This is a manuscript version of the article published in International Journal of Sustainable Energy in 2018.
Link to published version: https://doi.org/10.1080/14786451.2018.1448398

Cost-optimal energy performance measures in a new daycare building in cold climate

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New municipal service buildings must be energy effective, and cost-optimality is one of the criteria for selecting the suitable energy performance improvement measures. A daycare building in a cold climate was studied by means of simulation-based, multi-objective optimization. Using a genetic algorithm, both target energy use and life-cycle cost of the selected measures were minimized. It was found that extensive insulation of the building envelope is not a cost-optimal method to reduce the daycare building energy use. Improving energy efficiency of the ventilation system, utilizing solar energy on-site and employing a light control strategy are preferable ways of improving the building energy performance. Ground-source heat pump is a more cost-optimal heating system for the daycare building than district heating. The cost-optimal sizing of the heat pump is small, only 28% of the required maximum heating power.

Keywords: building simulation; simulation-based optimization; daycare building; target energy use; life-cycle cost; multi-objective optimization

1. Introduction

1.1 Background

In order to reach the targets of the Paris Agreement, negotiated in 2015 and ratified in 2016, the nations of the world must curb their greenhouse gas emissions drastically. Building sector is one of the largest energy consumers: in the EU area, according to the statistics provided by the European Commission, the building sector is accountable for 40% of the energy consumption and 36% of the CO_2 emissions. EU has a long term target of diminishing CO_2 emissions by 88–91% by 2050, compared with the 1990 level (ECOFYS Germany 2012). To achieve this, the energy performance of both new and existing buildings must improve rapidly. The current building refurbishment rate within the EU is rather low: 0.5–1.2% in a year,

depending on the region (Cubi, Ortiz, and Salom 2014). The refurbishment rate includes all refurbishments, even those that do not include energy saving measures. This underlines the pressure of improving the energy efficiency of the newly erected buildings in an ambitious manner.

The recast of the Energy Performance of Buildings Directive (EPBD) is one of the key EU policy instruments regarding the emission goals in the building sector (EPBD recast 2010). The EPBD recast states that all new buildings must be nearly zero energy buildings (nZEB) by 2021, and new public buildings must comply with the nearly zero energy requirements already by 2019. "Nearly zero energy building" is defined in the directive as a building with a very high energy performance, with the remaining enery needs covered by renewable energy production to a significant extent (EPBD recast 2010).

The quantitative criteria for nearly zero energy buildings are defined by each member state in their national building code. An assessment of the still-ongoing implementation process is provided by D'Agostino (2015). The Finnish nZEB criteria are also in process of being implemented, and are expected to be finalized during the year 2017.

The construction of all new municipal buildings in the EU will be directly affected by the forthcoming nZEB regulations, and studies in the energy performance of municipal buildings are of immediate importance. The EPBD also states that cost-optimal energy performance measures should be selected, and therefore the cost-optimality of the solutions should be considered alongside the building energy performance. However, the cost-optimality of the available energy saving measures depends on the municipal building type. Municipalities have public buildings with varying functions, such as school and daycare buildings, administrative buildings, assisted housing buildings, museums, et cetera. Conclusions drawn from studies of, for example, administrative buildings (see e.g. García-Sanz-Calcedo and López-Rodríguez 2017) or museum buildings (see e.g. Zannis et al. 2006) cannot be directly applied for educational buildings such as schools and daycare buildings, because of the different building usage profiles. Energy use benchmarking in especially in municipal service buildings has been discussed by e.g. Cipriano, Carbonell, and Cipriano (2009).

This study at hand presents a case of a new Finnish municipal daycare building and its energy performance, where cost-optimality is also an optimization target besides the building energy use. Its objective is to assist in choosing energy saving measures for new municipal daycare buildings in Northern European climates. The study was performed as a part of a Finnish research project "Comprehensive development of nearly zero-energy municipal service buildings" (COMBI).

1.2 Previous research

Energy consumption of Finnish daycare buildings has been reported by Sekki, Airaksinen, and Saari (2015) and Sekki et al. (2016). In the existing daycare buildings, both heating and electricity consumption vary significantly: there can be a tenfold difference in the electricity and heat consumption between the most energy-efficient and the poorest performing buildings. Lately several energy-efficient daycare buildings have been erected in Finland. The case building of this study, Luhtaa daycare, is one of them.

The design of highly energy-efficient daycare buildings, either new or newly renovated, has been examined in a number of previous international studies, but not in the specific case of Finnish daycare buildings. Furthermore, in the previous studies concerning daycare buildings, the building energy performance has been quantified with the help of building simulations, but simulation-based optimization has not been applied to find the overall best solutions.

Hammad, Ebaid, and Al-Hyari (2014) have studied a daycare energy retrofit in the climate of Amman, Jordania. They examined energy efficiency improvements including energy-efficient lighting, improved thermal insulation, solar water heating system, photovoltaic (PV) panels and heat recovery from ventilation. These measures were evaluated and ranked, based on the energy saving potential and the financial payback period. It was found that in the climate of Jordania, installing own solar energy production was preferable to improving the thermal insulation of the building. However, simulation-based optimization was not applied to examine the interconnections between the selected measures. Although some options were found to be more cost-effective than others, it is not certain that the optimal combination of all energy saving measures was found.

Another daycare retrofit study was performed by Causone et al. (2015). Their target building was a daycare in Italy, and the aim of the retrofit design was to reach a zero energy building (ZEB) level, while maintaining good indoor climate conditions. Chosen energy performance improvement measures included solar screens, own solar PV production, LED lamps, improved thermal insulation and ventilation strategy. The amount of solar PV was allowed to increase, until an annual net zero primary energy balance was reached. The suitability of the potential measures was estimated by simulating the building energy performance in various pre-chosen scenarios; thus the interplay between the individual measurements was accounted for to an extent, but again the overall optimal solution was not guaranteed.

A case of designing a new energy-efficient daycare building is reported by Arumägi and Kalamees (2016). A target of reaching either ZEB or nZEB level was chosen as the basis of the architectural design. Different energy efficiency measures were modelled with a number of simulation cases, but not as a simulation-based optimization problem. It was demonstrated that a daycare building can reach the Estonian ZEB level only by very careful and detailed building energy system design, and with application of solar PV.

Simulation-based optimization has been applied in previous studies concerning various other building types. Niemelä, Kosonen, and Jokisalo (2016) have used simulation-based optimization to identify energy-efficient and cost-optimal renovation measures for a university campus building in a cold climate. Niemelä, Kosonen, and Jokisalo (2017a, 2017b) have also applied the method for apartment buildings in cold climate. Delgarm et al. (2016) have used simulation-based optimization to optimize the energy performance of an office building in the climate of Iran. Carlucci et al. (2015) have utilized simulation-based optimization to design a nearly zero energy detached house in Southern Italian climate. In all these studies the selected optimization algorithm is a Non-dominated Sorting Genetic Algorithm II (NSGA-II), which is well suited for such complex multi-objective optimization tasks (Deb et al. 2002), and also utilized in this study.

To the authors' knowledge, there is no prior study where simulation-based, multiple objective optimization has been applied in a case of a new daycare building in a cold climate. Especially in the EU, where new public and municipal buildings must be nearly zero energy buildings from the year 2019, such studies are valuable in identifying the cost-effective and energy-efficient building solutions in the European climates. Results pertaining to a building in a Finnish climate will assist in choosing suitable solutions in the Northern European countries with a similar climate.

2. Methods and data

2.1 Case study building description

The case study building is Luhtaa daycare centre located in Tampere, Finland (61º30' N, 23º52' E) (see Figure 1). Erected in 2012, Luhtaa daycare is one of the low energy pilot buildings of Tampere city, and it was the first Finnish daycare building to reach the passive building standards. The building has a net floor area of 1438 m^2 and provides care for 120 children (Sankelo 2016.). In this study, the existing building is simulated with the help of a simulation model, in order to explore various building system and structural solutions: both those that were actually implemented in the Luhtaa daycare, and those that were not.

