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Cost-Effective Measures of New Low Energy Office Buildings in Cold Climate

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Abstract
The paper presents cost-effective measures in new low-energy office buildings located in cold climate. The results of this study can be generalized to similar climates and techno-economic environments. The paper studies the impact of different measures on the energy consumption and on the life-cycle cost of the studied office building located in Tallinn, Estonia to determine the cost-optimal measures to build a new low-energy office building. The research method used in this study was simulation-based multi-objective optimization analysis, which has been proved to be an efficient method to determine the cost-optimal measures in multi-objective building performance analyzes. According to the results of the study, the ground source heat pump system with relatively small dimensioning power output used for combined heating and cooling provides the best improvements on the energy performance of the studied office building. Other cost-effective and recommendable measures include demand-controlled ventilation system in office and parking hall spaces, LED-based lighting system with occupancy and constant light control system and a solar-based electricity production system with a moderate area of PV-panels.

Keywords – cost-effectiveness; optimization; cost-optimal measure; energy efficiency

1. Introduction

The Energy Performance of Buildings -directive (EPBD) of the European Commission sets tightened demands for the member states to improve energy performance of new and existing buildings [1-3]. The recast EPBD-directive requires that the nearly zero-energy building (nZEB) regulations are applied to all new buildings from 2020 onward and to all new buildings used by authorities from 2018 onward [1]. The most noticeable changes are the implementation of the total primary energy consumption of buildings and the implementation of the Energy Performance Certificates (EPCs) [1,3].

The requirements of the EPBD-directive are interpreted a little differently in different member states, but the nZEB is mainly defined according to the total primary energy consumption of a building [1,4]. For example in Finland and in Estonia, the total primary energy consumption of buildings is a calculated value according to the standardized use of a certain building type, such as an office or an educational building type [3,5,6]. In modern new office buildings there can easily be thousands or even millions of different energy performance options, especially when the renewable energy production systems, such as heat pump systems and solar-based energy production systems, are taken into account [6-9].

This creates a problem in designing of an nZEB, as the selection of cost-effective energy performance measures and technical systems should always be based on the real use of the building, not solely on the calculated energy consumption in standardized use of a similar building type to reach the requirements of an nZEB [5-9]. Typically the selection of measures based solely on the calculated energy consumption in standardized use of similar buildings doesn’t correspond accurately enough to the technical features and usage of an individual building to deliver cost-optimal overall solutions [9,10].

The objective of this study was to determine cost-optimal energy performance measures and overall solutions in a typical new low-energy office building built in cold climate areas. The studied building is located in Tallinn, Estonia and it represents a typical modern office building type built in the Scandinavian countries and in Estonia. The results of this study can be generalized to similar climates and techno-economic environments.

2. Methods

2.1. Studied Building and Climate Conditions

The main floor layout of the office floors of the studied building is presented in Fig. 1. A total of 6 floors are included in the studied building with 3 office floors, 1 commercial floor and 2 underground parking floors. The total heated net floor area of the building, including the parking floors, is 6 472 m^2 and the total heated volume is 20 420 m^3, respectively. The building is located in the urban environment of Tallinn, Estonia.

The building is assumed to be used like a typical modern office building with similar features. The main use of the building and the internal gains of different space groups are presented in Table 1. The HVAC and other technical systems of the studied building are typical energy efficient systems selected in modern low-energy office building concepts [9,10]. The air flow rates, set points of different HVAC systems and other features of the technical systems are selected according to the real design values of the building and also according to the regulations and guidelines of current Finnish and Estonian building regulations [5,11,12].

