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Investigation of Energy Efficiency in Buildings and HVAC Systems

ALLAN HANI

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TALLINN UNIVERSITY OF TECHNOLOGY
Faculty of Civil Engineering
Department of Environmental Engineering

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Supervisor: Professor Teet-Andrus Kõiv, Faculty of Civil Engineering, Tallinn University of Technology

Opponents: Professor Emeritus Enno Abel, Chalmers University of Technology, Sweden

Associate Professor Anatolijs Borodinecs, Riga Technical University, Latvia

Reviewer: PhD Vitalis Pavlovas, Peab AS, Oslo, Norway

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

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Hoonete ja nende tehnosüsteemide energeetilise efektiivsuse uurimine

ALLAN HANI

TTÜ KIRJASTUS

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ABSTRACT

In the present dissertation energy calculation methods for buildings are researched. Detailed analysis of energy consumption for residential, educational and public buildings is also carried out.

The literature review includes scientific research of the last 10 years on:

- the possibilities of reducing energy consumption;
- the utilization of simulation-optimization tools for energy calculations;
- indoor climate analysis for school buildings;
- sea water heat pump solutions for district heating and cooling.

The first part of the dissertation includes energy estimation methods, such as degree-day calculations, dynamic simulations and simulation-optimization combination.

Based on the research simple degree-day calculations can be used where the effect of solar heat gain is relatively low (small window sizes in typical Soviet apartment buildings). Validated with real measured energy consumption data, dynamic simulation tools are a powerful tool for creating different energy saving scenarios. Nevertheless, the parameters must be manually altered. The manual alteration process of parameters can be automated with the optimization process. During this process advanced understanding of dynamic simulation files is necessary. The advantages of this principle are maximizing the usage of computational power and minimizing manual interaction in the calculation process.

The second part of the thesis contains an analysis of energy consumption in residential, educational and public buildings. In addition, it includes research on indoor climate in educational buildings and the possibilities of sea water district heating and cooling for the coastal area of Tallinn.

The analysis of energy consumption in residential buildings is based on 40 apartment buildings. Detailed energy balances for thermal and electrical energy were researched for 14 apartment buildings. Based on the results energy consumption has decreased in the recent years due to renovation processes and the constantly rising energy prices. There is more need for ventilation reconstruction work due to tighter building envelopes.

Energy consumption in school buildings is relatively low but it often leads to poor indoor climate conditions. Usually natural in older buildings and centralized mechanical ventilation (new constructions or reconstructions) with heat recovery are existing. Real indoor climate measurements in one school are included. Different ventilation systems, such as natural, centralized mechanical, and room unit based ones, were studied. The room unit based ventilation system was analyzed more deeply. The results show the possibility of using the system in school buildings, but the system is preferable for apartment buildings and old people's homes.

44 public buildings are included in the current dissertation. The average share of thermal energy consumption was 60%, and of electrical energy 40%. Based on the results of this work (quite wide range of energy consumption results) it is recommended that all energy research on public buildings be carried out case by case. The measured energy balance of a modern ten-storey building is presented. In conclusion the share of thermal energy consumption was only 30%. Based on that attention should be paid to electrical energy consumption in new public buildings (the energy consumption of cooling, server rooms and ventilation is a concern).
In Appendix A an analysis of sea water district heating and cooling is presented for the coastal area of Tallinn. It is suggested that 21 buildings be connected to the network. The open loop system is presented although it is problematic in the Gulf of Finland due to the relatively conservative depth of the sea. The temperatures vary remarkably during the year in the depth of 25m, which means that sea water district heating and cooling is feasible near the coast (ca 500m). Nevertheless, the possibilities of using sea water as a renewable energy source should be researched further.

Keywords: the degree-day method, dynamic simulations, building optimization, residential buildings, educational buildings, public buildings

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KOKKUVÕTE

Käeolevas töös on uuritud meetodeid hoonete energiaarvutuste koostamiseks. Samuti on välja toodud elamute, haridusasutuste ja ühiskondlike hoonete energiatarbe analüüs.

Kirjandusülevaade annab ülevaate viimase 10a teadusuuringutest alljärgnevatel teemadel:

- Energiatõhususe valdkond;
- simulatsiooni ja optimeerimise kombineerimine hoone energiaarvutusteks;
- koolihoonete sisekliima analüüs;
- merevee kasutusvõimalused sooljuspumbal põhinevale kaugküttele ja –jahutusele.