Luhtaa daycare building has a wood frame construction. The total thickness of the walls is 500 mm, incorporating 400 mm of mineral wool insulation. The U-value targets for the building envelope were 0.09 W/m^2K for the external walls, 0.06 W/m^2K for the roof and 0.07 W/m^2K for the base floor. The windows have a U-value of 0.66 W/m^2K, and passive methods are applied for solar shading. Heat recovery from the ventilation exhaust air has a temperature efficiency of 60–80 %, depending on the air handling unit (AHU). 56 TopSun TS-S390 solar panels are installed on the south-west facing roof section, each with a nominal power of 390 W_p, totalling 22 kW_p of own solar PVgeneration. (Nyman 2016, Sankelo 2016.)

Luhtaa daycare is connected to the local district heating (DH) network, with connection dimensioned at 102kW. District heating network provides heating for spaces, ventilation and domestic hot water (DWH). Heat is distributed via water-based floor heating on the ground floor, as well as radiators in the basement and ventilation system. The heating set-point temperature is 21 °C, and dimensioning temperatures of the floor heating and radiators are 35/30 °C. Supply air temperature is controlled as a function of return air temperature, with maximum supply air temperature of 24 °C. Dimensioning of floor heating and radiator heating capacities in the building model was performed according to the Tampere design temperature of -29 °C. (Nyman 2016, Sankelo 2016.)

The building basement houses three centralized AHUs, providing a constant air volume (CAV) ventilation system with a schedule control. One AHU is designated for the kitchen only, and provides also cooling for the kitchen. The main AHUs are all equipped with a heat recovery unit (HRU). There are also separate exhausts in the toilet areas, with no heat recovery installed. In reality only the kitchen space is cooled, but while modelling the building, it was found that the maximum indoor temperature target of 25 °C was violated. In order for the simulations to preserve the maximum indoor temperature of 25 °C, which is recommended by Finland's

national building code (Ministry of the Environment, 2012a), the building model was equipped with supply air cooling in the AHUs.

In a previous study, the daycare building was simulated with several possible heating solutions (district heating, pellet boiler, air-to-water heat pump, ground source heat pump), in order to determine the cost-optimal heating option (Nyman 2016). When the heating system was considered alone, without altering the building structure or other building systems, ground-source heat pump (GSHP) was found to be the cost-optimal heating solution. In this study, both district heating and ground-source heat pump solutions are considered as separate optimization cases, and finally compared with each other. This reveals whether GSHP is still the more cost-optimal solution, when other building systems and structures can be modified as well.

The suitability of building energy performance improvements depends closely on the building usage profiles. The usage profiles used in the study are described in detail by Nyman (2016). The used occupancy profile is based on survey data collected from the actual building users (Figure 2). DHW consumption profile in the building models is based on the measured DHW consumption of the building which is 188 dm^3/m^2,a at annual level. The fixed DHW consumption (53 dm^3/h) during the weekdays is used in the simulation while there is no DHW consumption during the unoccupied days (during the weekends and from late June to early August).

Figure 1. Luhtaa daycare centre (upper) and its floor plan (lower).

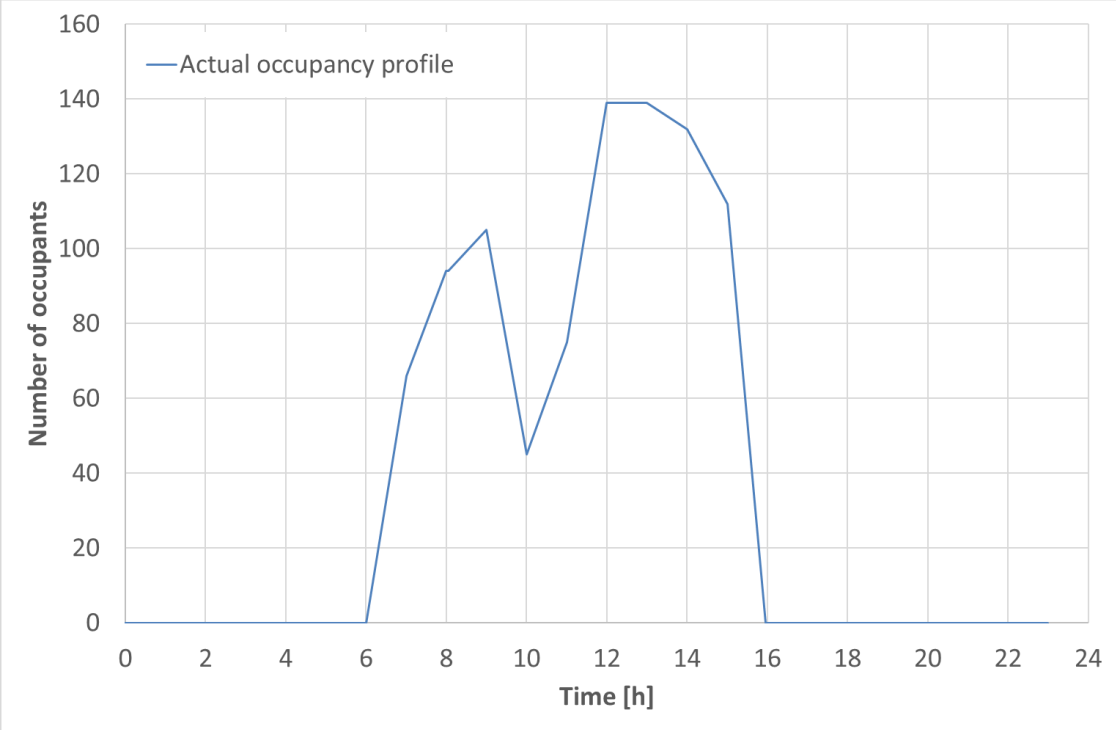

Figure 2. The occupancy profile of Luhtaa daycare centre.

2.2 Weather data

Finland is divided into four climate zones (I–IV) according to the Finnish building code for building energy performance calculation (Ministry of the Environment 2012b). According to this classification, the case study building in Tampere is located in zone I, which is the southernmost climate zone in Finland.

The hourly test reference year (TRY) used in this study represents the current climatic conditions of the climate zone I, and is described in Kalamees et al. (2012). The TRY was developed based on weather data measured at the weather station of Helsinki-Vantaa airport by the Finnish Meteorological Institute. The annual average temperature of the used weather data is +5.4 °C, and the average degree day number is 3952 Kd at indoor temperature of 17.0 °C.

2.3 Simulation-based optimization

Simulation-based optimization is gaining popularity as a method in building energy performance analysis. Buildings are complex systems, often with zones intended for different usages, incorporating an assortment of technologies, and subject to varying weather conditions. In a simulation-based optimization problem, the decision variables are passed on to the building simulation model, which in turn returns the desired end results to the optimization engine. With a suitable optimization algorithm, the optimal combinations of decision variables solutions are found reasonably quickly, even when the number of possible combinations reaches millions. For a review on simulation-based building performance optimization see e.g. Nguyen, Reiter, and Rigo (2014).

In this study, the building simulations are performed with a simulation software IDA Indoor Climate and Energy (IDA ICE) version 4.7 (Sahlin et al. 2004). IDA ICE has been validated in several studies (Travesi et al. 2001, Achermann and Zweifel 2003, Loutzenhiser, Manz, and Maxwell 2007, Equa Simulation AB 2010). In this optimization task IDA ICE is used in tandem with Multi-Objective Building Optimization Tool (MOBO) version beta 0.3b (Palonen, Hamdy, and Hasan 2013).