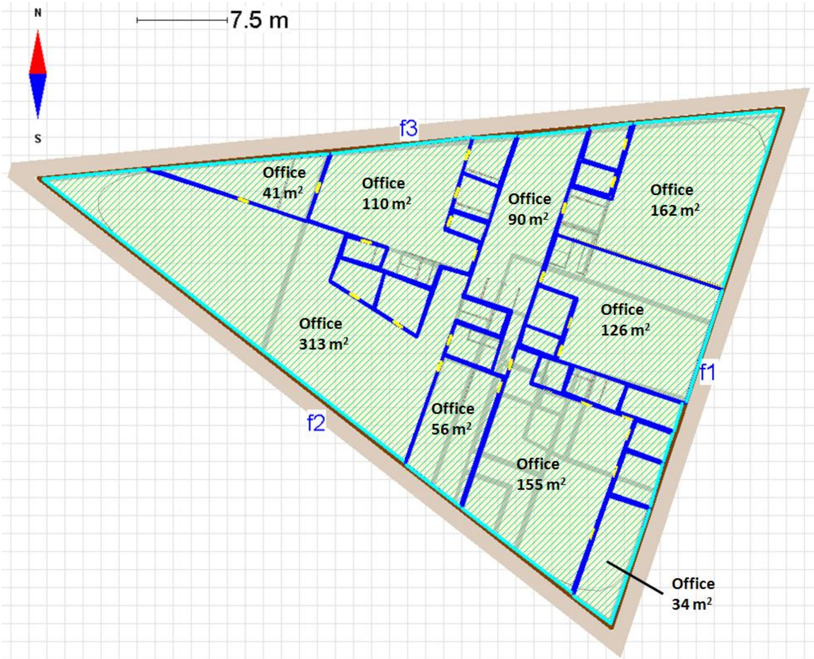

Fig. 1. The floor plan of the office floors, areas of open office spaces presented.

Table 1. The internal gains from occupants, office appliances and lighting and the main use of the studied office building.

Occupants	According to the estimated real use. An average sensible gain from occupants for the building is 2.7 W/m^2, which equals to an annual gain of 2.1 kWh/(m^2,a).
Office appliances	According to the estimated real use. An average gain from office appliances for the building is 7.7 W/m^2, which equals to an annual gain of 6.9 kWh/(m^2,a).
Lighting system, either modern fluorescent- or LED-based lighting system (decision variable in the SBO analysis)	According to the estimated real use. An average gain from lighting for the building is 6.9 W/m^2 (fluorescent) or 5.0 W/m^2 (LED), which equals to an annual gain of 8.1 kWh/(m^2,a) (fluorescent) or 6.0 kWh/(m^2,a) (LED).
Use of the studied office building	The building is used during weekdays (Monday-Friday, excluding holidays) from 8 to 17. The building is not used at other times.

The air-tightness of the studied building is assumed to be at the energy efficient level of similar new low-energy office buildings. The q_{50}-value used in the dynamic energy simulations was 2.0 $m^3/(m^2\ h)$, which is the reference value of the current Finnish building regulations (NBCF D3 (2012)) for new buildings [5]. The thermal bridges of the external structure joints were also selected according to the reference values of the NBCF D5 (2012) for new buildings [12].

The weather data used in the SBO analysis was selected according to the location of the studied building. The updated Estonian test reference year (Estonia TRY-8784) weather data was used in the dynamic energy simulations [13]. The average annual ambient air temperature is +5.7 °C and the average annual heating degree day number S_{17} (at indoor air temperature 17 °C) is 4160 Kd [13].

2.2. Studied Measures and Cost Data

Table 2 presents the relevant cost data related to the maintenance and renewal of different measures and technical systems [14]. Table 3 presents the relevant investment cost data related to the studied measures. The studied energy performance measures of the simulation-based optimization (SBO) analysis are presented in Table 4. The cost data of different measures was mainly determined by a group of experts [14]. Cost data of relevant previous studies regarding energy performance measures of new low-energy office buildings was also utilized to the appropriate extent [9]. Only the cost estimates of the main components related to the measures are presented, as the cost difference between different measures is the most important input data of the SBO analysis [14]. The Estonian VAT is not included in any of the prices presented in Table 2 and Table 3. Renewal costs related to different ventilation systems are presented in Table 3, respectively [14].

Table 2. The relevant cost data related to maintenance and renewal of different systems [14].

System	Maintenance and renewal cost
GSHP system	Annual maintenance cost: 1.0 %/a from the total initial investment cost of the system Renewal cost: 180 €/kW after 15 years, when compressors, exchange valves and circulation pumps are renewed
Solar-based electricity production system, PV-panels	Annual maintenance cost: 2.0 %/a from the total initial investment cost of the system Renewal cost: -, the system is assumed to be operational for the 25-year discount period

Table 3. Relevant cost data of different measures used in the SBO analysis [14].

