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Cost-optimal renovation solutions to maximize environmental performance, indoor thermal conditions and productivity of office buildings in cold climate

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Abstract
The paper presents cost-optimal renovation solutions and economic viability of different renovation measures to maximize environmental performance, thermal comfort conditions and productivity of workers in office buildings built in the late 1970s and 1980s in cold climate regions. The study also analyzes optimal combinations of renovation measures and HVAC system set points to maximize thermal comfort conditions and productivity of the building users. The productivity loss caused by unfavorable indoor thermal comfort conditions was integrated in the LCC analysis (15-year life-cycle period) of the study using an appropriate method to estimate the amount of lost performance of workers caused by the productivity loss. Simulation-based multi-objective optimization analysis was used as the research method of the study. Environmental impact of the renovation measures was studied by assessing the CO₂ emissions of the delivered energy consumption. The results demonstrate that as high as 65% return on investment and 63% reduction in the CO₂ emissions of operation can be achieved in owner occupied office buildings, when both the energy efficiency and the thermal comfort conditions are cost-optimally improved simultaneously. According to the results, the cost optimum energy production system concept is a ground source heat pump system used for combined heating and cooling.

Keywords – cost-optimal renovation; productivity; thermal comfort; energy performance; low-carbon office building; multi-objective building performance optimization
1. Introduction

The specific delivered and primary energy (PE) consumption of office buildings is one of the highest compared to other building types [1]. According to Juan et al. (2010) [1], improving both the energy performance and the indoor climate conditions in existing office buildings cost-effectively is challenging and increasing number of globally operating organizations have been investing substantial resources in sustainable building renovation processes over the last two decades. Furthermore, studies carried out by Juan et al. (2010) [1], Doukas et al. (2009) [2] and Cakmanus (2007) [3] indicate that various integrated decision support systems have been developed to assess the condition of existing office buildings and to determine recommendable renovation actions, where renovation costs, quality of the building and environmental aspects are taken into account. The property owners are interested in solid renovation measures and deep renovation concepts to maximize the return on investment (ROI), to decrease the annual operating costs and to improve the value of office buildings [1-3]. In addition, studies conducted by Seppänen et al. (2006a, 2006b) [4,5] conclude that improving the indoor climate conditions during operating times of office buildings enhances work efficiency.

Several studies have investigated the effect of different facade and building envelope solutions on the energy performance and indoor climate conditions of office buildings over the last years [6-10]. Majority of the previous studies have focused on measures applied in office buildings located in hot or intermediate climates, where the dimensioning and operation of air-conditioning systems is one of the essential factors in office buildings, when energy performance, indoor climate conditions and performance of workers are discussed [8-13]. Typically improved indoor climate conditions lead to increased energy consumption in office buildings and it is challenging to improve the energy performance and to decrease the environmental impact of buildings towards low-energy, low-carbon and nearly zero-energy buildings, and to provide productive and comfortable indoor climate conditions at the same time [10-12]. Previous studies indicate that the effects of low-carbon and high energy performance office building designs and technologies on the indoor environment quality are still relatively unknown and require further research and validation [11-13]. Furthermore, the popularity of different environmental classifications, such as LEED and BREEAM, among major property owners to improve the value of their buildings has increased in connection with deep renovations and retrofitting measures [11-13]. However, recent studies indicate that the users of high energy performance office buildings also having a high level environmental certification have not experienced higher indoor climate conditions and satisfaction than the users of more conventional office buildings [11,13].

Multiple studies regarding the productivity loss of workers due to unfavorable or poor indoor air quality (IAQ) and thermal comfort conditions have been conducted to determine the cost implication in office buildings [14-21]. These studies [14-21] indicate that depending on the techno-economic environment, the monetary value of the productivity loss
due to decreased work efficiency can be up to 10–100 times greater than the operating costs of the building. This means that improving the indoor climate conditions in renovations of existing office buildings is essential and economically viable, especially if the building owner is the same organization, which is paying the salaries of the employees, such as a government office or equivalent organization [14-17].

Typically the objectives regarding the indoor climate conditions of the renovation can be a little different between a building owner, who is not responsible for the salaries of the employees, and a building owner, who is also paying the salaries in addition to the operating costs of the building [14,15]. Generally the objective of the renovation in tenant occupied office buildings is to provide an acceptable indoor environment for occupants, but not necessarily to maximize the thermal comfort and indoor air quality conditions [14-17]. Furthermore, the ideal target of the renovation in owner occupied office buildings is to determine cost-optimal compromise solutions to improve both the thermal comfort and indoor air quality conditions to maximize the productivity of workers and also to minimize the investment and life-cycle costs of the renovation [14-17]. In addition, both types of building owners have an increasing interest in reducing the carbon footprint of their buildings by investing in renewable energy sources and in measures that reduce the environmental impact of the buildings.

This study presents the cost-optimal renovation measures for typical office buildings built in Finland (cold climate region) in the late 1970s and in the 1980s. Previous studies have demonstrated the economic impact of productivity loss due to decreased performance of workers and suggested measures and design principles, such as airflow rates and individual microclimate controls, to improve the indoor environment conditions and to minimize the productivity loss [14,15,22,23]. However, these measures and design principles are conventionally applied to new office buildings and they are typically extremely difficult, expensive, impractical and often also impossible to implement in renovations of existing office buildings due to space constraints. Furthermore, there are millions of different renovation package combinations that can be selected, when deep renovations of office buildings are conducted and this makes it impossible to determine the global optimum combination of measures by using the conventional parametric-based analysis methods. The building ownership aspects (owner-user and tenant) haven’t been addressed in previous studies focusing on renovation of office buildings and they are resolved in this study. The methodology, results and conclusions presented in the study complement the existing body of literature in the field of cost-effective renovation of office buildings located in cold climate conditions. The presented methodology can also be applied in office building studies related to different climates and techno-economic environments. It can be used to maximize the energy performance, environmental impact reduction potential and the productivity of building users and to minimize both the operating and construction costs.
Energy performance is studied from the delivered energy consumption’s perspective and economically viable renovation measures to reduce the environmental impact of the studied building type towards low-carbon office buildings, with excellent thermal comfort conditions, maximum return on investment and minimum investment and life-cycle costs are also determined. The study includes up to three conflicting objectives, such as economic indicators (LCC, return on investment), energy and environmental performance and also thermal comfort indices that are all optimized simultaneously by using a simulation-based multi-objective optimization analysis as the research method. The research method is applied in multi-objective deep renovation of existing office buildings for the first time and its effectiveness and usability are also studied and compared to the more conventional research methods used in the previous studies, where a few individual energy performance measures or measure packages are studied and compared. The objectives of this study are:

- to determine cost-optimal renovation concepts for owner-user and tenant occupied office buildings to reduce the environmental impact of the studied building stock;
- to determine measures to improve both the indoor thermal comfort conditions and the energy performance of a selected case building with minimum investment and life-cycle costs;
- to study the potential effect of the indoor thermal comfort conditions on the productivity of workers and to compare its significance to other life-cycle cost components, such as energy and investment costs;
- to determine the optimum combination of renovation measures and HVAC system set points to maximize the indoor thermal conditions and the productivity of the building users with minimum energy consumption and construction costs;
- to provide a useful and effective methodology to assess the overall performance of deep renovations of office buildings, which can also be applied to other climate conditions and techno-economic environments.

2. Methods

2.1. Case building, climate conditions and studied renovation measures

2.1.1 Selection of case building and its main features

The study aims to determine the economically viable renovation concepts of typical office buildings located in cold climate regions. An office building located in Lahti, Finland was selected as a case building. The studied office building stock represents the largest portion of the Finnish office building stock (see Fig. 1), when both the total floor area and the number of individual buildings are discussed. In addition, the office buildings built in the late 1970s and in the 1980s require major renovation measures in the near future. In the initial state of the study, no renovation measures have been carried out in the studied building.
The total floor area and number of office buildings (left) and the breakdown of buildings by the total floor area according to the year of construction (right) in Finland [24].

The geometry of the case building is shown in Fig. 2 and the floor layout of main office floors in Fig. 3. The distribution of occupant groups in the main office floors used in the calculation of thermal comfort indices is also presented in Fig 3. Each occupant group symbol represents a group of 25 occupants, resulting in a total of 225 occupants per floor, when all nine groups are summed up. The floor layout of the office floors consists originally from approximately 12-15 m² office rooms, but it is modified to open layout office in the deep renovation, as the open office layout design is more popular and typically more practical in most modern office buildings at the moment due to higher space efficiency.