The optimization algorithm chosen for the task is the genetic algorithm Pareto-archive NSGA-II. NSGA-II is shown to be a computationally fast algorithm in multi-objective optimization problems (Deb et al. 2002), and is therefore well suited for simulation-based building performance optimization. In the optimization tasks performed for this study, the genetic algorithm was applied with a population of 12–16 members, and left to run for a duration of 64–100 generations, totalling 769–1600 simulations. Based on initial testing, this amount of simulations was deemed sufficient for establishing the Pareto front of optimal solutions.

2.4 Definition of the optimization cases

The multi-objective optimization case takes the form:

Minimize

(Target energy use **and** LCC)

where

Target energy use is defined for the two separate optimization cases:

District heating (DH) case

Target energy use = $Q_{lighting} + Q_{cooling} + Q_{equipment} + Q_{AHU} + Q_{DH}$ (1)

where

$Q_{lighting}$	Delivered electricity consumed by lighting	[kWh/m^{2}a]
$Q_{cooling}$	Delivered electricity consumed by cooling	[kWh/m^{2}a]
$Q_{equipment}$	Delivered electricity consumed by equipment	[kWh/m^{2}a]
Q_{AHU}	Delivered electricity consumed by ventilation	[kWh/m^{2}a]
Q_{DH}	District heat delivered to the building	[kWh/m^{2}a]

Ground source heat pump (GSHP) case

Target energy use = $Q_{lighting} + Q_{cooling} + Q_{equipment} + Q_{AHU} + Q_{GSHP} + Q_{auxiliary}$ (2)

where

$Q_{lighting}$	Delivered electricity consumed by lighting	[kWh/m^{2}a]
$Q_{cooling}$	Delivered electricity consumed by cooling	[kWh/m^{2}a]
$Q_{equipment}$	Delivered electricity consumed by equipment	[kWh/m^{2}a]
Q_{AHU}	Delivered electricity consumed by ventilation	[kWh/m^{2}a]
Q_{GSHP}	Delivered electricity consumed by GSHP	[kWh/m^{2}a]
$Q_{auxiliary}$	Delivered electricity consumed by auxiliary heating	[kWh/m^{2}a]

Target energy use is a target level, which is set for actual energy consumption at design stage of a building. Note that target energy use is defined here as the electricity and heat *delivered* to the building from the ambient electrical grid or district heating network. The portion of the

demand that is covered by on-site generation is not included in target energy use: having own generation diminishes the need for energy delivered from the outside. It should also be noted that excess electricity sold to the grid does not lower the target energy use of the building: excess PV production in the summer cannot be used to counterbalance building electricity use at other times. This is in accordance with the legislation draft for the upcoming Finnish nZEB regulations.

Net present value of life-cycle cost is defined as:

$$\mathbf{LCC} = \sum I_{tot} + \sum M_{tot} + \sum R_{tot} - \sum Res_{tot} + \sum E_{delivered,tot} - \sum E_{sold,tot} \quad (3)$$

where

$\sum I_{tot}$	Investment costs	[€]
$\sum M_{tot}$	Maintenance costs	[€]
$\sum R_{tot}$	Replacement costs	[€]
$\sum Res_{tot}$	Residual value of the investments after a lifetime of 20 years	[€]
$\sum E_{delivered,\ tot}$	Cost of delivered energy (electricity + heat) for 20 years	[€]
$\sum E_{sold,tot}$	Profit from selling the excess energy (solar electricity)	[€]

LCC also includes the investment, maintenance, replacement and residual costs of the main heating systems (DH and GSHP), because in this manner the overall life-cycle costs of the two systems can be compared with each other. However, LCC does not represent all the costs incurring from the building construction. For example, the poorest building envelope insulation is considered a zero-cost option, whereas better insulation incurs costs. In this way, the LCC defined here is not a definite price tag for erecting a specific type of building, but rather an indicator for assessing and comparing the cost-optimality of the specific energy-saving measures examined here.

2.5 Building system and structural solutions

The following building systems and structural solutions were investigated in this study, and thus selected as decision variables in the optimization cases:

- Solar PV panel installation
- Solar thermal collection installation (incl. hot water storage tank)
- Sizing of the ground source heat pump (in the GSHP optimization case)
- External wall, external roof and base floor insulation levels
- Window type selection
- Effectiveness of heat recovery from the main AHUs
- Installation of heat recovery units (HRUs) in the toilet separate exhausts
- Installation of variable air volume (VAV) ventilation system with CO_2 control
- Installation of light control strategy (constant, daylight and occupancy control)

All decision variables are listed in Table 1 and described more closely below. The building architecture itself is not altered in the simulations, because the investigation on the architectural design is not within the scope of this research.

With the chosen decision variables, the total number of possible combinations is 1.7 million in the district heating case, and nearly 156 million in the ground source heat pump case. With such a vast number of possible combinations, a parametric study would not suffice to find the globally optimal solutions.

Table 1. Decision variables for the optimization cases, corresponding to the building performance improvement options.

Decision variables	**Minimum value**	**Maximum value**	**Variable type**
Solar panel area [m^2]	1.6	600	Continuous
Solar thermal collector area[1] [m^2]	0 / 6	24	Continuous
Ground source heat pump capacity [kW] (only in the GSHP case)	1	72	Continuous
External wall U-value [W/m^2K], 3 options (0.17, 0.14, 0.08)	0.17	0.08	Discrete
Base floor U-value [W/m^2K], 2 options	0.16	0.10	Discrete
Roof U-value [W/m^2K], 2 options	0.09	0.07	Discrete
Window U-value [W/m^2K], 6 options	1.0	0.5	Discrete
Ventilation heat recovery efficiency [%]	60	80	Discrete
Heat recovery efficiency in separate exhausts [%]	0	60	Discrete
Ventilation control strategy (CO_2 control)	Not installed	Installed	Discrete
Light control strategy (occupancy, daylight and constant light control)	Not installed	Installed	Discrete

[1] Minimum area for solar thermal collectors is 0 m^2 in the GSHP case and 6 m^2 in the DH case.

Solar PV panel installation

Own solar PV generation is already utilized in Luhtaa daycare, which is not a common practice in a Finnish daycare building. In Finland the municipal daycare buildings are generally closed during mid-summer. Luhtaa daycare is unoccupied for 5 weeks in the summer, from late June to early August. The mid-summer closure affects the financial profitability of own PV generation, because the most profitable arrangement is to utilize as much as possible of the on-site generation.

In the actual daycare building, the panels occupy 143 m^2 of the south-west facing part of the roof. In the building simulation, a more advanced solar panel model is used, with

efficiency improved from 15.25% to 17.21%. The simulated panel area is allowed to vary from 0 m^2 to 600 m^2, which is roughly realistic within the actual building geometry. The direction of the panels is south-west in the model, as well as in reality. Solar panel pricing is based on Ahola (2015), Auvinen et al. (2016), Fraunhofer Institute for Solar Energy Systems ISE (2016) and Sankelo (2016), as well as direct price quotes from the industry.

Solar thermal collection installation

Currently solar heat is not utilized in the Luhtaa daycare. In the building model, the area of the solar thermal harvesting panels was allowed to vary between 6 m^2 to 24 m^2 in the district heating case, and between 0 m^2 and 24 m^2 in the ground-source heat pump case. The area constraints were chosen with the help of preliminary simulations. Solar thermal collector pricing is based on Niemelä (2015), Auvinen et al. (2016) and Nyman (2016), as well as direct communication with solar thermal panel marketers. The efficiency of solar thermal collectors was assigned as 0.92 based on solar radiation conversion factor (η_0) of a commercial product. Heat loss coefficients a_1 and a_2 were 3.35 W/m^2K and 0.026 W/m^2K^2 respectively. The longitudinal and tangential incident angle modifiers were 0.93 (at 50°) for modeling the biaxial behavior of the collectors. Alongside solar thermal collection, adequate hot water storage must also be in place. For every 6 m^2 of solar thermal panels installed, 300 l of hot water storage is added. In the DH case no previous storage tank exists, and the maximum tank volume installed is 1.2 m^3, serving 24 m^2 of solar thermal panels. In the GSHP case a 0.4 m^3 tank is already in place, and it can be enlargened up to 1.6 m^3 as required. The cost of this is based on price quotes from hot water storage tank providers.

