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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

28 **1. Introduction**

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

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

55 Multiple studies regarding the productivity loss of workers due to unfavorable or poor indoor air quality (IAQ) and
56 thermal comfort conditions have been conducted to determine the cost implication in office buildings [14-21]. These
57 studies [14-21] indicate that depending on the techno-economic environment, the monetary value of the productivity loss

58 due to decreased work efficiency can be up to 10–100 times greater than the operating costs of the building. This means
59 that improving the indoor climate conditions in renovations of existing office buildings is essential and economically
60 viable, especially if the building owner is the same organization, which is paying the salaries of the employees, such as a
61 government office or equivalent organization [14-17].

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

72 This study presents the cost-optimal renovation measures for typical office buildings built in Finland (cold climate
73 region) in the late 1970s and in the 1980s. Previous studies have demonstrated the economic impact of productivity loss
74 due to decreased performance of workers and suggested measures and design principles, such as airflow rates and indi-
75 vidual microclimate controls, to improve the indoor environment conditions and to minimize the productivity loss
76 [14,15,22,23]. However, these measures and design principles are conventionally applied to new office buildings and
77 they are typically extremely difficult, expensive, impractical and often also impossible to implement in renovations of
78 existing office buildings due to space constraints. Furthermore, there are millions of different renovation package combi-
79 nations that can be selected, when deep renovations of office buildings are conducted and this makes it impossible to
80 determine the global optimum combination of measures by using the conventional parametric-based analysis methods.
81 The building ownership aspects (owner-user and tenant) haven't been addressed in previous studies focusing on renova-
82 tion of office buildings and they are resolved in this study. The methodology, results and conclusions presented in the
83 study complement the existing body of literature in the field of cost-effective renovation of office buildings located in
84 cold climate conditions. The presented methodology can also be applied in office building studies related to different
85 climates and techno-economic environments. It can be used to maximize the energy performance, environmental impact
86 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.

Fig. 1. 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.

External structures and air-tightness		
Thermal transmittance of external walls, [W/m²K]	0.35	
Thermal transmittance of roof, [W/m²K]	0.29	
Thermal transmittance of base floor, connected to the ground, [W/m²K]	0.40	
Thermal transmittance of windows, 3-pane structure, [W/m²K]	2.1	g-value: 0.60 ST-value 0.52 Depth of frame: 170 mm
Integrated window shading		None
Thermal transmittance of external doors, [W/m²K]	1.4	
Air-tightness of the building, the q ₅₀ -value	6.00 m³/(m² h)	According to the Decree for the energy performance certificate (176/2013) [25]

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-

ing the 1970s and 1980s, where no deep renovation measures have been conducted. The domestic hot water (DHW) consumption was selected according to the National Building Code of Finland (NBCF) part D3 (2012) [26].

145

146 **Table 2.** The main HVAC systems of the original case office building with main features presented.

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

147

148 2.1.3 Internal heat gains

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

154

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

Internal heat gains from occupants, lighting and office appliances	
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

156

157 *2.1.4 Minimum indoor environment requirements of the case building renovation*

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

164

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

167

168 *2.1.5 Climate conditions and weather data*

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

174

175 *2.1.6 Cost data of studied renovation measures*

176 Tables 4 and 5 present the studied renovation measures and the relevant construction cost data [29-31]. The value
177 added tax (VAT), which is currently 24% in Finland, is not included in the cost data. Majority of the studied measures
178 improve both the energy performance and the thermal comfort of the building and also reduce the environmental impact

179 of the building. A ground source heat pump system (GSHP) used for combined heating and cooling was also studied as a
180 main energy system. In addition, the district heating system, which is the original main heating system of the studied
181 office building was also studied and compared to the GSHP energy system.