The thermal transmittances of external structures, in the initial state before the renovation, are shown in Table 1. The building has a total of 5 floors, with top four floors being open office floors (Fig. 3) and the bottom floor including a combination of open office space and meeting rooms. The top most floors are technical spaces including the air handling units (AHUs) of the building. The total heated volume of the building is approximately 44 700 m³ with the total heated net floor area being approximately 13 400 m², respectively.

Fig. 2. The geometry of the case office building.
Fig. 3. The layout of main office floors and the distribution of occupants. The occupants are assumed to be sitting.

Table 1. The thermal transmittances of external structures.

<table>
<thead>
<tr>
<th>External structures and air-tightness</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal transmittance of external walls, [W/m²K]</td>
<td>0.35</td>
</tr>
<tr>
<td>Thermal transmittance of roof, [W/m²K]</td>
<td>0.29</td>
</tr>
<tr>
<td>Thermal transmittance of base floor, connected to the ground, [W/m²K]</td>
<td>0.40</td>
</tr>
<tr>
<td>Thermal transmittance of windows, 3-pane structure, [W/m²K]</td>
<td>2.1</td>
</tr>
<tr>
<td>g-value: 0.60</td>
<td></td>
</tr>
<tr>
<td>ST-value 0.52</td>
<td></td>
</tr>
<tr>
<td>Depth of frame: 170 mm</td>
<td></td>
</tr>
<tr>
<td>Integrated window shading</td>
<td>None</td>
</tr>
<tr>
<td>Thermal transmittance of external doors, [W/m²K]</td>
<td>1.4</td>
</tr>
<tr>
<td>Air-tightness of the building, the q₅₀-value, [m³/(m² h)]</td>
<td>6.00 m³/(m² h)</td>
</tr>
<tr>
<td>According to the Decree for the energy performance certificate (176/2013) [25]</td>
<td></td>
</tr>
</tbody>
</table>

2.1.2 Main HVAC systems

The main HVAC systems of the case office building in the original state before the renovation are presented in Table 2. The technical features of the HVAC and building technical services systems are typical for office buildings built dur-
Table 2. The main HVAC systems of the original case office building with main features presented.

<table>
<thead>
<tr>
<th>HVAC and building services systems</th>
<th>Mechanical supply and exhaust air ventilation system, no heat recovery system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventilation system</td>
<td>Monday-Friday, 11 h/day (7-18) 1/1-speed, other times moderate speed (15 %) to reduce indoor material pollutants and indoor air temperatures</td>
</tr>
<tr>
<td>Operation schedule of the ventilation system, based on the actual use of the building</td>
<td>±2.0 dm$^3$/s/m$^2$ during occupied time, ±0.3 dm$^3$/s/m$^2$ during unoccupied time, Constant air volume (CAV) -based ventilation system in all spaces</td>
</tr>
<tr>
<td>Supply and exhaust air flow rates of the ventilation system</td>
<td>18 °C, constant temperature during heating season, supply air temperature according to the outdoor air temperature during summer time</td>
</tr>
<tr>
<td>Supply air temperature set point of the ventilation system</td>
<td>2.50 kW/(m$^3$/s)</td>
</tr>
<tr>
<td>The specific fan power of the ventilation system, the SFP-value</td>
<td>Water radiator heating system</td>
</tr>
<tr>
<td>Heat distribution system</td>
<td>70/40 °C</td>
</tr>
<tr>
<td>Dimensioning temperatures of the heat distribution system</td>
<td>Supply water temperature control according to the outdoor temperature</td>
</tr>
<tr>
<td>Control method of space and ventilation heating systems</td>
<td>No centralised cooling system for room spaces or air handling units</td>
</tr>
<tr>
<td>Cooling system</td>
<td>21.0 °C in all room spaces</td>
</tr>
<tr>
<td>Room temperature set point for heating</td>
<td>103 dm$^3$/m$^2$,a</td>
</tr>
<tr>
<td>Domestic hot water consumption</td>
<td>58/55 °C (designing temperatures)</td>
</tr>
<tr>
<td>Domestic hot water circulation system</td>
<td>0.22 dm$^3$/s (designing water flow rate)</td>
</tr>
</tbody>
</table>

2.1.3 Internal heat gains

The internal heat gains and usage profiles used in the energy simulations of the delivered energy consumption are shown in Table 3. The internal heat gain from the lighting system (see Table 3) was determined according to the minimum requirements regarding the lighting system of office buildings, which is to produce over 500 lx illuminance in working areas. A specific power output of LED-based lighting system is also presented, as it was one of the studied energy performance improving measures.

Table 3. The internal heat gains used in the energy simulations from occupants, lighting and office appliances [27].

<table>
<thead>
<tr>
<th>Internal heat gains from occupants, lighting and office appliances</th>
</tr>
</thead>
</table>
| **Occupants**, the average usage rates are:  
0.7 during 1.1–15.6;  
0.5 during 16.6–30.6;  
0.15 during 1.7–31.7 (summer vacation);  
0.5 during 1.8–15.8;  
0.7 during 16.8–31.12.  
The average usage rates occur during operating times of the building (Monday-Friday, 8-17, other times no usage, including weekends and holidays) |
| An average of 1 occupant per 12 m$^2$ with activity level of 1.2 met, which equals to an average sensible specific heat gain of 7.1 W/floor-m$^2$, internal heat gain from occupants equals to 10.0 kWh/(m$^2$,a) with the described usage |
| **Lighting**, same average usage rates as with the occupants |
| An average heat gain of 10.0 W/m$^2$ (fluorescent) or 7.0 W/m$^2$ (LED) to produce 500 lx illuminance in office and equivalent spaces, internal heat gain from lighting equals to 14.9 kWh/(m$^2$,a) (fluorescent) or 10.4 kWh/(m$^2$,a) (LED) with the described usage |
| **Office appliances**, same average usage rates as with the occupants and lighting |
| An average heat gain of 15.0 W/m$^2$, internal heat gain from office appliances equals to 22.4 kWh/(m$^2$,a) with the described usage |
2.1.4 Minimum indoor environment requirements of the case building renovation

The indoor climate target after the renovation was selected according to the voluntary-based Finnish Classification of Indoor Environment (FCIE) 2008 class S2 [27]. Fig. 4 shows the room air temperature set point profile, minimum and maximum limits for the operative temperature and the maximum limit for CO₂-concentration in the occupied building for the S2 class of the FCIE [27]. The S2 class of the FCIE can be obtained with centralized cooling system. Typically cooling of the supply air by using cooling coils in the air handling units is required as the minimum measure to reach the S2 class indoor climate criteria, depending on the individual case features.

![Fig. 4. The room temperature set point profile, minimum and maximum limits for operative temperature and the maximum limit for CO₂-concentration during the occupancy time according to the Finnish Classification of Indoor Environment 2008 [27].](image)

2.1.5 Climate conditions and weather data

The Finnish weather data of climate zone I of the test reference year 2012 (TRY2012) was used in the energy simulations of the study. Hourly-specific data for different elements, e.g. temperature, solar radiation, wind speed and direction, relative humidity etc., are included in the analyzes. For a reference, the average annual temperature of climate zone I is +5.6 °C and the average annual degree day number S17 is 3 952 Kd, respectively. The weather data used in the energy simulations is described in more detail by Kalamees et al. (2012) [28].

2.1.6 Cost data of studied renovation measures

Tables 4 and 5 present the studied renovation measures and the relevant construction cost data [29-31]. The value added tax (VAT), which is currently 24% in Finland, is not included in the cost data. Majority of the studied measures improve both the energy performance and the thermal comfort of the building and also reduce the environmental impact.
of the building. A ground source heat pump system (GSHP) used for combined heating and cooling was also studied as a main energy system. In addition, the district heating system, which is the original main heating system of the studied office building was also studied and compared to the GSHP energy system.