Sizing of the ground source heat pump

The ground-source heat pump model used in the building simulation is described in detail by Nyman (2016). Coefficient of performance (COP) of the studied GSHP is 4.5 at rating conditions (0/35 °C). In this study, the heat pump capacity is allowed to vary from 0 kW to 72 kW. The maximum required heating power keeps the indoor temperature at the set point (21°C) during the heating season, even with the poorest insulation options. GSHP system has an electric boiler as auxiliary heating solution, the cost of which is included in the life-cycle cost calculation. Pricing of the GSHP and the auxiliary heating system is based on Nyman (2016).

Building envelope insulation levels

Luhtaa daycare building is in actuality very well insulated. One of the aims of this study is to establish whether it is cost-efficient to aim at such high insulation levels, or to reduce the building energy consumption with alternative technical and structural solutions. The insulation levels chosen for the building simulations therefore represent a high grade insulation (external wall U-value 0.08 W/m^2K, external roof U-value 0.07 W/m^2K, base floor U-value 0.10 W/m^2K) and standard insulation levels in accordance with the national building code (wall 0.17 W/m^2K, external roof 0.09 W/m^2K, base floor 0.16 W/m^2K). For the external walls, an

intermediary option is also provided (U-value 0.14 W/m^{2}K). Pricing for the insulation options is based on report from the Ministry of the Environment (2012c) and Reinikainen (2015), as well as direct contact with the industry. The poorest insulation option is treated as the base case, and the costs of the insulation improvements are given relative to the zero-cost base case.

Window type selection

In the building simulation model, 6 different window types are allowed, with U-values ranging from 0.5 to 1.0 W/m^{2}K. This represents the U-value of the whole window complex (glass + frame). No active shading mechanisms, such as automatic or schedule-operated shutters, are considered; the building itself is designed to utilize passive solar shading. The window prices and specifications (U-values, g-values) are acquired directly from a window company. The direct and visible solar transmittances of the selected windows are calculated by Pilkington Spectrum window design tool and taken into account in the study. The window option with the poorest U-value of 1.0 W/m^{2}K is again considered as the zero-cost base case, and all improvements carry a life-cycle cost compared with the base case.

Effectiveness of heat recovery

Two methods of improving the ventilation heat recovery are considered. Firstly, heat recovery of the main air handling units can be carried out by a plate heat exchanger with 60% or by a hygroscopic rotary heat exchanger with 80% temperature efficiency. The minimum allowed exhaust temperatures of these heat exchangers are +1 and -15°C respectively. Heat recovery with efficiency of 60% is considered a zero-cost option, and only the improved heat recovery carries a life-cycle cost. Secondly, a HRU can be installed to the separate exhausts, serving the toilet areas. In the existing daycare building, the toilet separate exhausts do not have any heat recovery installed; this study helps to assess whether or not this was a wise choice. Pricing of the improved heat recovery is based on Reinikainen (2015).

Ventilation control strategy

In a daycare building, the occupancy and usage of the zones varies through the day. The children spend time both outside and inside, sometimes playing or resting in their separate group homerooms, or assembled in the event hall for a common activity. It may be advisable to install CO_2 level controller systems into the ventilation, varying the air flows so that the CO_2 levels are kept at a desired interval. When occupancy is low, air flows need not be as high as at times of high occupancy.

Here a CO_2 control is simulated with proportional controller driving the air flows, keeping CO_2 levels within most occupied zones between 600 and 900 ppm. The ventilation control strategy is applied in all spaces except toilets and the kitchen. Pricing of the CO_2 control strategy is based on Reinikainen (2015) and direct contacts with the building consultant industry.

Light control strategy

As a default, all the light systems of the daycare are considered to be modern LED lighting, with electricity consumption of 8 W/m^2. The relevant energy saving measure is to simulate a light control strategy comprising occupancy control, constant light control and daylight control. The occupancy control turns lights on when a person enters the room while the constant light control keeps the lighting level at a predefined set point. Since the daylight control is used as well, the constant light control adjusts the artificial lighting level taking the daylight level into account. All these three control options can be realized simultaneously with the same light control system. Their combined energy-saving effect is assessed according to a guide provided by Ministry of the Environment (2015), and it amounts to 40% of electricity savings, compared with no light control strategy, is used in the simulation without simulating the light control in detail. Cost information of the light control is based on Reinikainen (2015) and direct contact with light control system provider.

2.6 Cost data

The costs of the energy performance measures under investigation are given in Table 2. The utilized technologies are current off-the-shelf models, with price quotes readily available from the industry. The aim of the study is not to explore the possibilities of state-of-the-art technology options, with high costs and highest possible performance, but rather to assess the cost-optimality of modern solutions that are within a realistic price range today.

Although the more energy-efficient solutions are termed “improvements” compared with the less energy-efficient ones, this is not a research case where a renovation of a building is considered. The existing Luhtaa daycare building is newly erected and in no need of deep renovation yet. This study explores the options that *might* have been taken already in the building stage. Costs for actual renovation measures would be somewhat different from the ones quoted here.

Table 2. Cost data for building performance improvement options and associated costs.

Energy performance improvement	**Cost (VAT 0%)**	**Maximum total cost € (VAT 0%)**
Solar panels	1.2 €/W_p	127016.1
Solar thermal collectors	544.35 €/m^2	13064.4
Storage tank for solar thermal system:		
DH case (max. vol. 1.2 m^3)	519.7 €/m^3 + 1029.4 €	1653.0
GSHP case (max. vol. 1.6 m^3 with 0.4 m^3 tank already in place)	560.4 €/m^3	672.5
Ground source heat pump (only in the GSHP case)	1209.7 €/kW	87 098.4
Wall U-value improvement: from 0.17 W/m^{2}K to…		

… 0.14 W/m^{2}K	17.7 €/wall-m^2	11518.4
…0.08 W/m^{2}K	58.6 €/wall-m^2	38183.8
Base floor U-value improvement: from 0.16 to 0.10 W/m^{2}K	12.8 €/floor-m^2	15401.0
Roof U-value improvement: from 0.09 to 0.07 W/m^{2}K	18.4 €/roof-m^2	21742.6
Window U-value improvement: from 1,0 W/m^{2}K to…		
…0.9 W/m^{2}K	6 €/window-m^2	592.0
…0.8 W/m^{2}K	17 €/window-m^2	1677.4
…0.7 W/m^{2}K	24 €/window-m^2	2368.1
…0.6 W/m^{2}K	37 €/window-m^2	3650.8
…0.5 W/m^{2}K	49 €/window-m^2	4834.8
Ventilation heat recovery efficiency improvement (60% to 80%)	10.1€/m^2 (conditioned area)	14495.0
Heat recovery installation in separate exhausts (efficiency 72%)	4.3 €/m^2 (conditioned area)	6212.2
Ventilation CO_2 control installation	10.8€/m^2 (conditioned area)	15530.4
Light control installation	4 €/m^2 (illuminated area)	4796.0

Other relevant calculation parameters and cost data are listed in Table 3. Note that investment costs for the main heating options are also needed for determining the life-cycle cost. In the LCC calculation, all values are discounted back to the present-day values, assuming a real interest rate of 3% and energy price escalation of 2%. These were chosen in accordance with the COMBI research project. Separate optimization runs were performed for the GSHP case, for the DH case, and for a total of 7 sensitivity analysis scenarios, where the calculation parameters were altered (see Table 3).