182

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

District heating system (DH concept)	Minimum value	Maximum value	Variable
- Area of PV-panels, m ²	0	500	Continuous
- Additional thermal insulation (mineral wool) thickness of external walls or just the basic refurbishment, mm	0, basic refurbishment	300	Discrete, 6 options
- Additional thermal insulation (mineral wool) thickness of roof or just the basic refurbishment, mm	0, basic refurbishment	400	Discrete, 6 options
- Replacement of windows to new windows or just the basic refurbishment of the original windows / thermal transmittance	Basic refurbishment of original windows / 2.1 W/(m ² K)	Replacement to new windows / 0.6 W/(m ² K) and g-value of 0.31	Discrete, 6 options
- Integrated window shading, installation of blinds between panes	None	Blinds between the inner panes (47% reduction in the g-value of windows)	Discrete, 2 options
- Lighting system, type of lighting system	Fluorescent (10 W/m ²)	LED (7 W/m ²)	Discrete, 2 options
- Control type of lighting system	No automated control, regular control system	Occupancy + constant light control system	Discrete, 2 options
- Ventilation system, replacement of the original AHUs with high efficiency (76 %) heat recovery system	None	Renovated with energy efficient AHUs	Discrete, 2 options
- Ventilation system, installation of demand-controlled ventilation (DCV) system to office and equivalent space groups, DCV-controlled zones are approx. 150-200 m ² in open layout offices (12-16 control zones per floor)	None	DCV + control system for temperature, occupancy and CO ₂	Discrete, 2 options
- Cooling system, installation of centralized water cooling system for cooling of supply air of AHUs and room cooling units	None	Water cooling system with cool storage tank	Discrete, 2 options
- Cooling system, installation of centralized room cooling system with ceiling cooling panels, two cooling panels (600x3000 mm) per 12 m ² in open layout office spaces, requires the installation of the centralized water cooling system	None	Ceiling cooling panels with room/zone specific controls, control area circa 50-100 m ² (25-50 control zones per floor)	Discrete, 2 options
Total number of renovation combinations: 2.76 million	-	-	-
Ground source heat pump system (GSHP concept)	Minimum value	Maximum value	Variable
- Dimensioning power output of the GSHP system, kW	20	450	Continuous
- Other measures are the same as with the DH system concept	-	-	-
Total number of renovation combinations: 276 million	-	-	-

184

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

Measure	Investment cost
Solar-based electricity production system with PV-panels, €/panel-m ²	180 (1.2 €/W _p)
Refurbishment of external walls, €/ex.wall-m ²	
- basic refurbishment, patching and painting of original walls (no insulation) (0.35 W/m ² K)	20
- 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/m ² K)	180
- same as previous measure, but new thermal insulation thickness is: 150 mm (0.23 W/m ² K)	185
- 200 mm (0.18 W/m ² K)	196
- 250 mm (0.14 W/m ² K)	205
- 300 mm (0.12 W/m ² K)	212

Refurbishment of roof, €/roof-m ²	
- basic refurbishment, renewal of the top layer of original roof (no insulation) thermal insulation layer (mineral wool insulation) and new roof top layer (0.29 W/m ² K)	50
- 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/m ² K)	152
- same as previous measure, but new thermal insulation thickness is: 250 mm (0.14 W/m ² K)	158
- 300 mm (0.12 W/m ² K)	163
- 350 mm (0.10 W/m ² K)	171
- 400 mm (0.09 W/m ² K)	178
Refurbishment of windows, €/window-m ²	
- patching, painting and resealing 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/m ² K and g-value 0.50	273
- same as previous measures, but new windows are: thermal transmittance 1.0 W/m ² K and g-value 0.41	292
- thermal transmittance 0.84 W/m ² K and g-value 0.39	304
- thermal transmittance 0.69 W/m ² K and g-value 0.30	317
- thermal transmittance 0.6 W/m ² K and g-value 0.31	327
Installation of blinds between the inner panes of windows, €/window-m ²	30
Refurbishment of lighting system, installation of new lighting system, €/floor-m ²	
- modern fluorescent lighting system (10 W/m ² to produce 500 lx illuminance)	21
- modern LED-based lighting system (7 W/m ² to produce 500 lx illuminance)	29
Installation of occupancy + constant light control system, €/floor-m ²	4
Refurbishment of the ventilation system, €/floor-m ²	
- 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-m ²	
- 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-m ²)

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].