### Table 4. Studied renovation measures in the multi-objective optimization analysis.

<table>
<thead>
<tr>
<th>District heating system (DH concept)</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area of PV-panels, m²</td>
<td>0</td>
<td>500</td>
<td>Continuous</td>
</tr>
<tr>
<td>Additional thermal insulation (mineral wool) thickness of external walls or just the basic refurbishment, mm</td>
<td>0, basic refurbishment</td>
<td>300</td>
<td>Discrete, 6 options</td>
</tr>
<tr>
<td>Additional thermal insulation (mineral wool) thickness of roof or just the basic refurbishment, mm</td>
<td>0, basic refurbishment</td>
<td>400</td>
<td>Discrete, 6 options</td>
</tr>
<tr>
<td>Replacement of windows to new windows or just the basic refurbishment of the original windows / thermal transmittance</td>
<td>Basic refurbishment of original windows / 2.1 W/(m² K)</td>
<td>Replacement to new windows / 0.6 W/(m² K) and g-value of 0.31</td>
<td>Discrete, 6 options</td>
</tr>
<tr>
<td>Integrated window shading, installation of blinds between panes</td>
<td>None</td>
<td>Blinds between the inner panes (47% reduction in the g-value of windows)</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Lighting system, type of lighting system</td>
<td>Fluorescent (10 W/m²)</td>
<td>LED (7 W/m²)</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Control type of lighting system</td>
<td>No automated control, regular control system</td>
<td>Occupancy + constant light control system</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Ventilation system, replacement of the original AHUs with high efficiency (76 %) heat recovery system</td>
<td>None</td>
<td>Renovated with efficient AHUs</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Ventilation system, installation of demand-controlled ventilation (DCV) system to office and equivalent space groups, DCV-controlled zones are approx. 150-200 m² in open layout offices (12-16 control zones per floor)</td>
<td>None</td>
<td>DCV + control system for temperature, occupancy and CO₂</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Cooling system, installation of centralized water cooling system for cooling of supply air of AHUs and room cooling units</td>
<td>None</td>
<td>Water cooling system with cool storage tank</td>
<td>Discrete, 2 options</td>
</tr>
<tr>
<td>Cooling system, installation of centralized room cooling system with ceiling cooling panels, two cooling panels (600x3000 mm) per 12 m² in open layout office spaces, requires the installation of the centralized water cooling system</td>
<td>None</td>
<td>Ceiling cooling panels with room/zone specific controls, control area circa 50-100 m² (25-50 control zones per floor)</td>
<td>Discrete, 2 options</td>
</tr>
</tbody>
</table>

**Total number of renovation combinations: 2.76 million**

<table>
<thead>
<tr>
<th>Ground source heat pump system (GSHP concept)</th>
<th>Minimum value</th>
<th>Maximum value</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensioning power output of the GSHP system, kW</td>
<td>20</td>
<td>450</td>
<td>Continuous</td>
</tr>
<tr>
<td>Other measures are the same as with the DH system concept</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

**Total number of renovation combinations: 276 million**

### Table 5. Cost data of studied refurbishment measures [29-31].

<table>
<thead>
<tr>
<th>Measure</th>
<th>Investment cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar-based electricity production system with PV-panels, €/panel-m²</td>
<td>180 (1.2 €/Wp)</td>
</tr>
<tr>
<td>Refurbishment of external walls, €/ex.wall-m²</td>
<td></td>
</tr>
<tr>
<td>- basic refurbishment, patching and painting of original walls (no insulation) (0.35 W/m²K)</td>
<td>20</td>
</tr>
<tr>
<td>- demolition of outer concrete layer and thermal insulation, new 100 mm thermal insulation layer (mineral wool insulation) and new concrete outer layer (0.33 W/m²K)</td>
<td>180</td>
</tr>
<tr>
<td>- same as previous measure, but new thermal insulation thickness is: 150 mm (0.23 W/m²K)</td>
<td>185</td>
</tr>
<tr>
<td>- 200 mm (0.18 W/m²K)</td>
<td>196</td>
</tr>
<tr>
<td>- 250 mm (0.14 W/m²K)</td>
<td>205</td>
</tr>
<tr>
<td>- 300 mm (0.12 W/m²K)</td>
<td>212</td>
</tr>
</tbody>
</table>
Refurbishment of roof, €/roof-m²
- basic refurbishment, renewal of the top layer of original roof (no insulation) 50
- thermal insulation layer (mineral wool insulation) and new roof top layer (0.29 W/m²K) 152
- demolition of top structure layers and thermal insulation, new 200 mm thermal insulation layer (mineral wool insulation) and new roof top layer (0.18 W/m²K) 158
- same as previous measure, but new thermal insulation thickness is: 250 mm (0.14 W/m²K) 163
- 300 mm (0.12 W/m²K) 171
- 350 mm (0.10 W/m²K) 178

Refurbishment of windows, €/window-m²
- patching, painting and rescaling of original windows to extend the operation time 100
- replacement of windows (includes demolition of original windows + installation of new windows), new windows: thermal transmittance 1.0 W/m²K and g-value 0.50 292
- same as previous measures, but new windows are: thermal transmittance 1.0 W/m²K and g-value 0.41 304
- thermal transmittance 0.84 W/m²K and g-value 0.39 317
- thermal transmittance 0.69 W/m²K and g-value 0.30 327

Installation of blinds between the inner panes of windows, €/window-m² 50

Refurbishment of lighting system, installation of new lighting system, €/floor-m²
- modern fluorescent lighting system (10 W/m² to produce 500 lx illuminance) 21
- modern LED-based lighting system (7 W/m² to produce 500 lx illuminance) 29

Installation of occupancy + constant light control system, €/floor-m² 4

Refurbishment of the ventilation system, €/floor-m²
- replacement of the original AHUs with high efficiency (77 %) heat recovery system 30
- installation of demand-controlled ventilation (DCV) system to office and equivalent spaces, including required ventilation duct modifications and new installations 33

Cooling system of the building, €/floor-m²
- installation of new centralized water cooling system for cooling of supply air of AHUs and room cooling units (ceiling cooling panels) 14
- installation of centralized room cooling system with cooling panels, piping and zone-specific control system, requires also the investment in the centralized water cooling system described above, if no GSHP system used for combined heating and cooling is installed 116

Ground source heat pump system, total installation cost of the system, €/kW 1 200 + 15 000 €

Demolition and renewal of the original district heating system substation, € 30 000 (2.2 €/floor-m²)

The relevant annual maintenance and renewal costs regarding different measures and technical systems have also been taken into account in the study as shown in Table 6. Other measures and technical systems are assumed to be used without major maintenance or renewal costs for 15 years, which was the discount period of the economic calculations. In addition, the potential residual value of different measures after 15 years was excluded from the economic calculations of the study due to its relatively low impact on the outcome of the life-cycle cost analysis [29-32].

Table 6. Maintenance and renewal costs of different measures and technical systems (the 24 % VAT excluded) [29-32].

<table>
<thead>
<tr>
<th>Renovation measure</th>
<th>Annual maintenance cost</th>
<th>Renewal cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>District heating system</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>GSHP system</td>
<td>0.6% from the investment cost</td>
<td>None</td>
</tr>
<tr>
<td>Solar electricity system (PV-panels)</td>
<td>2.0% from the investment cost</td>
<td>None</td>
</tr>
<tr>
<td>Renewal of basic refurbishment (patching and painting) of external walls</td>
<td>None</td>
<td>20 €/ex.wall-m², after 8 years</td>
</tr>
<tr>
<td>Replacement of all fluorescent tubes after approximately 20 000 hours of operation</td>
<td>None</td>
<td>2 €/floor-m², after 8 years (only the tubes must be replaced)</td>
</tr>
</tbody>
</table>
2.2. Assessment of productivity loss caused by unfavorable thermal comfort conditions

2.2.1 The effect of perceived thermal conditions on productivity loss

Several studies have developed models to predict the productivity loss of workers and the possible economic impacts of unfavorable or poor indoor climate and thermal conditions [14,15,22,23]. It is essential to notice that the productivity loss and the optimal indoor thermal conditions are highly connected to the perceived thermal comfort conditions and they are typically predicted using the whole thermal sensation indices such as the Predicted Mean Vote (PMV) and the Predicted Percentage of Dissatisfied (PPD) [33], which represent the average thermal sensation of a person in specific indoor thermal conditions. Furthermore, the same level of thermal comfort and productivity can be obtained from many different combinations of clothing and indoor thermal conditions [14,15,22,23]. Typically there are always at least 5 % dissatisfaction to indoor climate conditions among building users, regardless of the actual indoor climate conditions of the building [14,15,22,23]. The PPD index is calculated by Eq. (1)

\[
PPD = 100 - 95e^{-\left[0.03353PMV + 0.2179PMV^2\right]}
\]

(1)

where: PPD is the predicted percentage of dissatisfied; PMV is the predicted mean vote [33]. The PMV index is calculated according to the Fanger’s thermal comfort model and it is affected by factors such as clothing (clo-index) and metabolic rate (MET-index) of occupants, air temperature, mean radiant temperature, air velocity and relative humidity (RH) of air [33].