Table 3. Additional cost data and LCC calculation parameters.

District heating investment cost [€]	16 355
District heating connection cost [€]	13 500
District heating annual power fee [€]	2676
GSHP auxiliary heater investment cost [€]	9600
Electricity price:	
Base cases	0.0922 € / kWh
Sensitivity cases	± 10%
District heating price	0.0521 € / kWh

Excess electricity selling price	0.0279 € / kWh
Value added tax	0% for a municipal building
LCC calculation life-time	20 years
Real interest rate:	
Base cases	3%
Sensitivity analysis cases	1%, 5%
Energy price escalation:	
Base cases	2%
Sensitivity cases	0%, 4%

3. Results

3.1 Results from the main optimization cases

Figure 3 shows the results from the two optimization cases, with either district heating or ground-source heat pump as the main heating option. Because the investment and maintenance costs of the heating systems have been accounted for in the LCC calculation, the LCC of the two options can now be directly compared with each other. Red and blue markers indicate solutions from DH and GSHP cases, respectively. Pareto fronts, comprising the solutions that best fulfil the dual goal of minimum target energy use and minimum LCC, are shown with white markers. Life-cycle cost is normalized to the building area.

It is immediately clear from Figure 3 that of the two main heating solutions, GSHP is preferable in terms of energy and cost effectiveness. Even the least costly solution on the GSHP Pareto front consumes less energy (41 kWh/m^{2}a, for 145 €/m^2) than the most costly solution on the DH Pareto front (43 kWh/m^{2}a, for 232 €/m^2). In terms of life-cycle cost alone, the two main heating options settle in the same regime: LCC for the optimal GSHP solutions ranges from 145 €/m^2 to 225 €/m^2, whereas LCC for the optimal DH solutions lies between 162 €/m^2 and 232 €/m^2. The essential difference between the systems is that choosing GSHP over DH yields significantly better energy performance for similar life-cycle costs.

For the sake of illustration: the lowest LCC of the DH case is 162 €/m^2, and this cost is associated with target energy consumption of 79 kWh/m^{2}a. If the main heating system were chosen as GSHP, then the LCC of 162 €/m^2 is associated with much lower energy consumption, only 26 kWh/m^{2}a. For this selected value of LCC, choosing GSHP over DH lowers the energy consumption by as much as 67%.

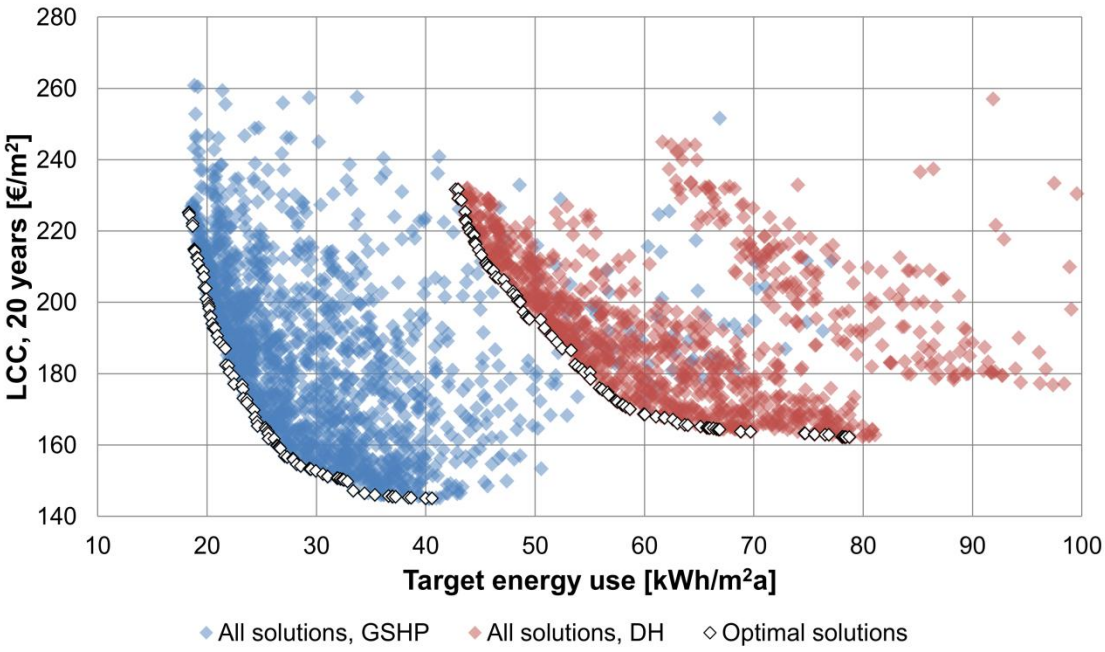

Figure 3. Target energy use vs. life-cycle cost for Luhtaa daycare with either district heating (DH) or ground-source heat pump (GSHP). Pareto-optimal solutions for both main heating configurations are shown with white markers.

By examining the Pareto fronts, and the decision variable combinations that have led to the optimal solutions, the next immediate conclusion emerges: all solutions on both Pareto fronts incorporate light control, variable air volume ventilation and heat recovery from the separate exhausts. Selecting these upgrades does not involve a trade-off between cost and energy performance; boosting the energy performance with these solutions also diminishes the cost, whichever the heating option (DH / GSHP).

To further illustrate the effects of the various other decision variables, Table 4 presents a selection of solutions chosen from the GSHP and DH Pareto fronts, with their associated values of decision variables. Light control strategy, ventilation CO_2 control strategy and heat recovery in the toilet separate exhausts are not listed in Table 4, because – as pointed out above – they are always selected in the optimal solutions. The separate cases of Luhtaa DH and Luhtaa GSHP are discussed more closely in the following sub-sections.

Table 4. A selection of decision variable values for solutions from the GSHP and DH system Pareto fronts

Target energy use [kWh/m²a]	**LCC [€/m²]**	**PV area [m²]**	**ST area [m²]**	**GSHP power [kW]**	**Wall U-value [W/m²K]**	**Roof U-value [W/m²K]**	**Base floor U-value [W/m²K]**	**Window U-value [W/m²K]**	**Heat recovery [%]**
DH: Minimum LCC solution									
79	162	23	6	N/A	0.17	0.09	0.16	0.8	60
DH: Minimum LCC solution for target energy use ≤ 70 kWh/m²a									
70	164	24	6	N/A	0.17	0.09	0.16	0.8	80
DH: Minimum LCC solution for target energy use ≤ 60 kWh/m²a									
60	169	112	24	N/A	0.17	0.09	0.16	0.8	80
DH: Minimum LCC solution for target energy use ≤ 50 kWh/m²a									
49	195	311	24	N/A	0.08	0.09	0.16	0.6	80
DH: Minimum target energy use solution									
43	232	586	24	N/A	0.08	0.07	0.10	0.5	80
GSHP: Minimum LCC solution (also the global minimum)									
41	145	18	6	18	0.17	0.09	0.16	0.9	60
GSHP: Minimum LCC solution for target energy use ≤ 30 kWh/m²a									
30	153	168	6	15	0.17	0.09	0.16	0.9	80
GSHP: Minimum LCC solution for target energy use ≤ 20 kWh/m²									
20	201	584	18	22	0.14	0.09	0.10	0.6	80
GSHP: Minimum target energy use solution (also the global minimum)									
18	225	594	24	21	0.08	0.07	0.10	0.6	80

3.1.1 Luhtaa daycare with GSHP

From Figure 3 and Table 4 it is evident that the minimum LCC and minimum target energy use solutions of the GSHP case are also the global minimum solutions. The lowest LCC, 145 €/m^2, is realized with the following technology and structural options: modest area of solar PV and solar thermal collectors (18 m^2 and 6 m^2, respectively), heat pump sizing of 18 kW, building envelope insulation at the minimum required level, the second poorest windows (U-value 0.9 W/m^{2}K) and less efficient heat recovery from the ventilation system (efficiency 60% instead of 80%). As noted above, the ventilation CO_2 control strategy, light control strategy and HRU in the separate exhausts are always profitable.