Renovation measure	Annual maintenance cost	Renewal cost
District heating system	None	None
GSHP system	0.6% from the investment cost	None
Solar electricity system (PV-panels)	2.0% from the investment cost	None
Renewal of basic refurbishment (patching and painting) of external walls	None	20 €/ex.wall-m ² , after 8 years
Replacement of all fluorescent tubes after approximately 20 000 hours of operation	None	2 €/floor-m ² , after 8 years (only the tubes must be replaced)

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)

$$PPD = 100 - 95e^{[-(0.03353PMV^4 + 0.2179PMV^2)]} \quad (1)$$

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:
 - PMV-index -1: occupants wear maximum clothing (1.10)
 - 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

254 (LCC) analysis of deep renovation of the case office building. In addition to the direct salary of workers, the side costs
255 such as the social security costs and other indirectly related salary expenses were also taken into account in the calcula-
256 tions. However, the potential overhead factors related to the salaries of employees of commercial companies were not
257 taken into account in the analysis.

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

- 262 • $23.3 \text{ €/h} \times 1.62 = 38 \text{ €/h}$ [36-38].

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

265

266 2.2.4 Additional analyzes to maximize indoor thermal conditions and productivity of building users

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

278 The total hours of people dissatisfied (PDH) was selected as an indicator to represent the quality of the indoor ther-
279 mal conditions in the additional analyzes. The total PDH (dissatisfied hours/occupant per year) is a sum of all the annual
280 individual PPD calculation results (e.g. 9 individual PPD calculation locations including 25 occupants in each location in
281 Fig. 3) of all occupied room spaces during the operating time of the building. As the total PDH index of the building
282 includes all individual PPD calculation results of occupied zones, it can be reliably used as an accurate average index to
283 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.

313 The CO₂ emission factors of different energy carriers were selected according to the average Finnish emission fac-
314 tors as follows [39]:

- 315 • 183 kgCO₂/MWh for district heating (3-year average value, combined heat and power production);
- 316 • 209 kgCO₂/MWh for electricity (5-year average value).

317

318 2.4. Multi-objective optimization analysis

319 2.4.1 Optimization method

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

332

333 2.4.2 Simulation method

334 The energy simulations of the multi-objective optimization analyzes were performed by using the IDA Indoor Cli-
335 mate and Energy (IDA ICE, version 4.7) dynamic simulation tool. IDA ICE software has been validated (including tests
336 against measurements) in multiple previous studies as a reliable, accurate and versatile dynamic simulation tool to be
337 used in building performance simulations [44-50]. In addition to fully dynamic energy simulations, IDA ICE can be used
338 to perform various indoor climate and thermal comfort simulations. The performance of the studied renewable energy
339 production systems was assessed by using the Early Stage Building Optimization (ESBO) Plant model of IDA ICE. The
340 ESBO Plant model makes it possible to model and simulate the renewable energy production systems as a part of dynam-
341 ic energy simulation of buildings.

342 The GSHP model used in the study was calibrated by using a detailed calibration method described in a recent study
 343 conducted by Niemelä et al. (2016) [51]. The average coefficient of performance (COP) of the calibrated simulation
 344 model at 8 different rating conditions (e.g. 0/45 °C) was approximately 1.2% lower than the average COP of the corre-
 345 sponding real GSHP system. The combined heating and cooling operation of the GSHP system can also be modelled in
 346 detail using the ESBO Plant model.