In addition, perceived air quality, pollution loads, ventilation efficiency, lighting conditions and acoustics privacy affect the productivity and the potential productivity loss of occupants in office buildings [14,15].

2.2.2 Calculation of productivity loss

Due to the fact that a similar PMV index and thus similar productivity loss can be achieved by many different combinations of thermal comfort factors, some simplifications and assumptions have to be made in indoor climate condition and productivity loss analyzes [14,15]. The basic assumptions regarding the thermal comfort factors used in the study are as follows:

- air velocity in the occupied zone is 0.15 m/s;
- the room air is fully mixed;
- metabolic rate of occupants is 1.2 MET (represents average office work);
• clothing of occupants is 0.85 ± 0.25 clo, clothing of occupants is automatically adapted between the following limits to obtain comfort:
  o PMV-index -1: occupants wear maximum clothing (1.10)
  o PMV-index +1: occupants wear minimum clothing (0.60)
  • typically the preferable PMV index range for thermal comfort according to the ASHRAE Standard 55-2013 is recommended to be between -0.5–0.5 for an indoor space [34]. However, the higher PMV-index levels used in the automatic adaptation of clothing are used to represent the fact that in reality the occupants will not immediately change dress;
• the radiant temperatures of different spaces, room air temperatures and relative humidity of indoor air throughout the year are calculated in the hourly-based dynamic energy simulation.

Furthermore, Wyon [18] has determined that the productivity loss according to the PMV index is different for thinking and typing related tasks, estimating that the productivity loss is higher in typing related tasks, when the PMV index increases from its optimal value of -0.21. For this reason, Wyon [35] has developed a simplified method to estimate the overall productivity loss from workers resulting from too high or too low operative temperatures (over or under heating) in the occupied zone of a room. In this simplified model, productivity is not lost on average for operative temperatures between 20 and 25 °C, when it is assumed that occupants can affect the indoor thermal comfort sensation by adding or removing clothing to adapt to the thermal conditions according to the perceived thermal comfort. When the operative temperature is below 20 °C or above 25 °C, the overall productivity loss is assumed to be 2%/°C, e.g. 8 % at an average operative temperature of 29 °C and 10 % at an average operative temperature of 30 °C [35]. The relative reduction in performance of building users according to the indoor temperature in office buildings has been presented in a meta-analysis conducted by Seppänen et al. (2006), resulting in similar conclusions [5].

The simplified model derived by Wyon [35] was selected to determine the productivity loss caused by unfavorable indoor thermal comfort conditions. Furthermore, the productivity loss was assessed according to the thermal comfort conditions of the building, as the effect of factors such as lighting conditions and ventilation efficiency on the productivity loss were assumed to be constant and thus relatively low, when productivity loss caused by these factors is discussed [14,15,22,23].

2.2.3 Economic impact of lost work

The economic impact of the productivity loss was calculated by using average salary data of government office workers to form an entirety, where the monetary impact of the productivity loss can be combined with the life-cycle cost
(LCC) analysis of deep renovation of the case office building. In addition to the direct salary of workers, the side costs such as the social security costs and other indirectly related salary expenses were also taken into account in the calculations. However, the potential overhead factors related to the salaries of employees of commercial companies were not taken into account in the analysis.

The average monthly direct salary of a Finnish government official is 3,550 €/month (in 2014), which is approximately 23.3 €/h with an average of 152.5 working-h/month [36-38]. The side costs of government official salaries are approximately 61-62% in Finland (in 2012–2015) [38]. This means that the total salary expenses for the employer are approximately:

- 23.3 €/h x 1.62 = 38 €/h [36-38].

The hourly-based cost of 38 €/h was used as the value of the lost work due to unfavorable indoor thermal comfort conditions in the LCC analysis.

2.2.4 Additional analyzes to maximize indoor thermal conditions and productivity of building users

Additional analyzes were conducted to determine the cost-optimal measures to maximize the productivity of occupants. The main purpose of the additional analyzes was to determine the global optimum measures to maximize the productivity of building users and to compare the measures with the results of the principal analyzes, where the main objective was to determine the global cost optimum overall solutions. The additional analyzes were conducted due to the fact that the optimum measures to maximize the productivity are not necessarily the same as the measures to deliver the cost optimum overall solutions. Results and developed models of previous studies were used to predict the productivity loss caused by different thermal factors [14,15]. The limitations caused by the technical space requirements (suspended ceilings and vertical ventilation shafts) were also taken into account and it was determined that increasing the airflow rate of the original ventilation system over 3.0 dm$^3$/h(m$^2$) was not possible, which typically is the case in the renovation of majority of existing office buildings. This limitation of the airflow rate of the ventilation system was selected as a constraint parameter in the additional analyzes carried out to maximize the indoor thermal conditions.

The total hours of people dissatisfied (PDH) was selected as an indicator to represent the quality of the indoor thermal conditions in the additional analyzes. The total PDH (dissatisfied hours/occupant per year) is a sum of all the annual individual PPD calculation results (e.g. 9 individual PPD calculation locations including 25 occupants in each location in Fig. 3) of all occupied room spaces during the operating time of the building. As the total PDH index of the building includes all individual PPD calculation results of occupied zones, it can be reliably used as an accurate average index to compare overall indoor thermal comfort between different design and renovation alternatives. The PDH index will al-
ways be at least 5% of the total occupant hours of the building (see Eq. (1)), regardless of the actual conditions [14,15].

The distribution of occupant groups in an office floor that was used to determine the average annual PMV- and PPD-indices for the studied case building was shown in Fig. 3. Each occupant group location shown in Fig. 3 consists of 25 sitting occupants, which equals to the overall occupant density and specific internal heat gain shown in Table 3.

2.3. Energy efficiency and environmental impact calculations

2.3.1 Calculation of delivered energy consumption

The actual delivered total energy consumption of different energy carriers was used in the energy simulations of the study. The delivered target energy consumption represents the actual use of the building better than the calculation of the primary energy consumption, which is nevertheless used to determine the energy performance ratings of the energy performance certificates (EPCs) and the requirements of the nearly zero-energy buildings (nZEBs). The individual specifications and preferences, e.g. the effect of holidays on the occupancy of the building users, of the building can be more accurately taken into account in the calculation of the delivered target energy consumption.

The room air temperature set point for heating was 21.0 °C and the set point for cooling was 24.5 °C in the analysis. The set points were selected according to the estimated actual use of the building after the renovation to represent typical indoor climate temperature set points used in modern office buildings to provide high-quality thermal comfort conditions. The selected set points also meet the minimum thermal comfort criteria of the deep renovation shown in Fig. 4.

2.3.2 Assessment of environmental impact

As a major energy efficiency improving and environmental impact reduction potential is included in deep renovations of existing buildings compared to new construction, an assessment of environmental impact reduction potential was included in the study. The environmental impact was assessed according to the CO₂ emissions of the case building and appropriate simplifications and assumptions were applied in the analysis. The CO₂ emissions caused by the delivered energy consumption of the building were determined to be dominant over the CO₂ emissions of construction materials and the transportation of the materials to the construction site, forming over 80% of the overall CO₂ emissions. For this reason the system boundary of the study was selected so that the environmental impact analysis was focused on studying the renovation measures that cost-effectively reduce the delivered energy consumption of the case building, as it was determined to be the most important aspect to significantly reduce the overall environmental impact and carbon footprint of the studied building stock towards low-carbon office buildings.
The CO₂ emission factors of different energy carriers were selected according to the average Finnish emission factors as follows [39]:

- 183 kgCO₂/MWh for district heating (3-year average value, combined heat and power production);
- 209 kgCO₂/MWh for electricity (5-year average value).