Esimene osa tööst hõlmab endas energiaarvutuste meetodeid: kraadpäevadega arvutused, dünaamilised simulatsioonid ning simulatsiooni-optimeerimise kombinatsioon.

Käesoleva töö analüüsi põhjal võib väita, et kraadpäevadega energiaarvutused sobivad hästi hoonetele, kus päikese vabasoojuse mõju on väike (tüüpilised väikeste akendega nõukogudeaegsed korruselamud). Reaalsete energiatarbimisandetega valideeritud dünaamilise simulatsiooni mudel võimaldab läbi mängida erinevaid hoone energiatarbimise stsenaariumeid lähtuvalt füüsikaliste parameetrite muutmisest. Sealjuures on just töömahukas parameetrite muutmine. Käsitsi pidevat parameetrite muutmise protsessi saab lihtsustada optimeerimistarkvara abiga. Selle protsessi eelduseks on detailne simulatsioonitarkvara failide tundmine. Antud lähenemise eeliseks on maksimaalne arvutijõudlise ärakasutamine minimaalse inimsekkumisega.

Teine osa käseolevast uuringust kästileb erinevate hoonetüüpide: elamud, haridusasutused ning ühiskondlikud hooned, energiatarbe analüüsi. Lisaks on uuritud sisekliima probleeme koolihoonetes ning merevee kasutusvõimalusi kaugkütteks ning –jahutuseks.

Elamute energiatarbe analüüs põhineb 40 korruselamul. Detailsed soojuse– ja elektrienergia bilansid koos keskmiste väärtustega on välja toodud 14 hoone puhul. Uuringutulemused näitavad energiatarbe vähenemist elamute sektoris, mis tuleneb rekonstrueerimistest ning pidevalt kasvavatest energihindadest. Kuna hooned on parema õhupidavusega, tuleb rõhku panna ventilatsiooni süsteemide rekonstrueerimisele.

Koolide energiatarbimine on suhteliselt madal, mis on sageli tingitud ebarahuldavast sisekliimast. Tavajuhtudel on kasutusel loomulik ventilatsioon (vanemad hooned) ning mehaaniline tsentraalne soojustagastusega ventilatsioon (uued või rekonstrueeritud hooned). Ühe kooli puhul on välja toodud sisekliima mõõtmistulemused. Samuti on käsitletud kolme ventilatsioonisüsteemi tüüpi: loomulik, mehaaniline ning soojustagastusega ruumiagregaatidel põhinev.

Ruumiagregaatidel põhinevat süsteemi on käsitletud põhjalikumalt. Analüüsi põhjal võib öelda, et see süsteem on koolihoonetes kasutatav, kuid paremini sobib ruumiagregaatidega lahendus elamutele ning vanadekodudele.
Uuring käsitleb ka 44 ühiskondlikku hoonet. Keskmine soojuseenergia osakaal analüüsi tulemusel on 60% ning elektrienergiale 40%. Eraldi on välja toodud kaasaegse kümnekorruselise büroohoone detailne mõõdetud energiabilanss. Kokkuvõtteks oli soojuse osakaal energiabilansist ainult 30%. Erilist tähelepanu tuleb uute büroohoonete puhul elektrienergiatarbimisele (eriti jahutusele, serveriruumidele ning ventilatsioonile kuluv elekter).
Lisas A on esitatud mereveel põhinev soojuspumpade lahendus kaugkütteks ja – jahutuseks Tallinna ranniku alale. 21 hoonet on arvestatud liituma võrguga. Esitatud on merevee kasutamiseks avatud lahendus, samas tuleb kaaluda edaspidi ka suletud ringiga süsteemi, kuna Soome lahe sügavus on tagasihoidlik. Merevee temperatuuri amplituud on lai, sügavuses -25m, mis mõistlikus kauguses rannast (ca 500m). Merevee temperatuur ärakasutamine, taastuva energiaallikana vajab kindlasti ka edaspidist uurimist.

Märksõnad: kraadpäevade meetod, dünaamiline simulatsioon, hoonete optimeerimine, elamud, õppeasutused, avalik-ühiskondlikud hooned

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Preface

The dissertation is a conclusion of my research work conducted in 2008-2012 in the Chair of Heating and Ventilation, in the Institute of Environmental Engineering of Tallinn University of Technology.