347

348 2.5. Principles of life-cycle cost analysis and economic calculations

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

358

$$359 \quad NPV_{LCC,15a} = \sum I_{0,total} + \sum MR_a \frac{1-(1+r)^{-n}}{r} + \sum R_M \frac{1}{(1+r)^k} + \sum E_a \frac{1-(1+r_e)^{-n}}{r_e} + \sum t_{lost} Va_{work} \frac{1-(1+r_w)^{-n}}{r_w} \quad (2)$$

360

361 where: $NPV_{LCC,15a}$ is the net present value of the LCC over a 15-year time period, €; $\sum I_{0,total}$ is the overall investment cost
 362 of the renovation measures (see Table 5), €; $\sum MR_a$ is the overall annual repair and maintenance cost of the measures, €/a;
 363 $\sum R_M$ is the overall renewal cost related to the measures, €; $\sum E_a$ is the overall annual energy cost of the case building, €/a; r
 364 is the real interest rate selected in the LCC analysis; r_e is the escalated real interest rate selected in the LCC analysis,
 365 including an estimated energy price escalation rate in the future; n is the selected life-cycle period (15 a), a ; k is the time
 366 step (year) from the start of the life-cycle period, when a specific renewal measure is conducted; $\sum t_{lost}$ is the sum of annu-
 367 al lost working hours due to productivity loss caused by unfavorable indoor climate conditions, h/a; Va_{work} is the total
 368 value of the work, €/h; r_w is the estimated average annual increase in the total value of the work in the future.

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

370

$$371 \quad i = \frac{1-(1+i)^{-n}}{I_0/A} \quad (3)$$

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, the net profit, €/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].

Energy prices (the 24% VAT excluded)	
Electrical energy	90 €/MWh
District heating energy, priced according to the season of the year in Lahti	
- 1.11–31.3 (winter season)	58.4 €/MWh
- 1.4–31.5 (spring season)	50.9 €/MWh
- 1.6–31.8 (summer season)	28.6 €/MWh
- 1.9–31.10 (autumn season)	50.9 €/MWh
District heating capacity fee, determined according to the maximum annual heating power demand of the building	
- In the initial condition, before the deep renovation	22 600 €/a
- After the deep renovation	Capacity fee reduced according to the reduction in the maximum heating power demand of the building, €/a
Parameters of the life-cycle cost analysis	
Real interest rate	4.0%
Energy price escalation rate	+2.0 %/a for electricity and district heating
Average annual increase in the total value of the work	+2.0 %/a

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).

Optimization analysis	Type of building	Minimized objectives and type of LCC calculation
1: CO ₂ emissions of DE consumption, DH concept	Owner occupied	CO ₂ emissions of DE consumption, net present value of 15-year LCC (extended), investment cost
2: CO ₂ emissions of DE consumption, GSHP concept	Owner occupied	CO ₂ emissions of DE consumption, net present value of 15-year LCC (extended), investment cost
3 CO ₂ emissions of DE consumption, DH concept	Tenant occupied	CO ₂ emissions of DE consumption, net present value of 15-year LCC (conventional)
4: CO ₂ emissions of DE consumption, GSHP concept	Tenant occupied	CO ₂ emissions of DE consumption, net present value of 15-year LCC (conventional)
5: Thermal comfort conditions, conventional airflow rate potential	-	Total PDH, investment cost, CO ₂ emissions of DE consumption (no LCC calculation)

390

391 Cases 1-2 shown in Table 8 were conducted to determine the cost-optimal renovation solutions for building owner-
392 users. In this owner occupied scenario, the building owner typically gets all the benefits from the improved indoor cli-
393 mate conditions and reduced productivity loss. Cases 3-4 shown in Table 8 were conducted to determine the cost-optimal
394 solutions for building owners who are not responsible for the salaries of the building users, but who are responsible for
395 the operating costs of the building. In this tenant occupied scenario, the building owner typically doesn't get major bene-
396 fits from the improved indoor climate conditions, except by increasing the rent of the building. However, typically it is
397 difficult to justify a sudden substantial increase in rent to tenants, even if major renovation measures are conducted to
398 improve the indoor climate conditions.

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

404

405 *3.1. Cost-optimal renovation solutions for owner occupied buildings*

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

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

415 The main objective of the analysis was to determine the cost-optimal renovation solutions from the building owner's
416 or employer's point of view, where the target is typically to provide excellent thermal conditions, but still low operating
417 costs, with as cost-efficient measures as possible to minimize the productivity loss and to maximize the energy perfor-
418 mance.