### 2.4. Multi-objective optimization analysis

#### 2.4.1 Optimization method

The multi-objective optimization analysis was performed by using the MOBO (Multi-Objective Building Optimization, version 0.3b) optimization tool, which has been developed by Aalto University and VTT Technical Research Centre of Finland from 2010 onwards [40]. MOBO includes a total of 7 different optimization algorithms that can be used in building performance analyzes, depending on the specifications of the analysis. The Pareto-Archive NSGA-II genetic algorithm was used in the multi-objective optimization analysis of the study. The Pareto-Archive NSGA-II algorithm is an advanced and further developed version of the regular NSGA-II genetic algorithm and it has been specifically developed to solve multi-dimensional optimization tasks. MOBO is benchmarked to different kinds of building performance optimization problems and its performance has been tested with good success in previous studies related to building performance optimization analyzes [40,41]. Despite being a new optimization tool, MOBO has already established a position as a popular optimization engine used in the multi-objective building performance optimization analyzes [41]. A more detailed description and the operation principle of the simulation-based multi-objective optimization analysis is presented in several recent studies [40-43].

#### 2.4.2 Simulation method

The energy simulations of the multi-objective optimization analyzes were performed by using the IDA Indoor Climate and Energy (IDA ICE, version 4.7) dynamic simulation tool. IDA ICE software has been validated (including tests against measurements) in multiple previous studies as a reliable, accurate and versatile dynamic simulation tool to be used in building performance simulations [44-50]. In addition to fully dynamic energy simulations, IDA ICE can be used to perform various indoor climate and thermal comfort simulations. The performance of the studied renewable energy production systems was assessed by using the Early Stage Building Optimization (ESBO) Plant model of IDA ICE. The ESBO Plant model makes it possible to model and simulate the renewable energy production systems as a part of dynamic energy simulation of buildings.
The GSHP model used in the study was calibrated by using a detailed calibration method described in a recent study conducted by Niemelä et al. (2016) [51]. The average coefficient of performance (COP) of the calibrated simulation model at 8 different rating conditions (e.g. 0/45 °C) was approximately 1.2% lower than the average COP of the corresponding real GSHP system. The combined heating and cooling operation of the GSHP system can also be modelled in detail using the ESBO Plant model.

2.5. Principles of life-cycle cost analysis and economic calculations

The net present value (NPV) of the life-cycle cost (LCC) model was used to determine the cost-optimality of studied renovation measures. The life-cycle period selected in the LCC analysis was 15 years, which is a typical duration of the lease in government and municipal office properties in Finland and also commonly used in life-cycle cost analyzes of non-residential buildings [32,42,43]. The mandatory maintenance repairs that must be carried out to use the building appropriately were also taken into account in the life-cycle cost analysis (see Tables 4 and 5) along with the renovation measures that improve the energy performance of the case building at the same time. Furthermore, the internal rate of return method (return on investment, internal interest rate) was also studied to determine the measures truly delivering the best return on the investments, in addition to delivering low life-cycle costs. The net present value of LCC over the 15-year life-cycle period was calculated by Eq. (2).

\[
NPV_{LCC,15a} = \sum I_{0,\text{total}} + \sum MR_a \frac{1-(1+r)^{-n}}{r} + \sum RM_a \frac{1}{(1+r)^k} + \sum E_a \frac{1-(1+re)^{-n}}{re} + \sum t_{\text{lost}} V_a \frac{1-(1+rw)^{-n}}{rw}
\]

(2)

where: \(NPV_{LCC,15a}\) is the net present value of the LCC over a 15-year time period, €; \(\sum I_{0,\text{total}}\) is the overall investment cost of the renovation measures (see Table 5), €; \(\sum MR_a\) is the overall annual repair and maintenance cost of the measures, €/a; \(\sum RM_a\) is the overall renewal cost related to the measures, €; \(\sum E_a\) is the overall annual energy cost of the case building, €/a; \(r\) is the real interest rate selected in the LCC analysis; \(re\) is the escalated real interest rate selected in the LCC analysis, including an estimated energy price escalation rate in the future; \(n\) is the selected life-cycle period (15 a); \(k\) is the time step (year) from the start of the life-cycle period, when a specific renewal measure is conducted; \(\sum t_{\text{lost}}\) is the sum of annual lost working hours due to productivity loss caused by unfavorable indoor climate conditions, h/a; \(V_a\) is the total value of the work, €/h; \(rw\) is the estimated average annual increase in the total value of the work in the future.

The internal rate of return (IRR) received from the renovation measure investments was calculated by Eq. (3)

\[
i = \frac{1-(1+i)^{-n}}{lnA}
\]

(3)
where: $i$ is the internal rate of return achieved by the renovation investments, %/a; $A$ is the difference of overall profits and costs compared to a specific reference solution, €/a; $I_0$ is the additional investment cost of the renovation measures compared to a specific reference solution, €.

The energy prices and other main parameters used in the life-cycle cost analysis are presented in Table 7. Additional sensitivity analyzes with different LCC parameters were also conducted to determine the impact of the parameters on the outcome of the LCC analysis.

Table 7. The energy prices and main parameters of the life-cycle cost analysis [36-38,52,53].

<table>
<thead>
<tr>
<th>Energy prices (the 24% VAT excluded)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical energy</td>
<td>90 €/MWh</td>
</tr>
<tr>
<td>District heating energy, priced according to the season of the year in Lahti</td>
<td></td>
</tr>
<tr>
<td>- 1.11–31.3 (winter season)</td>
<td>58.4 €/MWh</td>
</tr>
<tr>
<td>- 1.4–31.5 (spring season)</td>
<td>50.9 €/MWh</td>
</tr>
<tr>
<td>- 1.6–31.8 (summer season)</td>
<td>28.6 €/MWh</td>
</tr>
<tr>
<td>- 1.9–31.10 (autumn season)</td>
<td>50.9 €/MWh</td>
</tr>
<tr>
<td>District heating capacity fee, determined according to the maximum annual heating power demand of the building</td>
<td></td>
</tr>
<tr>
<td>- In the initial condition, before the deep renovation</td>
<td>22 600 €/a</td>
</tr>
<tr>
<td>- After the deep renovation</td>
<td>Capacity fee reduced according to the reduction in the maximum heating power demand of the building, €/a</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters of the life-cycle cost analysis</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Real interest rate</td>
<td>4.0%</td>
</tr>
<tr>
<td>Energy price escalation rate</td>
<td>+2.0 %/a for electricity and district heating</td>
</tr>
<tr>
<td>Average annual increase in the total value of the work</td>
<td>+2.0 %/a</td>
</tr>
</tbody>
</table>

3. Results

The results of the study consist of 5 individual simulation-based multi-objective optimization analyzes shown in Table 8. Table 8 also shows the studied building type and the optimized objectives of each analysis. The extended LCC shown in Table 8 is an LCC analysis, where the productivity loss of workers caused by unfavorable indoor thermal comfort conditions was taken into account and merged into the conventional LCC analysis related to the renovation and retrofitting measures. The recommended and cost-effective renovation solutions to reach different environmental impact criteria are also presented for both the owner and tenant occupied office buildings.

Table 8. Studied simulation-based multi-objective optimization analyzes (DE = delivered energy, PDH = occupant hours of dissatisfaction).

<table>
<thead>
<tr>
<th>Optimization analysis</th>
<th>Type of building</th>
<th>Minimized objectives and type of LCC calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: CO$_2$ emissions of DE consumption, DH concept</td>
<td>Owner occupied</td>
<td>CO$_2$ emissions of DE consumption, net present value of 15-year LCC (extended), investment cost</td>
</tr>
<tr>
<td>2: CO$_2$ emissions of DE consumption, GSHP concept</td>
<td>Owner occupied</td>
<td>CO$_2$ emissions of DE consumption, net present value of 15-year LCC (extended), investment cost</td>
</tr>
<tr>
<td>3 CO$_2$ emissions of DE consumption, DH concept</td>
<td>Tenant occupied</td>
<td>CO$_2$ emissions of DE consumption, net present value of 15-year LCC (conventional)</td>
</tr>
<tr>
<td>4: CO$_2$ emissions of DE consumption, GSHP concept</td>
<td>Tenant occupied</td>
<td>CO$_2$ emissions of DE consumption, net present value of 15-year LCC (conventional)</td>
</tr>
<tr>
<td>5: Thermal comfort conditions, conventional airflow rate potential</td>
<td>-</td>
<td>Total PDH, investment cost, CO$_2$ emissions of DE consumption (no LCC calculation)</td>
</tr>
</tbody>
</table>
Cases 1-2 shown in Table 8 were conducted to determine the cost-optimal renovation solutions for building owners. In this owner occupied scenario, the building owner typically gets all the benefits from the improved indoor climate conditions and reduced productivity loss. Cases 3-4 shown in Table 8 were conducted to determine the cost-optimal solutions for building owners who are not responsible for the salaries of the building users, but who are responsible for the operating costs of the building. In this tenant occupied scenario, the building owner typically doesn’t get major benefits from the improved indoor climate conditions, except by increasing the rent of the building. However, typically it is difficult to justify a sudden substantial increase in rent to tenants, even if major renovation measures are conducted to improve the indoor climate conditions.