<table>
<tr><th>Energy performance measure</th><th colspan="5">Options</th><th>Investment cost of the measure</th></tr>
<tr><td rowspan="4">Thermal insulation thickness of external walls</td><td colspan="5">- 100 mm</td><td>337 €/m²</td></tr>
<tr><td colspan="5">-150 mm</td><td>347 €/m²</td></tr>
<tr><td colspan="5">- 200 mm</td><td>357 €/m²</td></tr>
<tr><td colspan="5"></td><td></td></tr>
<tr><td rowspan="3">Thermal insulation thickness of roof</td><td colspan="5">- 150 mm</td><td>211 €/m²</td></tr>
<tr><td colspan="5">-250 mm</td><td>213 €/m²</td></tr>
<tr><td colspan="5">- 340 mm</td><td>215 €/m²</td></tr>
<tr><td rowspan="4">Windows</td><td></td><td>g-value 0.2</td><td>g-value 0.28</td><td>g-value 0.35</td><td>g-value 0.48</td><td rowspan="4"></td></tr>
<tr><td>U-value 0.7</td><td>478 €/m²</td><td>448 €/m²</td><td>408 €/m²</td><td>368 €/m²</td></tr>
<tr><td>U-value 0.8</td><td>439 €/m²</td><td>409 €/m²</td><td>369 €/m²</td><td>329 €/m²</td></tr>
<tr><td>U-value 0.9</td><td></td><td></td><td>349 €/m²</td><td>309 €/m²</td></tr>
<tr><td rowspan="11">Ventilation system, relevant cost data of main components related to the system</td><td colspan="5">- Parking areas, CAV-system (no maintenance)</td><td>9 700 €</td></tr>
<tr><td colspan="5">- Parking areas, VAV-system, maintenance/renewal 5 600 € (after 13 years)</td><td>16 100 €</td></tr>
<tr><td colspan="5">- 1st floor commercial space, CAV-system (no maintenance)</td><td>4 700 €</td></tr>
<tr><td colspan="5">- Commercial space, VAV-system, maintenance/renewal 2 600 € (after 13 years)</td><td>8 200 €</td></tr>
<tr><td colspan="5">- Office / floor, CAV-system (no maintenance)</td><td>6 900 €</td></tr>
<tr><td colspan="5">- Office / floor, VAV-system, maintenance/renewal 4 300 € (after 13 years)</td><td>12 800 €</td></tr>
<tr><td colspan="5">- Cafeteria, CAV-system (no maintenance)</td><td>2 700 €</td></tr>
<tr><td colspan="5">- Cafeteria, VAV-system, maintenance/renewal 4 300 € (after 13 years)</td><td>5 300 €</td></tr>
<tr><td colspan="5">- Entrance hall / lobby area, CAV-system (no maintenance)</td><td>2 400 €</td></tr>
<tr><td colspan="5">- Entrance hall / lobby area, VAV-system, maintenance/renewal 1 100 € (after 13 years)</td><td>3 300 €</td></tr>
<tr><td colspan="5">- Preliminary cost estimate of recommendable air handling units</td><td>270 000 €</td></tr>
<tr><td rowspan="2">Solar electricity system</td><td colspan="5" rowspan="2">- Solar-based electricity production system installed, with PV-panels</td><td>240 €/panel-m²</td></tr>
<tr><td>~1.5 €/W_p</td></tr>
<tr><td rowspan="2">Lighting control, relevant cost data of main components</td><td colspan="5">- No automatic control, traditional lighting control with switches</td><td>5 000 €</td></tr>
<tr><td colspan="5">- Yes, occupancy controlled lighting system with constant light control (dimmed according to the outside light)</td><td>18 700 €</td></tr>
<tr><td rowspan="2">Lighting type</td><td colspan="5">- modern fluorescent lighting (installed in office and equivalent space groups)</td><td>90 000 €</td></tr>
<tr><td colspan="5">- LED-based lighting (installed in office and equivalent space groups)</td><td>120 000 €</td></tr>
<tr><td rowspan="6">Energy piles and GSHP system with installation</td><td colspan="5">- 40 kW</td><td>68 000 €</td></tr>
<tr><td colspan="5">- 50 kW</td><td>73 700 €</td></tr>
<tr><td colspan="5">- 55 kW</td><td>77 300 €</td></tr>
<tr><td colspan="5">- 60 kW</td><td>81 300 €</td></tr>
<tr><td colspan="5">- 70 kW</td><td>90 600 €</td></tr>
<tr><td colspan="5">(including energy collector pipes, installation, accumulators, heat pump units, installation equipment, etc.)</td><td>(total cost estimate)</td></tr>
</table>

Table 4. The optimized decision variables of the SBO analysis.