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. 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.

<i>CO₂ emissions [kgCO₂/m²,a]</i>	<i>7.5</i>	<i>9</i>	<i>10</i>	<i>12.5</i>	<i>15, GOS²</i>
<i>Net present value of extended LCC, 15 years [€/m²]</i>	341	305	244	218	205
<i>Investment cost of studied measures [€/m²]</i>	291	250	175	140	108
<i>Internal interest rate of the renovation measure package [%/a]</i>	13.8	17.6	29.6	41.7	64.7
<i>Additional thermal insulation of external walls or BR¹ [mm]</i>	+300	+100	0, BR	0, BR	0, BR
<i>Additional thermal insulation of roof or BR¹ [mm]</i>	+400	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR¹, thermal transmittance and g-value of windows [W/m² K]</i>	Yes, 0.60, g-value 0.31	Yes, 0.60, g-value 0.31	Yes, 1.0, g-value 0.50	Yes, 1.0, g-value 0.50	No, BR
<i>Installation of blinds between the inner panes of windows</i>	Yes	Yes	Yes	Yes	Yes
<i>Area of PV-panels [m²]</i>	484	486	401	500	13
<i>Installation and power output of the GSHP system [kW]</i>	Yes, 430	Yes, 339	Yes, 131	Yes, 181	Yes, 161
<i>Renovation of air handling units</i>	Yes	Yes	Yes	Yes	Yes
<i>Renovation of ventilation system to DCV³-based system</i>	Yes	Yes	Yes	No	No
<i>Type of renovated lighting system</i>	LED	LED	LED	Fluorescent	Fluorescent
<i>Installation of occupancy + constant light control system</i>	Yes	Yes	Yes	Yes	Yes

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

- 447 ¹ Basic Refurbishment
448 ² Global Optimum Solution
449 ³ Demand-Controlled Ventilation
450

451 The global optimum solution is achieved by investing in a GSHP system with a relatively small dimensioning power
452 output and by also investing in measures improving the thermal comfort conditions of the building. The original district
453 heating system is remained as the main heating system of the building, but the GSHP system with optimum power output
454 is installed to cover the cooling demand of the building and also to cover a significant amount of the annual heating de-
455 mand at the same time. To compare the selected reference and global optimum overall solutions and to highlight the
456 extended life-cycle cost factors (the refurbishment of the building and the productivity of workers) of the solutions, Fig. 7
457 presents the breakdown of LCC of the reference solution, where only the minimum measures are conducted, and the
458 breakdown of LCC of the recommended global optimum overall solution.

459 **Fig. 7.** The breakdown of extended LCC analysis for the selected reference solution (left, 591 €/m²) and the global optimum solution
460 (right, 205 €/m²).
461

462
463 As it is demonstrated in Fig. 7, the cost impact of productivity loss is the most significant factor in the extended LCC
464 analysis of owner occupied office buildings, where the productivity loss is combined with the traditional LCC analysis,
465 which is typically limited to study the economic viability of different energy efficiency improving measures. According
466 to the selected productivity loss assessment methodology, productivity loss of occupants is not occurring when the opera-
467 tive temperatures of office spaces are maintained between 20-25 °C. However, it is essential to notice that if the upper
468 temperature limit of the model was reduced from 25 °C to e.g. 24 °C, the overall content of the global optimum renova-
469 tion concept would likely be a little different.

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 CO₂ 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 1500 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.

Fig. 8. Cost-optimal renovation solutions in tenant occupied office buildings.

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 10. Recommended renovation measures in tenant occupied office buildings.