Case 5 shown in Table 8 was conducted to determine the cost-effective solutions to maximize the thermal comfort conditions of occupants. All essential factors affecting productivity were taken into account and the total occupant hours of dissatisfaction (PDH) were used to assess the thermal comfort conditions. However, to give a more realistic view on the measures that are also able to be practically conducted, appropriate constraints, such as maximum ventilation airflow rates that can be used in the studied building, were used in case 5.

3.1. Cost-optimal renovation solutions for owner occupied buildings

Figs. 5-6 present the cost-optimal solutions for owner occupied office buildings. Three different but equally valuable objectives were minimized in the analyzes (see Figs. 5 and 6) to determine cost-effective solutions for decision making of building owners. These aspects include e.g. initial investment cost and thermal conditions or LCC, low operating costs, high environmental impact reduction potential and thermal conditions, respectively. Fig. 6 highlights the concept of Pareto-optimality and the Pareto-optimal solutions of a three-dimensional optimization problem including three individual optimized objectives, which are conflicting each other. The optimized objectives in the analysis were:

- the net present value of LCC over the 15-year discount period (minimized objective 1);
- the CO₂ emissions of the delivered energy consumption (minimized objective 2);
- the overall investment cost of the renovation measures (minimized objective 3).

The main objective of the analysis was to determine the cost-optimal renovation solutions from the building owner’s or employer’s point of view, where the target is typically to provide excellent thermal conditions, but still low operating costs, with as cost-efficient measures as possible to minimize the productivity loss and to maximize the energy performance.
Only the Pareto-optimal solutions of each optimization analysis are shown in Figs. 5 and 6, as over 2 500 individual energy simulations were performed to determine the Pareto-optimal solutions. To further clarify the analysis, certain main conclusions and logic of the solutions to meet the three optimized objectives are highlighted to make the interpretation of the results easier. The selected reference solution shown in Figs. 5-6 consists of only the mandatory minimum renovation measures that must be conducted to prevent decay and to decrease the renovation debt of the building. The reference solution consists of:

- basic refurbishment of external walls with no additional thermal insulation installed, the renewal of the measure after 8 years is also included;
- basic refurbishment of roof with no additional thermal insulation installed;
- basic refurbishment of windows, no blinds installed;
- renewal of the original district heating substation, no GSHP system installed;
- the original lighting system is renovated to correspond to the modern lighting requirements, fluorescent-based lighting system with basic switch-based control system, no automatic control system is installed, the renewal of the fluorescent tubes after 8 years of operation is also included;
- no renewable energy sources are installed.

![Fig. 5](image)

**Fig. 5.** Cost-optimal renovation solutions in owner occupied office buildings, minimized objectives net present value of LCC and CO₂ emissions shown.
Fig. 6. Cost-optimal renovation solutions in owner occupied office buildings, all minimized objectives (net present value of LCC, CO₂ emissions and investment cost) shown.

Table 9 presents the recommended renovation concepts for owner occupied office buildings to reach different environmental performance criteria. The recommended renovation concepts are selected from the Pareto-optimal solutions shown in Figs. 5 and 6.

Table 9. Recommended renovation measures in owner occupied office buildings.

<table>
<thead>
<tr>
<th>CO₂ emissions [kgCO₂/m², a]</th>
<th>7.5</th>
<th>9</th>
<th>10</th>
<th>12.5</th>
<th>15</th>
<th>GOS²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net present value of extended LCC, 15 years [€/m²]</td>
<td>341</td>
<td>305</td>
<td>244</td>
<td>218</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td>Investment cost of studied measures [€/m²]</td>
<td>291</td>
<td>250</td>
<td>175</td>
<td>140</td>
<td>108</td>
<td></td>
</tr>
<tr>
<td>Internal interest rate of the renovation measure package [%/a]</td>
<td>13.8</td>
<td>17.6</td>
<td>29.6</td>
<td>41.7</td>
<td>64.7</td>
<td></td>
</tr>
<tr>
<td>Additional thermal insulation of external walls or BR² [mm]</td>
<td>+300</td>
<td>+100</td>
<td>0, BR</td>
<td>0, BR</td>
<td>0, BR</td>
<td></td>
</tr>
<tr>
<td>Additional thermal insulation of roof or BR¹ [mm]</td>
<td>+400</td>
<td>0, BR</td>
<td>0, BR</td>
<td>0, BR</td>
<td>0, BR</td>
<td></td>
</tr>
<tr>
<td>Replacement of windows or BR¹, thermal transmittance and g-value of windows [W/m² K]</td>
<td>Yes, 0.60, g-value 0.31</td>
<td>Yes, 0.60, g-value 0.31</td>
<td>Yes, 1.0, g-value 0.50</td>
<td>Yes, 1.0, g-value 0.50</td>
<td>No, BR</td>
<td></td>
</tr>
<tr>
<td>Installation of blinds between the inner panes of windows</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Area of PV-panels [m²]</td>
<td>484</td>
<td>486</td>
<td>401</td>
<td>500</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Installation and power output of the GSHP system [kW]</td>
<td>Yes, 430</td>
<td>Yes, 339</td>
<td>Yes, 131</td>
<td>Yes, 181</td>
<td>Yes, 161</td>
<td></td>
</tr>
<tr>
<td>Renovation of air handling units</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>Renovation of ventilation system to DCV³-based system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>Type of renovated lighting system</td>
<td>LED</td>
<td>LED</td>
<td>LED</td>
<td>Fluorescent</td>
<td>Fluorescent</td>
<td></td>
</tr>
<tr>
<td>Installation of occupancy + constant light control system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>
The global optimum solution is achieved by investing in a GSHP system with a relatively small dimensioning power output and by also investing in measures improving the thermal comfort conditions of the building. The original district heating system is remained as the main heating system of the building, but the GSHP system with optimum power output is installed to cover the cooling demand of the building and also to cover a significant amount of the annual heating demand at the same time. To compare the selected reference and global optimum overall solutions and to highlight the extended life-cycle cost factors (the refurbishment of the building and the productivity of workers) of the solutions, Fig. 7 presents the breakdown of LCC of the reference solution, where only the minimum measures are conducted, and the breakdown of LCC of the recommended global optimum overall solution.

As it is demonstrated in Fig. 7, the cost impact of productivity loss is the most significant factor in the extended LCC analysis of owner occupied office buildings, where the productivity loss is combined with the traditional LCC analysis, which is typically limited to study the economic viability of different energy efficiency improving measures. According to the selected productivity loss assessment methodology, productivity loss of occupants is not occurring when the operative temperatures of office spaces are maintained between 20-25 °C. However, it is essential to notice that if the upper temperature limit of the model was reduced from 25 °C to e.g. 24 °C, the overall content of the global optimum renovation concept would likely be a little different.

<table>
<thead>
<tr>
<th>Installation of centralized water cooling system</th>
<th>No</th>
<th>No</th>
<th>No</th>
<th>No</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation of centralized room cooling system with ceiling cooling panels</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>The total annual amount of lost work due to productivity loss from 1 472 000 working hours of all occupants [h/a]</td>
<td>1</td>
<td>1</td>
<td>173</td>
<td>67</td>
<td>214</td>
</tr>
</tbody>
</table>

1 Basic Refurbishment
2 Global Optimum Solution
3 Demand-Controlled Ventilation

Fig. 7. The breakdown of extended LCC analysis for the selected reference solution (left, 591 €/m²) and the global optimum solution (right, 205 €/m²).
3.2. Cost-optimal renovation solutions for tenant occupied buildings

Fig. 8 presents the cost-optimal solutions for tenant occupied office buildings. The minimized objective functions in the analysis were the net present value of the 15-year LCC and the CO\textsubscript{2} emissions of the delivered energy consumption of the case building. The extended LCC analysis method, where the cost impact of productivity loss is included in the overall LCC analysis, was not included in the tenant occupied building type analyzes. The net present value of the 15-year LCC was calculated according to Eq. (2), but excluding the value of the work factor used in the equation. The main objective of the analysis was to determine the cost-optimal renovation solutions from the lessor’s point of view, where the target is typically to provide sufficient and acceptable indoor thermal comfort conditions, but not necessarily to guarantee high performance of occupants.

