy reaching 2.8 kWh/m^2. Although the number itself does not seem large it still can have a significant influence on the building design. In Estonia the primary energy requirement for nearly zero office buildings is 100 kWh/m^2, which is 20 kWh/m^2 lower than the primary energy target 120 kWh/m^2 of low energy buildings. The difference in calculated energy use could be approximately 10% of difference between a nearly zero energy building and low energy building. Therefore the choice of window model can have a remarkable influence on dimensioning the renewable energy systems (e.g. PV panels) to reach nearly zero energy building level. We recommend using detailed window models to calculate the total primary energy and more accurately predict the energy use of a building.

5 Conclusions

Energy modelling is nowadays often performed in case of new buildings and simulations are used to optimize building facade solutions even in common construction projects. One method of optimizing is minimizing the NPV, which includes both investment costs and operational cost. Correct calculation of NPV requires both accurate modelling, determining of economic variables and construction costs. The main purpose of our analysis was to currently valid cost-effective facade solutions and to illustrate the importance of different variables such as accuracy of window models in simulations, construction costs, energy prices, interest rate and inflation. We conducted office building facade analysis with varying external wall insulation thicknesses, standard and detailed window models, updated energy prices, construction costs, interest and inflation rates to identify the most important variables in facade design and determine the possible changes in optimal facade solutions. The net present value (NPV) of a 20 year period was calculated for each studied facade solution to assess financial feasibility and we compared the solutions while changing variables.

The analysis showed that cost-optimal facade solutions were:

- South, East and West facade: Triple windows with internal shading and window-to-wall ratio 25-40%, external wall mineral wool insulation thickness 150 mm.
- North facade: Triple windows with internal shading and window-to-wall ratio 40-60%, external wall mineral wool insulation thickness 150 mm.

The insulation thickness had dropped from 200 mm to 150 mm, but based on 2013 price data we recommend using 200 mm of insulation.

The facade solutions were ranked according to NPV and the ranking order was most influenced by the combination of varying inflation, energy price escalation, interest rates, construction costs and energy prices. The economic variables and construction costs had the largest influence as a single variable. The low interest rates and inflation had increased the optimal window sizes compared to years 2012-2013. Quadruple windows could be used to improve energy efficiency of an office building, whereas lowest energy use was achieved with quadruple externally shaded windows with WWR 60% and insulation thickness 250 mm and an advanced shading control algorithm was required to reach low primary energy.

The energy simulations showed that space heating dominated the energy need for most cases except for ones with large window and internal shading in South, East and West orientations, which had large cooling needs. The use of a more advanced control algorithm utilized daylight more efficiently and therefore automated blinds decreased lighting energy need compared to respective cases with internal blinds by up to 35%. Increasing the sizes of windows resulted in primary energy use increased up to 16.1 kWh/m^2 if equipped with internal shades. When equipped with external shade, the increase reached 2.4 kWh/m^2 or even decreased by up to 4.8 kWh/m^2. If the designers of an office building in a Nordic climate used automated external shading with an efficient control algorithm, then the architects could have more freedom in dimensioning windows.

The energy needs calculated with standard and detailed windows differed by up to 4.2 kWh/m^2, whereas largest gaps appeared in cooling and smallest in lighting. Generally heating need with detailed windows was higher in case of heating reaching 1.6 kWh/m^2 and largest differences appeared in case of triple windows. Detailed window models generally resulted in smaller cooling needs by up to 4.2 kWh/m^2, whereas largest differences appeared in case of large internally shaded South and East orientated windows. The lighting energy need was generally smaller with detailed window models reaching 0.9 kWh/m^2. Generally lower primary energy was achieved with detailed window models compared to standard window models with differences reaching 2.8 kWh/m^2. Usually detailed window models resulted in higher primary energy use in case of large externally shaded windows in East and West facades. Using standard window models instead of detailed did not influenced the cost-optimal facade solution, however we recommend using detailed models for assessing the energy use of an office building.

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