Measure	**Variable**	**Type of variable**	**Minimum value**	**Maximum value**
External walls	Thermal insulation thickness [mm]	Discrete (3 options)	100 mm (U-value: 0.18 W/m^{2}K)	200 mm (U-value: 0.12 W/m^{2}K)
Roof	Thermal insulation thickness [mm]	Discrete (3 options)	150 mm (U-value: 0.20 W/m^{2}K)	340 mm (U-value: 0.09 W/m^{2}K)
Windows, all facades of the building are studied separately	Type of windows, U-value and g-value	Discrete (10 options per facade)	U-value 0.9 W/m^{2}K, g-value 0.48	U-value 0.7 W/m^{2}K, g-value 0.20
Ventilation system, all office floors (3), commercial floor (1), parking floors (2), lobby area and cafeteria are studied separately	Constant air volume (CAV) or demand-controlled variable air volume (VAV) ventilation system	Discrete (2 options per floor/space group)	CAV-system	VAV-system
Lighting system in office and equivalent space groups	Type of lighting	Discrete (2 options)	Modern fluorescent system, 9 W/m^2	Modern LED-based system, 6 W/m^2
Control type of lighting system in office and equivalent space groups	Type of lighting control	Discrete (2 options)	Normal typically used lighting, no additional control	Occupancy + dimming / constant light control
Solar-based electricity production system	Area of PV-panels [m^2]	Discrete (33 options)	0 m^2	160 m^2
Ground source heat pump (GSHP) system with energy pile collectors	Dimensioning power output of the heat pump system [kW]	Continuous	40 kW	70 kW (Limited by maximum number of energy piles)

Other technical systems are assumed to be used without major renewal or maintenance costs for the selected discount period of 25 years [9,14].

The prices of different energy sources were selected according to the location of the studied office building (Tallinn, Estonia) [14]. The energy prices used in the economic calculations of the study were [18]:

- 77.6 €/MWh (VAT excluded) for electrical energy,
- 51.7 €/MWh (VAT excluded) for district heating energy.

2.3. Simulation-Based Optimization Analysis

Dynamic energy simulations conducted in this study were carried out using IDA Indoor Climate and Energy 4.6.2 (IDA-ICE, version 4.6.2) building simulation software. IDA-ICE has been tested against measurements and several independent inter-model comparisons have been conducted [15-17]. IDA-ICE software has been successfully used and validated in numerous studies before and it allows modeling of multi-zone building, HVAC-systems, internal and solar loads, outdoor climate, etc. and provides simultaneous dynamic simulation of heat transfer and mass flows [15-17]. The ESBO Plant model of IDA ICE was used to model the GSHP system and the solar-based electricity production system (PV-panels).

The optimization method used in the study was MOBO (Multi-Objective Building Performance Optimization), version beta 0.3b. The MOBO software is developed by Aalto University and VTT Technical Research Centre of Finland [18]. MOBO can solve single- and multi-objective optimization problems and it can handle discrete or continuous variables [18]. MOBO includes multiple different optimization algorithms for solving different types of optimization problems [18].

The minimized objective/target functions of the multi-objective optimization analysis in the study were the net present value of life-cycle cost during the 25-year discount period and the simulated energy consumption of the studied building. The simulated energy consumption is the estimated total energy consumption of the building, including heating energy consumption of spaces and ventilation systems (produced by the GSHP and district heating systems), electrical energy used for cooling of spaces and ventilation systems (free cooling of the GSHP system also taken into account), electrical energy used by the GSHP system (combined heating and cooling), electrical energy used by lighting, office appliances, HVAC and building services auxiliary systems, such as fans and circulation pumps. The electrical energy produced by the PV-panels has also been taken into account and deducted from the total electrical energy consumption of the building. The studied PV-panel system was dimensioned so that all of the produced electrical energy can be used on-site.

The life-cycle cost was calculated by using a 5 % real interest rate, 25-year discount period and a 2 %/a escalation rate for both electrical and district heating energy. The total investment cost, maintenance and renewal cost and energy cost during the 25-year discount period were taken into account in the calculation of life-cycle cost. The residual value of different measures was not taken into account in the economic calculations.

3.1. Cost-optimal energy performance solutions

The main results of the SBO analysis are presented in Fig. 2. Fig. 2 presents the present value of 25-year life-cycle cost as a function of the simulated energy consumption of the studied building. Only the life-cycle cost data related to the studied measures are presented in Fig. 2. The energy performance measures of the Pareto-optimal solutions are presented in chapter 3.2 in addition to the investment cost of the solutions.