The global optimum solution includes a GSHP system with a relatively small dimensioning power output, energy efficient air handling units and lighting with efficient control system and also a moderate area of PV-panels. As in the owner occupied building analysis, only the Pareto-optimal solutions of the optimization analyzes are shown in Fig. 8. Over 1 500 individual energy simulations were performed to determine the Pareto-optimal solutions. The selected reference solution shown in Fig. 8 includes the same renovation and retrofitting measures as the reference solution described in section 3.1.

![Graph showing cost-optimal renovation solutions in tenant occupied office buildings](image-url)
Table 10 presents the recommended renovation concepts for tenant occupied office buildings to reach different environmental performance criteria. The recommended renovation concepts are selected from the Pareto-optimal solutions shown in Fig. 8.

<table>
<thead>
<tr>
<th>Table 10. Recommended renovation measures in tenant occupied office buildings.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 emissions [kgCO2/m2.a]</td>
</tr>
<tr>
<td>Net present value of LCC, 15 years [€/m2]</td>
</tr>
<tr>
<td>Investment cost of studied measures [€/m2]</td>
</tr>
<tr>
<td>Internal interest rate of the renovation measure package [%/a]</td>
</tr>
<tr>
<td>Additional thermal insulation of external walls or BR1 [mm]</td>
</tr>
<tr>
<td>Additional thermal insulation of roof or BR1 [mm]</td>
</tr>
<tr>
<td>Replacement of windows or BR1, thermal transmittance and g-value of windows [W/m2 K]</td>
</tr>
<tr>
<td>Installation of blinds between the inner panes of windows</td>
</tr>
<tr>
<td>Area of PV-panels [m2]</td>
</tr>
<tr>
<td>Installation and power output of the GSHP system [kW]</td>
</tr>
<tr>
<td>Renovation of air handling units</td>
</tr>
<tr>
<td>Renovation of ventilation system to DCV3-based system</td>
</tr>
<tr>
<td>Type of renovated lighting system</td>
</tr>
<tr>
<td>Installation of occupancy + constant light control system</td>
</tr>
<tr>
<td>Installation of centralized water cooling system</td>
</tr>
<tr>
<td>Installation of centralized room cooling system with ceiling cooling panels</td>
</tr>
</tbody>
</table>

1 Basic Refurbishment
2 Global Optimum Solution
3 Demand-Controlled Ventilation

To compare the selected reference and global optimum overall solutions and to highlight the different life-cycle cost factors of the solutions, Fig. 9 presents the breakdown of LCC of the reference solution, where only the minimum measures are conducted, and the breakdown of LCC of the recommended global optimum overall solution.

![The breakdown of LCC analysis for the selected reference solution (left, 256 €/m²) and the global optimum solution (right, 192 €/m²).](image-url)
When comparing Fig. 9 to Fig. 7 it can be seen that the breakdown of the traditional LCC analysis is significantly different than the breakdown of the extended LCC analysis, where the cost impact of productivity loss is also taken into account. Furthermore, the return on investments are also significantly lower in the traditional LCC analysis, when compared to the return on investments of the extended LCC analysis including the cost impact of productivity loss.

3.3. Cost-effective solutions to maximize productivity of occupants

The total occupant hours of dissatisfaction (total PDH, see section 2.2.4) with the appropriate simplifications and constraints described in section 2.2 were used to determine the optimal measures to maximize the productivity of the building users. The additional analysis conducted to maximize the productivity consists of the following scenario:

- multi-objective optimization scenario, where realistic airflow rates of the case building were used. A realistic increase, when investment cost and practicality are discussed, in the airflow rate of the case building is 1.0 dm³/(s,m²) from the initial airflow rate of 2.0 dm³/(s,m²) to 3.0 dm³/(s,m²). The scenario includes a total of three individual optimized objectives as follows:
  - the total occupant hours of dissatisfaction (minimized objective 1);
  - the overall investment cost of the renovation measures (minimized objective 2);
  - the CO₂ emissions of the delivered energy consumption (minimized objective 3).

The main results of the analysis are shown in Figs. 10-11 and Table 11, which present the optimal renovation solutions and HVAC system set points. Fig. 11 is shown to highlight the concept of Pareto-optimality in a multi-dimensional optimization problem. The optimal room temperature set points for heating and cooling to maximize the indoor thermal conditions of occupants are also presented in Table 11.
Fig. 10. Optimal renovation solutions and HVAC system set points to maximize the indoor thermal conditions and to minimize both the investment cost and the CO₂ emissions of energy consumption in office buildings, minimized objectives total occupant hours of dissatisfaction and investment cost shown.

Fig. 11. Optimal renovation solutions and HVAC system set points to maximize the indoor thermal conditions and to minimize both the investment cost and the CO₂ emissions of energy consumption in office buildings with all optimized objectives (CO₂ emissions, investment cost and total occupant hours of dissatisfaction presented as average annual PPD-index) shown.
Table 11. Recommended renovation measures and HVAC system set points to maximize the indoor thermal conditions and to minimize both the investment cost and the CO₂ emissions of energy consumption in office buildings with typical (2-3 dm³/(s,m²)) airflow rates.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Set Point</th>
<th>Cost Impact</th>
<th>Productivity Loss</th>
<th>CO₂ Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional thermal insulation of external walls or BR² [mm]</td>
<td>0, BR</td>
<td>Yes, 0.69, 0.30</td>
<td>1.0, 0.75</td>
<td>160, 140</td>
</tr>
<tr>
<td>Additional thermal insulation of roof or BR² [mm]</td>
<td>0, BR</td>
<td>Yes, 0.69, 0.30</td>
<td>1.0, 0.75</td>
<td>160, 140</td>
</tr>
<tr>
<td>Replacement of windows or BR², thermal transmittance and g-value of windows [W/m² K]</td>
<td>No, BR</td>
<td>Yes, 0.69, 0.30</td>
<td>1.0, 0.75</td>
<td>160, 140</td>
</tr>
</tbody>
</table>

According to the definition of Pareto-optimality, all of the solutions shown in Figs. 10 and 11 are non-dominated solutions and mathematically equally valuable. They all meet the optimized objectives equally well, depending on the objectives and perspectives (weighting of the optimized objectives) of the analysis. To clarify the analysis, certain main conclusions and logic of the solutions to meet the three optimized objectives are highlighted to make the interpretation of the results easier. The reference solution presented in Figs. 10 and 11 includes the same renovation and retrofitting measures as the reference solution described in section 3.1.

4. Discussion

By using the extended life-cycle cost calculation method, where the cost impact of productivity loss is integrated into the traditional life-cycle cost calculation, in the owner occupied building type analysis, the results clearly indicate that the reduction in performance of workers due to unfavorable indoor thermal conditions has the highest individual economic impact on the total LCC. The cost impact of productivity loss accounts for up to 60-70% of the extended LCC over a life-cycle period of 15 years in the presented reference solution, where only the mandatory minimum renovation measures are conducted. By using a longer life-cycle period than 15 years, the proportion of the productivity loss is even higher.
Therefore, it is profitable and highly recommended for building owners to improve the thermal comfort conditions in deep renovations of existing owner occupied office buildings. According to the results of the optimization analyzes, investments in refurbishment measures deliver close to 65% return on investment in owner occupied office buildings, where the cost impact of productivity loss is taken into account in the analysis. The overall investment cost of the renovation measures was approximately 110 €/m² at the cost optimum level.