<i>CO₂ emissions [kgCO₂/m²,a]</i>	<i>7.5</i>	<i>9</i>	<i>10</i>	<i>12.5</i>	<i>14</i>	<i>16, GOS²</i>
<i>Net present value of LCC, 15 years [€/m²]</i>	332	289	232	212	197	192
<i>Investment cost of studied measures [€/m²]</i>	281	236	167	135	113	103
<i>Internal interest rate of the renovation measure package [%/a]</i>	-2.8	-0.5	4.9	8.9	13.4	16.4
<i>Additional thermal insulation of external walls or BR¹ [mm]</i>	+300	+250	0, BR	0, BR	0, BR	0, BR
<i>Additional thermal insulation of roof or BR¹ [mm]</i>	+300	0, BR	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR¹, thermal transmittance and g-value of windows [W/m² K]</i>	Yes, 0.69, g-value 0.30	Yes, 0.69, g-value 0.30	No, BR	No, BR	No, BR	No, BR
<i>Installation of blinds between the inner panes of windows</i>	Yes	No	Yes	No	No	No
<i>Area of PV-panels [m²]</i>	500	448	483	465	246	66
<i>Installation and power output of the GSHP system [kW]</i>	Yes, 370	Yes, 151	Yes, 291	Yes, 357	Yes, 238	Yes, 146
<i>Renovation of air handling units</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Renovation of ventilation system to DCV³-based system</i>	Yes	Yes	Yes	No	No	No
<i>Type of renovated lighting system</i>	LED	LED	LED	LED	Fluorescent	Fluorescent
<i>Installation of occupancy + constant light control system</i>	Yes	Yes	Yes	Yes	Yes	Yes
<i>Installation of centralized water cooling system</i>	No	No	No	No	No	No
<i>Installation of centralized room cooling system with ceiling cooling panels</i>	No	No	No	No	No	No

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 (15 a) of the reference solution

The breakdown of LCC (15 a) of the global optimum solution

■ Investment cost

■ Energy cost

■ Maintenance cost

Fig. 9. The breakdown of LCC analysis for the selected reference solution (left, 256 €/m²) and the global optimum solution (right, 192 €/m²).

505

506 When comparing Fig. 9 to Fig. 7 it can be seen that the breakdown of the traditional LCC analysis is significantly
507 different than the breakdown of the extended LCC analysis, where the cost impact of productivity loss is also taken into
508 account. Furthermore, the return on investments are also significantly lower in the traditional LCC analysis, when com-
509 pared to the return on investments of the extended LCC analysis including the cost impact of productivity loss.

510

511 *3.3. Cost-effective solutions to maximize productivity of occupants*

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

515 • multi-objective optimization scenario, where realistic airflow rates of the case building were used. A realis-
516 tic increase, when investment cost and practicality are discussed, in the airflow rate of the case building is
517 $1.0 \text{ dm}^3/(\text{s},\text{m}^2)$ from the initial airflow rate of $2.0 \text{ dm}^3/(\text{s},\text{m}^2)$ to $3.0 \text{ dm}^3/(\text{s},\text{m}^2)$. The scenario includes a total
518 of three individual optimized objectives as follows:

- 519 ○ the total occupant hours of dissatisfaction (minimized objective 1);
- 520 ○ the overall investment cost of the renovation measures (minimized objective 2);
- 521 ○ the CO₂ emissions of the delivered energy consumption (minimized objective 3).

522 The main results of the analysis are shown in Figs. 10-11 and Table 11, which present the optimal renovation solu-
523 tions and HVAC system set points. Fig. 11 is shown to highlight the concept of Pareto-optimality in a multi-dimensional
524 optimization problem. The optimal room temperature set points for heating and cooling to maximize the indoor thermal
525 conditions of occupants are also presented in Table 11.

526

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.

535
536
537
538

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.