Improving the energy performance to 30 kWh/m^{2}a requires growing the size of solar PV production area by 150 m^2 and improving the heat recovery efficiency of the ventilation to 80%. Wall, roof, base floor and window U-values remain the same, solar thermal collector area is unchanged, and heat pump sizing changes only by 3 kW. The conclusion is that in order to improve the energy performance of the building in the GSHP case, the initial cost-effective options are to increase solar PV production and improve the ventilation heat recovery system, and these should be considered before adding any insulation to the building envelope.

Reaching the energy use level of 20 kWh/m^{2}a requires added thermal insulation to the walls (U-value 0.17 W/m^{2}K → 0.14 W/m^{2}K) and to the base floor (U-value 0.16 W/m^{2}K → 0.10 W/m^{2}K), as well as improved windows (U-value 0.9 W/m^{2}K → 0.6 W/m^{2}K). The minimum energy use level of 18 kWh/m^{2}a requires even more insulation to the walls (U-value 0.14 W/m^{2}K → 0.08 W/m^{2}K), as well as added insulation to external roof (U-value 0.09 W/m^{2}K → 0.07 W/m^{2}K). The best windows, with U-value of 0.5 W/m^{2}K, are not required even for the smallest energy use levels: windows with U-value of 0.6 W/m^{2}K are sufficient.

An interesting result that emerges from the Pareto front of the GSHP solutions is that the heat pump capacity in the optimal solutions is rather low. A heat pump of 72 kW covers the heating needs of the daycare building at studied operating conditions (Nyman 2016), and this was selected as the maximum sizing of the GSHP in the optimization runs. A sizing recommendation by a heat pump manufacturer was 54 kW, or 75% of the maximum required heating power (Nyman 2016). However, in the Pareto front of the optimal solutions, heat pump sizing ranges from 14 kW to 30 kW, and in the majority of the optimal solutions it lies between 20±2 kW. A heat pump of 20 kW covers only 28% of the maximum required heating power, instead of the 75% recommended by the manufacturer. Clearly the cost optimal arrangement is to opt for rather small GSHP sizing, and to cover the rest of the heating needs with direct electric heating.

3.1.2 Luhtaa daycare with DH

Although GSHP would be the cost-optimal heating method, in practice it cannot always be chosen. Especially in a densely populated urban area it may be desirable to join the

existing district heating network, instead of drilling own ground heat boreholes. A selection of preferred technology solutions for the DH cases is given in Table 4.

For the minimum LCC solution in the DH case (79 kWh/m^2, 162 €/m^2), solar PV and solar thermal areas are small (23 m^2 and 6 m^2), building envelope does not have insulation exceeding the standard level, and ventilation heat recovery efficiency remains at 60%. Preferred windows are now one step better than in the GSHP minimum LCC case, having U-value of 0.8 W/m^{2}K instead of 0.9 W/m^{2}K. Ventilation CO_2 control strategy, light control strategy and HRU in the separate exhaust are again selected for all optimal solutions in the DH case, just like in the GSHP case.

Even when a daycare building is heated by district heating, selecting the most suitable technology and building structural solutions lowers the energy consumption substantially, and is initially associated with rather modest costs. This is clearly visible in Figure 3: in the DH case the LCC rises less steeply with diminishing target energy consumption than in the GSHP case.

To reach the energy consumption of 70 kWh/m^{2}a in the DH case, only the heat recovery efficiency of the ventilation must be improved (60% → 80%), which increases the life-cycle cost by no more than 2 €/m^2 (162 €/m^2 →164 €/m^2). To reach the target energy consumption of 60 kWh/m^{2}a, it is sufficient to increase the solar PV and solar thermal collector areas: insulation levels and window type can remain unchanged at this stage. For this target energy use level, the life-cycle cost is still only 7 €/m^2 above the minimum cost for the DH case (162 €/m^2 → 169 €/m^2). In summary, increasing the life-cycle cost by only 7 €/m^2 (4%), the energy consumption is already lowered by 19 kWh/m^{2}a (24%). When reaching for energy consumption levels below 50 kWh/m^{2}a, building insulation levels also need improvement, and this carries substantially higher life-cycle costs.

3.2 Sensitivity analysis

The reliability of the cost-optimal building solutions depends largely on the accuracy of the price information. Technology investment costs can change at great speed, as is the case now especially with solar PV technology. Another source of uncertainty is the future development of parameters such as real interest rate r or energy price escalation e. These cannot be reliably predicted, and assumptions must be made to perform the 20-year life-cycle cost calculation. However, the sensitivity of the outcome to the various parameters can be assessed with additional optimization runs.

In this study, sensitivity analysis optimization runs were performed mainly for the DH case, because the longer simulation times of the GSHP case made additional optimization runs impracticable. For the DH case, the sensitivity was examined by altering the real interest rate (r) by ±2%, altering the energy price escalation (e) by ±2%, and altering the electricity pricing by ±10%. For the base case, r was assumed to be 3% and e was assumed as 2%. One additional sensitivity analysis scenario was performed for the GSHP system, assuming electricity price +10%.

Figure 4 shows the Pareto fronts for DH cases r=1%, r=3% and r=5%, with e=2% and all other parameters unaltered. Figure 5 shows the Pareto fronts for Luhtaa DH cases e=0%, e=2% and e=4%, with r=3% and all other parameters unaltered. Lastly, Figure 6 shows the sensitivity case for Luhtaa DH, electricity price ± 10%, and for Luhtaa GSHP, electricity price +10%, with r=3% and e=2%. Note that in all these cases, the entire optimization run was performed anew, although for clarity's sake only the final Pareto fronts are shown here.

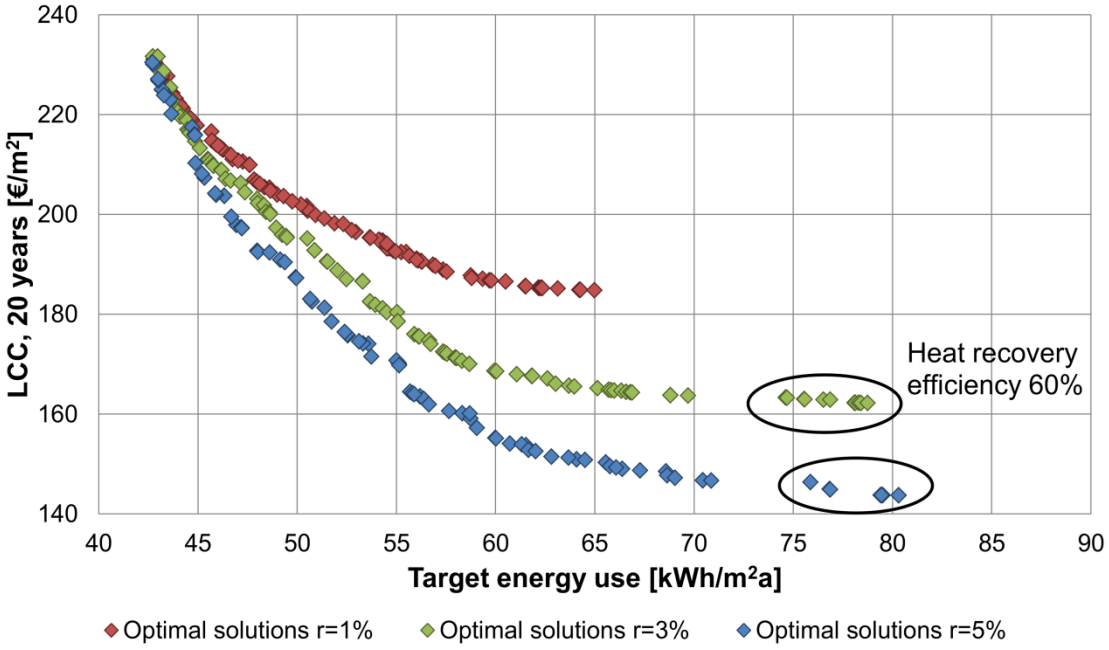

Figure 4. Sensitivity of the optimal DH solutions to varying real interest rate r, with e=2% and all other parameters unaltered.