According to the results of the tenant occupied office building analysis, the maximum return on investment achieved by the investments in the cost-optimal renovation concepts was approximately 15-17%, when compared to the over 60% return on investment of the owner occupied building scenario. The differences in the results of the two analyzes demonstrate that it is extremely profitable and highly recommended to invest in renovation measures that also improve the indoor thermal comfort conditions in addition to improving the energy performance. The best return on investment in the tenant occupied building scenario was achieved by investing approximately 100 €/m².

In tenant occupied buildings, the improved thermal comfort conditions and increased productivity must be taken into account by increasing the rent according to the potential financial benefits achieved by the building users due to improved performance of workers, to make the higher investment economically viable to the building owner. In many cases it can be difficult to justify the larger investment to tenants and building owners as the concept of productivity loss due to thermal comfort conditions is somewhat difficult to understand by other people than the technical personnel working in the building sector.

According to the results, the reference low-carbon criteria could be achieved with a 5% return on investment in tenant occupied office buildings and with up to 30% return on investment in owner occupied buildings. However, it is important to notice that the composition of delivered energy carriers plays a significant role in the analysis. If renewable electrical energy is purchased from the electricity grid, the operation emissions (CO₂e) can be significantly reduced. Furthermore, if the district heating energy is produced by using renewable energy sources, this also affects the CO₂e emissions significantly. Due to the aforementioned aspects, average Finnish CO₂ emission factors of different energy carriers were used in the study to represent a realistic scenario of the building stock.

The effect of summer vacation on the occupancy and internal heat gain profiles was also taken into account in the analysis. Additional optimization analysis was conducted for the owner occupied building scenario, where the average occupancy and internal heat gain profile of office spaces was 65% during the entire summer time. According to the results of the additional analysis, the occupancy and internal heat gain profile of summer time has a significant impact on the results of the analysis. However, even in this higher occupancy profile scenario, the room space-specific cooling system with ceiling cooling panels was not included in the cost-optimal overall solutions. In the higher occupancy profile
scenario, approximately 150 €/m² investments are required (approx. 110 €/m², when the summer vacations were taken into account, see Table 9) to reach the cost-optimal overall solutions. However, according to the previous studies that have analyzed the occupancy profiles, the actual occupancy rate during summer time could be as low as 10-35%. Thus, the 65% occupancy rate used in the additional sensitivity analysis was definitely overestimated.

When the productivity loss is taken into account in the extended LCC analysis, the global optimum overall concept is not achieved by investing substantially in the more expensive measures that improve the thermal comfort conditions further, e.g. investment in the room space-specific cooling system. The main reason for this is that the basic investment in the centralized air-conditioning system (cooling of the supply air of the ventilation system) already guarantees good thermal conditions, when the specific cooling load in the office spaces is low.

According to the results, the recommended and best alternative is to invest in a GSHP system, which can be used for combined heating and cooling, and to cool the supply air of the ventilation system. In addition, the GSHP system can be used to cover a significant amount of heat energy demand even with a relatively conservative power output dimensioning. Furthermore, measures such as improved windows with low g-value and integrated window shading, which significantly reduce the solar cooling loads and have fair return on investment, are relatively small investments compared to the centralized room space-specific cooling system. However, as the climate conditions, energy prices, techno-economic environments, energy and emission policies, local construction methods and CO₂ emission factors of different energy carriers can be significantly different in different countries and regions, the cost-optimal renovation concepts and recommended measures will also be different. The GSHP system is not as cost-effective investment in regions, where the price of electrical energy is significantly higher than the price of district heating or gas-based energy. Similar conclusion can also be made if there is a deep layer of soft ground soil material that must be penetrated to reach the bedrock layer. In addition, typically the more extensive measures that improve the indoor thermal conditions further and increase the cooling capacity, e.g. the room space-specific cooling system with chilled beams, ceiling cooling panels or fan coils, become more profitable in office buildings located in warmer climates, as the lost performance of occupants caused by the productivity loss has such a significant impact on the economic calculations.

The additional analysis conducted to determine the measures to maximize the productivity and indoor thermal conditions indicated that the best outcome can be gained by adjusting the operation set points of the HVAC systems in addition to the investments in renovation measures. According to the separate analysis, the optimal indoor air temperature set point for heating is approximately 22.5 °C and for cooling approximately 23.5 °C using the thermal comfort features and assumptions described in section 2.2.2. Excellent thermal comfort conditions (average annual PPD-index < 5.3%), without any lost working hours could be achieved in deep renovations by investing as low as 135-145 €/m² (see Table 11),
resulting simultaneously in 21-24 kgCO$_2$/m$^2$·a reduction in the CO$_2$ emissions of delivered energy consumption, which equals to a 50-60% reduction potential. However, it is also important to acknowledge that while the perceived indoor thermal environment has a significant impact on the productivity and on the performance of workers, it is highly dependent on the personal preferences of occupants.

An essential result of the conducted analyzes was that a room space-specific cooling system is not necessarily needed. However, this aspect highlights the limitations related to this study. The open layout office design of the case building shown in Fig. 3 has been modelled to correspond to the real design layout. In this scenario, the internal gains are assumed to be almost equally mixed in the entire open office space and the room temperature of the space represents the average temperature of the entire space, whereas in reality the temperature and internal load profiles are not uniform or equally distributed in the entire open office space. This also applies to the situation, where the entire floor is one uniform space without internal walls. In reality, there are also temperature differences between the perimeter and the inner areas of open layout offices, as the room air is not perfectly mixed in the entire room space. Furthermore, the draft rate (DR), which is typically the most common topic of complaint in office buildings, was not taken into account in the analyzes.

Relevant aspects that remained to be resolved in future research include similar analyzes for office buildings located in hot and tropical climates, e.g. in the Southeast Asia region or in the Mediterranean countries, where is a large demand for air-conditioned buildings and room for improvement in both the environmental performance and the thermal comfort conditions. More future research is also required to better understand the concept of productivity loss in different climate conditions and to further develop the multi-objective optimization method that can be used to study and optimize both the indoor environment conditions and the environmental impact reduction potential in deep renovations of office buildings in more detail. Further research is also required to develop design principles and cost-optimal overall solutions to optimize the indoor climate conditions, energy performance and thermal comfort metrics of office buildings located in different climates to reduce the environmental impact of existing office buildings towards low-carbon office buildings.

5. Conclusions

The objective of the study was to determine the cost-optimal renovation solutions and economic viability of different renovation measures to minimize the environmental impact and to maximize the energy performance and the indoor thermal comfort conditions of typical late 1970s and 1980s office buildings located in cold climate regions. The study applied an extended LCC analysis, where the lost performance of workers was combined with the standard LCC calculation method. The productivity loss caused by unfavorable indoor thermal comfort conditions was integrated in the LCC analysis of the owner occupied building study. Environmental impact reduction potential of the renovation measures was
studied by assessing the CO\textsubscript{2} emissions of delivered energy consumption, which were determined to be dominant over the embodied CO\textsubscript{2} emissions of construction materials over the studied 15-year life-cycle period.

According to the study, it can be concluded that:

- the cost-optimal renovation concepts deliver up to 65 %/a return on investment in owner occupied office buildings, whereas in tenant occupied buildings investments in similar measures deliver approximately 15-18 %/a return on investment, when the value of the lost work caused by the productivity loss is not taken into account in the analysis;
- the cost-optimal renovation concepts include as high as 60-63% reduction potential of CO\textsubscript{2} emissions of operation;
- the effect of the indoor thermal conditions on the productivity of workers is significant and can account for up to 55-75% of the overall life-cycle costs;
- multi-objective optimization and careful selection of renovation measures are required to determine the optimal renovation concepts that improve both the indoor thermal conditions and the energy performance of office buildings with minimum investment and life-cycle costs;
- room space-specific cooling system was not included in the cost-optimal overall solutions, as energy efficient lighting system, cost-effective solar shading and centralized cooling of supply air of the ventilation system delivered better cost-effectiveness and were also sufficient to maintain the operative temperatures below 25 °C during the summer time;
- excellent indoor thermal conditions (PPD-index < 5.5) can also be achieved in deep renovations with high energy performance and with relatively low investments, when the optimum renovation concepts are selected and combined with the optimum HVAC system set points;
- the methodology applied in the study can be generalized to different climate conditions and techno-economic environments to assess the environmental performance, indoor thermal comfort metrics and economic viability of different measures simultaneously and to determine the optimal concepts and design solutions for maximum building performance in both deep renovations and new construction. However, future research is still recommended to further develop the methodology.

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