<i>Average annual PPD-index of all occupants [%]</i>	<i>7.5</i>	<i>6</i>	<i>5.7</i>	<i>5.6</i>	<i>5.4</i>	<i>5.2</i>	<i>5.1, GOS¹</i>
<i>Total PDH [h/occupant,a]</i>	36.2	28.6	28.2	27.8	26.6	25.7	25.4
<i>The total annual amount of lost work due to productivity loss of all occupants [h/a]</i>	9 600	2 400	1 800	1 700	560	0	0
<i>Investment cost of studied measures [€/m²]</i>	57	61	69	91	94	141	234
<i>Renovation of ventilation system to DCV²-based system</i>	No	No	No	No	Yes	No	Yes
<i>Outdoor airflow rate of the ventilation system [dm³/s,m²]</i>	2.0	2.0	2.0	2.0	3.0	2.0	3.0
<i>Indoor air temperature set point for heating [°C]</i>	22.5	22.5	22.5	22.5	22.5	22.5	22.5
<i>Indoor air temperature set point for cooling [°C]</i>	23.3	23.4	23.4	23.4	23.4	23.5	23.5
<i>Installation of centralized water cooling system</i>	No	No	No	No	No	Yes	Yes
<i>Installation of centralized room cooling system with ceiling cooling panels</i>	No	No	No	No	No	No	No
<i>Additional thermal insulation of external walls or BR³ [mm]</i>	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR	+250
<i>Additional thermal insulation of roof or BR³ [mm]</i>	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR	0, BR
<i>Replacement of windows or BR³, thermal transmittance and g-value of windows [W/m² K]</i>	No, BR	No, BR	No, BR	Yes, 1.0, g-value 0.50	No, BR	Yes, 0.69, g-value 0.30	Yes, 0.69, g-value 0.30
<i>Installation of blinds between the inner panes of windows</i>	No	Yes	Yes	Yes	Yes	Yes	Yes
<i>Renovation of air handling units</i>	No	No	No	No	No	Yes	Yes
<i>Type of renovated lighting system</i>	Fluorescent	Fluorescent	LED	Fluorescent	Fluorescent	Fluorescent	LED
<i>Installation of occupancy + constant light control system</i>	No	No	No	Yes	No	Yes	No

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

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

548 4. Discussion

549 By using the extended life-cycle cost calculation method, where the cost impact of productivity loss is integrated into
550 the traditional life-cycle cost calculation, in the owner occupied building type analysis, the results clearly indicate that the
551 reduction in performance of workers due to unfavorable indoor thermal conditions has the highest individual economic
552 impact on the total LCC. The cost impact of productivity loss accounts for up to 60-70% of the extended LCC over a life-
553 cycle period of 15 years in the presented reference solution, where only the mandatory minimum renovation measures are
554 conducted. By using a longer life-cycle period than 15 years, the proportion of the productivity loss is even higher.

555 Therefore, it is profitable and highly recommended for building owners to improve the thermal comfort conditions in
556 deep renovations of existing owner occupied office buildings. According to the results of the optimization analyzes, in-
557 vestments in refurbishment measures deliver close to 65% return on investment in owner occupied office buildings,
558 where the cost impact of productivity loss is taken into account in the analysis. The overall investment cost of the renova-
559 tion measures was approximately 110 €/m² at the cost optimum level.

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

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

572 According to the results, the reference low-carbon criteria could be achieved with a 5% return on investment in ten-
573 ant occupied office buildings and with up to 30% return on investment in owner occupied buildings. However, it is im-
574 portant to notice that the composition of delivered energy carriers plays a significant role in the analysis. If renewable
575 electrical energy is purchased from the electricity grid, the operation emissions (CO_{2e}) can be significantly reduced. Fur-
576 thermore, if the district heating energy is produced by using renewable energy sources, this also affects the CO_{2e} emis-
577 sions significantly. Due to the aforementioned aspects, average Finnish CO₂ emission factors of different energy carriers
578 were used in the study to represent a realistic scenario of the building stock.

579 The effect of summer vacation on the occupancy and internal heat gain profiles was also taken into account in the
580 analysis. Additional optimization analysis was conducted for the owner occupied building scenario, where the average
581 occupancy and internal heat gain profile of office spaces was 65% during the entire summer time. According to the re-
582 sults of the additional analysis, the occupancy and internal heat gain profile of summer time has a significant impact on
583 the results of the analysis. However, even in this higher occupancy profile scenario, the room space-specific cooling
584 system with ceiling cooling panels was not included in the cost-optimal overall solutions. In the higher occupancy profile

585 scenario, approximately 150 €/m² investments are required (approx. 110 €/m², when the summer vacations were taken
586 into account, see Table 9) to reach the cost-optimal overall solutions. However, according to the previous studies that
587 have analyzed the occupancy profiles, the actual occupancy rate during summer time could be as low as 10-35%. Thus,
588 the 65% occupancy rate used in the additional sensitivity analysis was definitely overestimated.