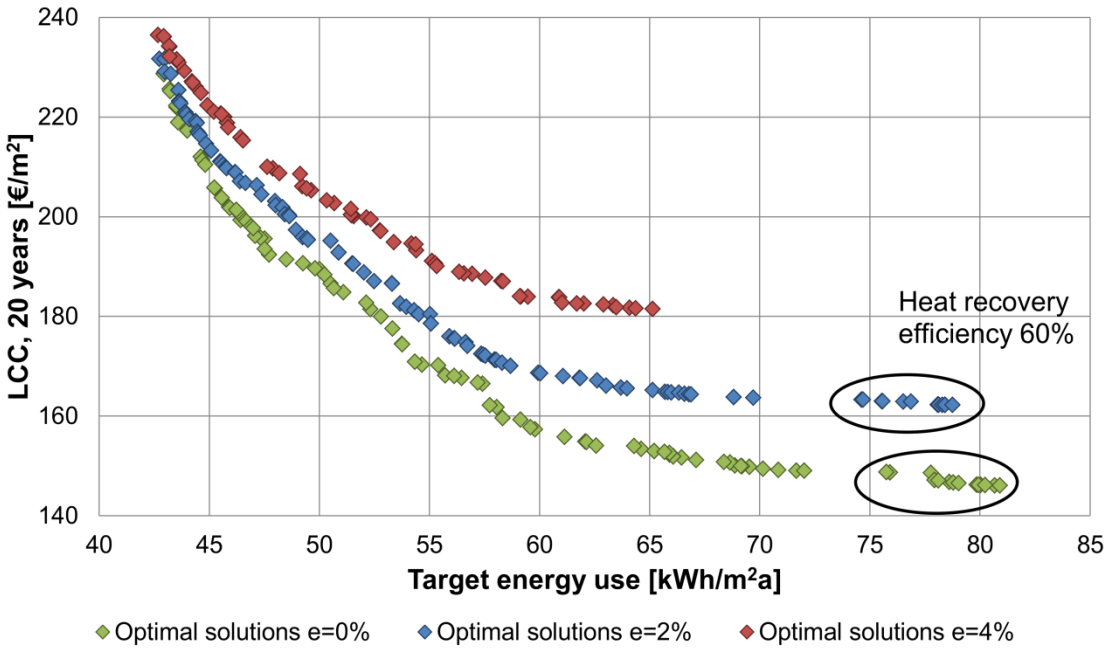

Figure 5. Sensitivity of the optimal DH solutions to varying energy price escalation e, with r=3% and all other parameters unaltered.

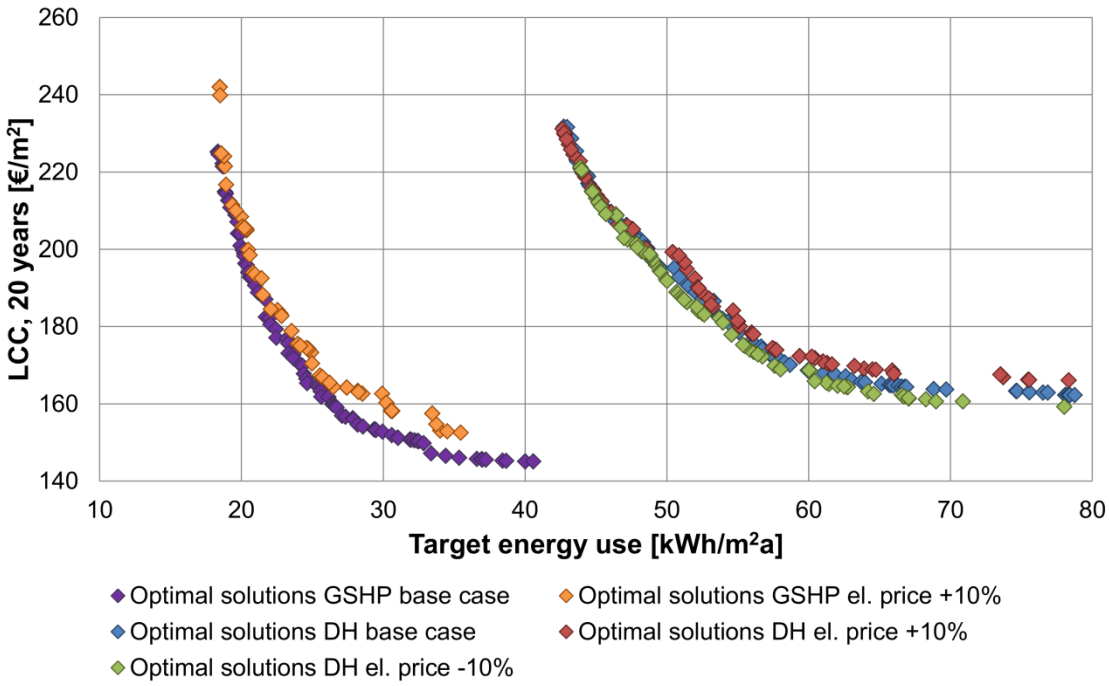

Figure 6. Sensitivity of the optimal DH and GSHP solutions to varying electricity price, with r=3%, e=2% and all other parameters unaltered.

The effects of assuming a smaller real interest rate (r=1%) or greater energy price escalation (e=4%) are very similar, in fact almost identical with each other. In both cases, the option of poorer heat recovery efficiency (60%) in the main AHUs becomes unprofitable. All optimal solutions with either r=1% (Figure 4) or e=4% (Figure 5) incorporate better heat recovery efficiency (80%). This is the main effect arising from the sensitivity analysis. Otherwise the solutions on the Pareto front are rather robust, especially in terms of the desired building envelope insulation levels. Some quantitative changes in the technology mix do occur, such as solar PV being more profitable with smaller real interest rate (r=1%) or steeper energy price escalation (4%). This in itself is an expected result. Sensitivity analysis was not performed for lower solar PV or solar thermal costs, but it is expected that lower investment costs for solar energy production further improves the profitability of own solar generation.

Varying the electricity price by ±10% has no great effect on the DH case optimal solutions (Figure 6). GSHP case is the one with more electricity use, and one additional optimization run was also performed with electricity price +10% (Figure 6). Even in the GSHP case, increasing the electricity price by 10% does not introduce major changes in the preferred technologies. Having electricity price increase by +10% does not cause the GSHP system to become more costly than the DH system: even with higher electricity

price, GSHP is still the overall cost-optimal heating solution. Larger solar PV areas become more profitable with higher electricity price, as can be expected.

3.3 Consideration of initial investment costs

In this study, the focus is on the life-cycle costs, instead of the initial investment cost for the improved energy efficiency. This choice reflects the importance of finding the most efficient solutions in the long term. However, in the building sector, initial investment costs are also a matter of interest, and communities will consider the initial investment costs when erecting a daycare building. A question may arise: what kind of correlation exists between the life-cycle costs presented in Figure 3, and initial investment costs for the selected solutions?

To shed light on this question, Figure 7 shows the initial investment costs as the function of target energy use. It should be understood that Figure 7 is a result of post-processing: it presents the same set of solutions that were already displayed in Figure 3, but this time presenting the initial costs associated with each target energy use. Another optimization run was *not* performed to minimize the initial investment costs, because this was not the focus of this research. Also it should be noted that these are the investment costs for improving the energy efficiency of the building: they do not encompass all the actual investment costs associated with erecting the building.