Special gratitude is expressed to my supervisor prof. Teet-Andrus Kõiv. Without his constant motivation and support the studies would definitely not have been successful. Especially the first years of my Ph.D. studies were strongly promoted by him and it gave both courage and strength to continue as an independent young researcher. Furthermore, by the period of dissertation writing his help was irreplaceable.

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Even more I would like to thank all of my family members for supporting me in joy and sadness. You have been patient and understanding and I love you all. There will be enough time for you as well.

During my studies I have worked in engineering and development companies. I believe this keeps the head clear and fully focussed on real problems faced in everyday design, construction and real estate development business. The applied science will touch their limits only in cooperation between companies and universities.

Allan Hani

Introduction

In the dissertation the issues of energy efficiency and building services for different types of buildings are analysed. During the last twenty years in Eastern Europe special attention has been paid to reducing energy consumption and creating comfortable indoor environment in buildings. Global warming is an issue in the whole world. Scientists argue whether it is directly caused by carbon dioxide emission or not. Actually it is not so important. It is more important that Kyoto protocol has been signed by most countries to fight global warming by lowering greenhouse gas emissions into the atmosphere and reducing waste of energy. The European Union (EU) member states have defined a challenging 20-20-20 target among themselves:
A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels;
20% of EU energy consumption to come from renewable resources;
A 20% reduction in primary energy use compared with projected levels, to be achieved by improving energy efficiency.
In buildings all these targets have to be achieved without lowering the quality of indoor climate. Due to relatively low energy prices during the Soviet period, the energy efficiency of the existing Eastern Europe building stock is low. Reconstruction has been started but a long way is still ahead. In Estonia the majority of building reconstruction is carried out in Tallinn. The contribution of other bigger towns is still modest. Attention has to be paid to both old and new buildings, therefore the minimum requirements for the energy efficiency of buildings have been defined by Estonian Government. These requirements are valid for both reconstruction and new buildings. Recently a new term Nearly Zero Energy Buildings (NZEB) was introduced, which will lead to local energy production. In case local energy production exceeds local energy consumption, the surplus can be sold to the network. This is the aim of the process, but legal and technical problems will be overcome by 31 December 2018 when all new public buildings in Estonia must meet NZEB requirements. At the beginning of 2020 all new buildings will be NZEB.

The literature review of the current dissertation is divided into four major sections, which give an overview of earlier research done on the energy efficiency of the building sector.

- energy consumption of buildings;
- optimization of building variables;
- indoor climate in school buildings;
- heat pumps for dictrict heating and cooling.

The first part of the current dissertation comprises energy calculation principles. Degree day calculations, dynamic simulations and the combination of dynamic simulation-optimization principles are presented.
The degree day calculation method for apartment buildings is analyzed. The comparison of degree day calculations and dynamic simulations is presented. The indicated degree day calculations can be used with sufficient accuracy only for typical Soviet apartment buildings. Very conservative variation of window sizes is allowed – change in the solar free heat gain spoils the accuracy of calculations.
A variety of dynamic simulation tools is available. Hourly basis calculations can be done with typical local climate data (Test Reference Year), indoor climate conditions, different structures and building systems. Validation of dynamic simulation tools as well as human errors affect the accuracy of calculations. In addition, the calculations of energy performance value of different energy sources are presented for apartment buildings.
In the past ten years a combination of simulation and optimization software has been developed. The combination of dynamic simulation tools and optimization solvers requires large computational power, but nowadays it is no longer a problem. An enormous amount of simulations can be done to find a solution to the objective function (minimum or maximum). Also constraints can be applied to the functions. The calculations and results can present economically feasible solutions of structural and building services with certain defined indoor climate conditions. Validation of the simulation model and human programming errors can lower the accuracy of these combined calculations. As a practical approach the demand for heating and cooling energy for different facades of office buildings is presented in relation with different window parameters.