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

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

609 The additional analysis conducted to determine the measures to maximize the productivity and indoor thermal condi-
610 tions indicated that the best outcome can be gained by adjusting the operation set points of the HVAC systems in addition
611 to the investments in renovation measures. According to the separate analysis, the optimal indoor air temperature set
612 point for heating is approximately 22.5 °C and for cooling approximately 23.5 °C using the thermal comfort features and
613 assumptions described in section 2.2.2. Excellent thermal comfort conditions (average annual PPD-index < 5.3%), with-
614 out any lost working hours could be achieved in deep renovations by investing as low as 135-145 €/m² (see Table 11),

615 resulting simultaneously in 21-24 kgCO₂/(m²,a) reduction in the CO₂ emissions of delivered energy consumption, which
616 equals to a 50-60% reduction potential. However, it is also important to acknowledge that while the perceived indoor
617 thermal environment has a significant impact on the productivity and on the performance of workers, it is highly depend-
618 ent on the personal preferences of occupants.

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

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

637 5. Conclusions

638 The objective of the study was to determine the cost-optimal renovation solutions and economic viability of different
639 renovation measures to minimize the environmental impact and to maximize the energy performance and the indoor
640 thermal comfort conditions of typical late 1970s and 1980s office buildings located in cold climate regions. The study
641 applied an extended LCC analysis, where the lost performance of workers was combined with the standard LCC calcula-
642 tion method. The productivity loss caused by unfavorable indoor thermal comfort conditions was integrated in the LCC
643 analysis of the owner occupied building study. Environmental impact reduction potential of the renovation measures was

644 studied by assessing the CO₂ emissions of delivered energy consumption, which were determined to be dominant over the
645 embodied CO₂ emissions of construction materials over the studied 15-year life-cycle period.

646 According to the study, it can be concluded that:

- 647 • the cost-optimal renovation concepts deliver up to 65 %/a return on investment in owner occupied office
648 buildings, whereas in tenant occupied buildings investments in similar measures deliver approximately 15-
649 18 %/a return on investment, when the value of the lost work caused by the productivity loss is not taken in-
650 to account in the analysis;
- 651 • the cost-optimal renovation concepts include as high as 60-63% reduction potential of CO₂ emissions of
652 operation;
- 653 • the effect of the indoor thermal conditions on the productivity of workers is significant and can account for
654 up to 55-75% of the overall life-cycle costs;
- 655 • multi-objective optimization and careful selection of renovation measures are required to determine the op-
656 timal renovation concepts that improve both the indoor thermal conditions and the energy performance of
657 office buildings with minimum investment and life-cycle costs;
- 658 • room space-specific cooling system was not included in the cost-optimal overall solutions, as energy effi-
659 cient lighting system, cost-effective solar shading and centralized cooling of supply air of the ventilation
660 system delivered better cost-effectiveness and were also sufficient to maintain the operative temperatures
661 below 25 °C during the summer time;
- 662 • excellent indoor thermal conditions (PPD-index < 5.5) can also be achieved in deep renovations with high
663 energy performance and with relatively low investments, when the optimum renovation concepts are select-
664 ed and combined with the optimum HVAC system set points;
- 665 • the methodology applied in the study can be generalized to different climate conditions and techno-
666 economic environments to assess the environmental performance, indoor thermal comfort metrics and eco-
667 nomic viability of different measures simultaneously and to determine the optimal concepts and design so-
668 lutions for maximum building performance in both deep renovations and new construction. However, future
669 research is still recommended to further develop the methodology.

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