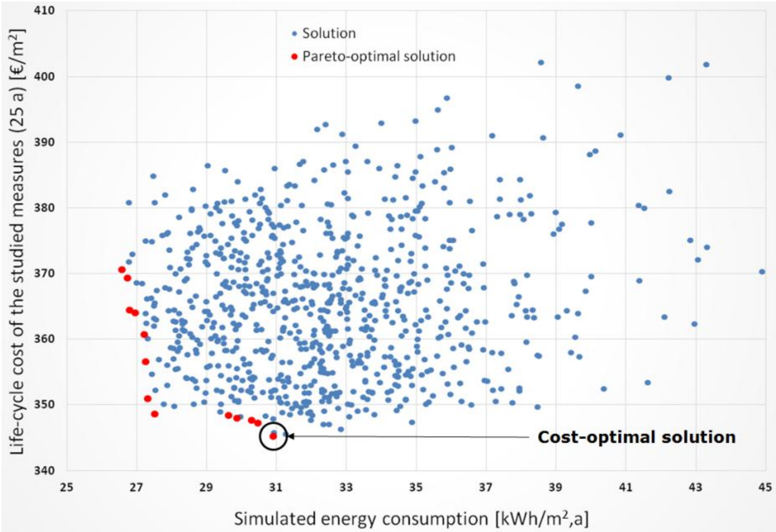

Fig. 2. Cost-optimal energy performance measures, present value of LCC for studied measures presented.

3.2. Cost-efficient measures

The recommendable energy performance measures are presented in Table 5 (first half of the measures) and in Table 6 (second half of the measures). Typically the energy performance measures of the cost-optimal solution are selected [9], as the additional investment cost to reach higher energy performance target levels increases significantly compared to the improvement in energy performance (see Table 5 and Table 6).

Table 5. Recommendable energy performance measures for the studied office building (1/2).

LCC (25a) of studied measures [€/m^2]	Investment cost of studied measures [€/m^2]	Simulated energy consumption [kWh/m^2,a]	Dimensioning power output of the GSHP system [kW]	Window type, south facade [U-value/g-value]	Window type, north facade [U-value/g-value]	Window type, east facade [U-value/g-value]	Type of the ventilation system, parking floors	Type of the ventilation system, 1st floor lobby area	Type of the ventilation system, 1st floor commercial space	Type of the ventilation system, 2nd floor office spaces
345	286	31	60	0.9/0.48	0.9/0.48	0.9/0.48	CAV	VAV	VAV	VAV
347	289	30	55	0.9/0.48	0.8/0.48	0.9/0.48	CAV	VAV	VAV	VAV
349	292	28	67	0.9/0.48	0.9/0.48	0.9/0.48	CAV	VAV	VAV	VAV
351	295	27	67	0.8/0.48	0.9/0.48	0.8/0.48	CAV	VAV	VAV	VAV

Table 6. Recommendable energy performance measures for the studied office building (2/2).

LCC (25a) of studied measures [€/m²]	Investment cost of studied measures [€/m²]	Simulated energy consumption [kWh/m²,a]	Type of the ventilation system, 3rd floor office spaces	Type of the ventilation system, 4th floor office spaces	Type of the ventilation system, cafeteria	Type of lighting in office and equivalent space groups	Control type of lighting system in office and equivalent spaces	Thermal insulation thickness of external walls [mm]	Thermal insulation thickness of roof [mm]	Area of PV-panels [m²]
345	286	31	VAV	VAV	VAV	LED	Occupancy +dimming/ constant light control	100 mm	250 mm	36
347	289	30	VAV	VAV	VAV	LED	Occupancy +dimming/ constant light control	100 mm	340 mm	50
349	292	28	VAV	VAV	VAV	LED	Occupancy +dimming/ constant light control	150 mm	340 mm	150
351	295	27	VAV	VAV	VAV	LED	Occupancy +dimming/ constant light control	100 mm	340 mm	140

3. Discussion and Conclusion

Cost-effective energy performance measures of new low-energy office buildings located in cold climate were determined in this study. The studied building represents a typical new low energy-office building built in the Scandinavian countries and in Estonia. All of the applicable measures were studied, including measures concerning the envelope of the building and measures concerning the HVAC and other building services systems of the building. In addition, renewable energy production systems, including installation of a GSHP system and a solar-based electricity production system with PV-panels, were also studied. The objective of the SBO analysis was to minimize both total delivered energy consumption and the present value of life-cycle cost during the 25-year discount period.

According to the study, the installation of a ground source heat pump system with a relatively small dimensioning power output proved to be the cost-optimal measure in the studied office building, when energy performance and economic viability are discussed. The GSHP system was assumed to be used for combined heating and cooling of the building. According to the results, other recommendable measures included demand-controlled ventilation systems in office, commercial and equivalent space groups, good thermal insulation of roof, LED-based lighting combined with occupancy and constant light control system, relatively energy efficient windows, blinds between panes for solar radiation protection, energy efficient air handling units and a solar-based electricity production system with a relatively small area of PV-panels.

According to the results of the SBO analysis, it is not cost-efficient to invest in additional thermal insulation of external walls or more energy efficient windows than the current Estonian and Finnish building regulations require. The results and recommendable energy performance measures presented in this study can be generalized to similar climates and techno-economic environments, when new low-energy office buildings are designed.

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