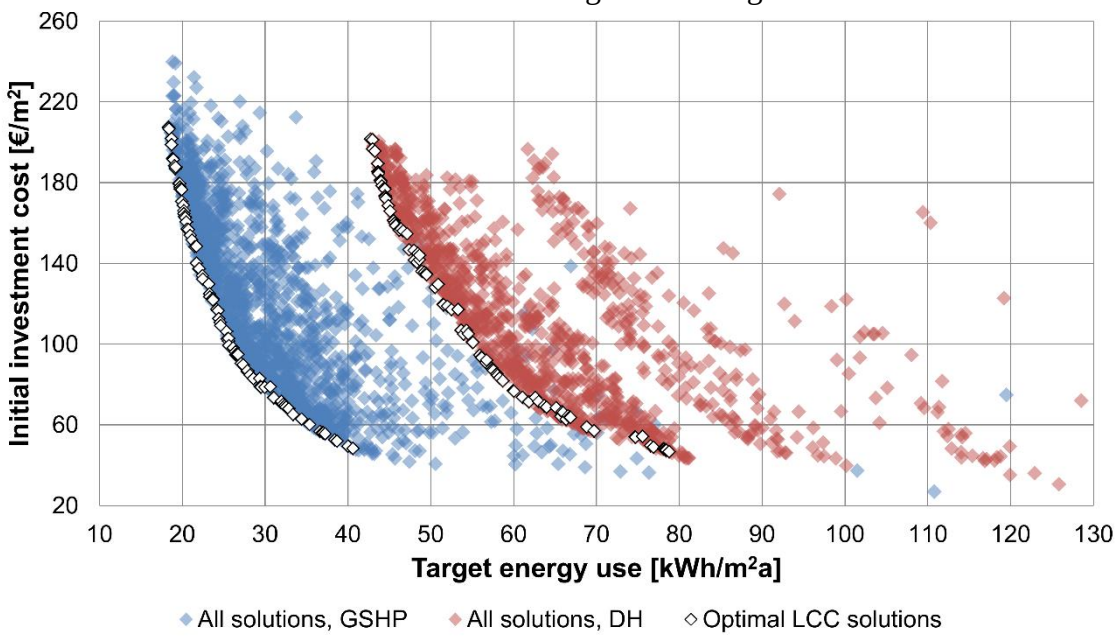

Figure 7. Target energy use vs. initial investment costs for Luhtaa daycare with either district heating (DH) or ground-source heat pump (GSHP). White markers show the Pareto-optimal solutions that are associated with the *lowest LCC* and the lowest target energy use: another optimization was not performed to minimize the initial investment costs.

The post-processed results in Figure 7 do not contradict the conclusions drawn from Figure 3, but rather strengthen them. Even considering the initial investment costs of the Pareto front solutions, a GSHP system yields significantly better energy efficiency per initial investment than a DH system. Note the solutions on the right-hand side of Figure 7, with the lowest initial investment costs: they have very poor energy efficiency, and this is true for both GSHP or DH cases. If the optimization were performed again, with energy efficiency and initial investment costs as the optimization targets, the new Pareto fronts would likely contain these solutions with the lowest investment costs and the poorest energy efficiencies. This stresses the importance of considering the life-cycle costs rather than the initial investment alone. However, investing in a more energy-efficient building does not increase the initial investment costs drastically. For both DH and GSHP cases, discarding the very cheapest solutions and investing 15 €/ more per m^2 can improve the energy efficiency by as much as 40–60 kWh/m^2 a, depending on the chosen mix of technologies. A reasonably modest increase in the initial investment costs also leads to buildings that are more economical to operate in the long run.

4 Discussion and conclusions

In the total optimization of building systems and structures, ground-source heat pump with auxiliary electric heating is the more cost-optimal solution, compared with district heating. If, however, ground-source heat pump cannot be chosen, and district heating becomes the main heating system for a new daycare building, there are several readily available options to improve the energy-efficiency of the building. A wise choice of technologies lowers the building energy use also in the DH case, and initially with rather low life-cycle costs. A careful building design is essential in achieving this result.

The cost-optimal sizing for a ground-source heat pump is rather small, only 28% of the maximum required power. This is in contrast with the heat pump manufacturer recommendation, which in this case was 75% of the maximum required power.

Although a smaller heat pump sizing turns out to be more cost-optimal, it is a matter of consideration whether under-dimensioning of heat pumps can be recommended in terms of the entire energy system. Having small heat pumps may accentuate the electricity peak loads in the coldest periods, placing a strain on the system, and perhaps causing more fossil-fuel based electricity generation in mid-winter. The EU target, as well as the global challenge, is to bring down emissions from the building sector. Small heat pumps with auxiliary electric heating may be cost-optimal in terms of an individual building, but not necessarily the best solution for the overall energy system, or the climate. More optimization studies should be made with the explicit objective of minimizing the CO_2 equivalent emissions from the buildings, as well as building energy use.

Another key finding is that having passive-level insulation is not the cost-effective manner of lowering daycare energy use in a cold climate, regardless whether the main heating option is ground-source heat pump or district heating. Improving heat recovery from the ventilation system, installing modern lighting solutions and utilizing own solar

energy generation are more effective methods of improving the building energy performance. Interestingly, this is in line with findings by e.g. Hammad et al. (2014), although the climates of Finland and Jordania are very different.

Again, it should be pointed out that there are other goals in the building sector that minimizing the building delivered energy use and life-cycle costs. The overall desirability of having well insulated walls can be examined by other means, and other objectives can be defined. For example, here only the U-values of the building envelope were considered, not the choice of the insulation materials themselves. A thorough building life-cycle approach could also take into account the insulation materials and their embodied energy and / or emissions. These are important subjects for further research.

Even in a northern European country like Finland, all new daycare buildings should be designed with suitable installation area for solar panels. Having own solar energy generation lowers the building energy use in a cost-effective manner. Preferably there should be room for both for solar PV generation and solar thermal collection. The ambient energy system should again be considered: having hugely oversized solar PV systems is probably not a good idea, at least not without the possibility for seasonal electricity storage. Seasonal heat storage is not examined in this study, but it could also be utilized, especially with a GSHP system.

Generally, the outlook for solar energy seems bright. In the future, with lower solar PV pricing and improved storage options, even larger solar panel installation areas than suggested here may become recommendable for daycare buildings. These present and future possibilities should not be hampered by the building design of today.

This study presented the general guidelines for building and HVAC design of new municipal daycare buildings and the results of this study can be generalized to similar climates and techno-economic environments. But this study do not replace the need of detailed design of daycare buildings with the actual information of the building properties (geometry, window areas etc.), usage of the building and HVAC systems.

Acknowledgments

This study was performed as a part of a project "Comprehensive development of nearly zero-energy municipal service buildings" (COMBI). It has received partial funding from European Regional Development Fund, as a part of Innovative Cities project of the Finnish Funding Agency for Innovation (TEKES). Significant financing has also been granted from project partner companies.

ABBREVIATIONS

AHU	air handling unit
CAV	constant air volume
COMBI	Comprehensive development of nearly zero-energy municipal service buildings
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
EPBD	Energy Performance of Buildings Directive
EU	European Union
FINVAC	Finnish Association of HVAC Societies
GSHP	ground source heat pump
HRU	heat recovery unit
IDA ICE	IDA Indoor Climate and Energy
LED	light emitting diode
MOBO	Multi-Objective Building Optimization Tool
NSGA-II	Non-dominated Sorting Genetic Algorithm II
nZEB	nearly zero energy building
PV	photovoltaic
TRY	test reference year
VAV	variable air volume
ZEB	zero energy building

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