The second part of the disseration includes an investigation and analysis of energy efficiency and building services for residential, educational and public buildings.
The energy consumption of apartment buildings is analyzed. The results are presented in figures to give a quick overview. Only the measured data (thermal energy and electrical energy) are presented in the main figures.
An untraditional ventilation solution for school buildings - decentralized ventilation with room units - is investigated. Carbon dioxide measurement results are presented together with more traditional centralized and natural ventilation. In addition, data on thermal energy and electrical energy consumption are presented.
In addition to apartment and school buildings energy consumption figures are presented for public buildings. Also the energy balance of a high rise office building is analyzed and presented. The information can be applied as one piece of puzzle to renew the energy performance calculation requirements for office buildings. However, other similar buildings have to be analyzed to have reliable data. A preliminary investigation of the heat pump solution for office buildings for the coastal area of central Tallinn has been carried out, in which both heating and cooling opportunities are analyzed.

1. Literature Review

1.1 Energy consumption of buildings

Energy prices are rising continuously in most countries in the world. Currently the targets are to consume less energy and produce more green energy. The building sector is responsible for approximately 40% of the consumption from the total energy balances of countries in the EU and USA. In developing countries the value is around 20%. A comprehensive research conclusion was presented in 2007 [1] by Luis Pérez-Lombard, José Ortiz and Christine Pout. The biggest consumers of the non-domestic building sector are supermarkets, hospitals, restaurants and SPAs. Research on the distribution of urban energy consumption in the USA [2] shows a variety of energy consumption of residential, public and industrial buildings. Also energy balances for residential and public buildings are presented. Electrical energy consumption in public buildings is a concern. Public buildings in London have been researched by [3,4] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni and Ruchi Choudhary. In conclusion, the range of specific energy consumption values of office buildings is very wide. In addition, a scenario of energy consumption in London until 2050 is presented. Similar scenarios could also be suggested for other countries. Statistical analysis of Chinese buildings has been carried out to some extent [5, 6]. Dispersion diagrams are presented (offices, hotels, governmental buildings). Malaysian office buildings are compared with other countries [7]. Also economic calculations of variable speed drives of electrical motors were carried out and this solution can be suggested. The calculated energy consumption and real measurement results differ 1.2-1.5 times in many cases [8,9]. The calculation methods should be revised. In order to have more precise calculation results the iterative calibration process for dynamic simulations has been prepared [10]. Already in 2002 strategies based on envelope shape and other building parameters were suggested for designing low energy office buildings [11]. This information is valuable and can be used by architects, engineers and design companies. In China the trends for heating and cooling energy consumption in different climate areas have been researched. The scenario for the period of 2009-2100 has been presented by [12] Kevin K.W. Wan, Danny H.W. Li, Dalong Liu and Joseph C. Lam. To lower the cooling load and glaring of light in buildings windows can be coated with protective films [13]. The solution suits well for older buildings. A very interesting research on LEED certification effects on energy consumption has been done in North America [14]. On average, LEED buildings consume 18-39% less energy per floor area than others. However, 28-35% of LEED buildings consume more energy per floor area than others. Lowering the air change rates of ventilation reduces energy consumption. A good solution is to use 8 l/s per person and lower the ventilation rate when unoccupied [15]. There are no certain saving measures that are applicable to all buildings. Energy saving measures for public buildings can only be selected case by case. To some extent certain energy saving packages can be created for residential buildings.

1.2 Optimization of building variables

Building optimization has recently been used in a number of countries to perform an enormous number of iteration calculations to find cost optimal solutions for buildings. Daniel Tuhus-Dubrow, Moncef Krarti have used DOE-2, Perl application and Matlab for optimizing the shape of a residential building envelope [16] [17]. TRNSYS and Matlab calculations have been done for the optimization of the cooling system by K.F. Fong, V.I. Hanby, T.T. Chow [18]. Hanna Jedrzejuk, Wojciech Marks have used a tailor-made solution for the optimization of the walls and heat source of a building [19]. Gianluca Rapone, Onorio Saro researched solutions for office building shading with the combination of Energy Plus and GenOpt in 2011 [20]. Energy Plus and GenOpt have been combined for indoor comfort and hydronic heating optimization by Natasa Djuric, Vojislav Novakovic, Johnny Holst, Zoran Mitrovic [21]. Multi-layered walls have been optimized with genetic algorithms by V. Sambou, B. Lartigue, F. Monchoux, M. Adj [22]. Energy Plus and Matlab have been used by Jingran Ma, JoeQin, TimothySalsbury, PengXu to show the economic efficiency of demand controlled ventilation systems in [23]. Weimin Wang, Radu Zmeureanu, Hugues Rivard have described the concept of green building optimization with multi-objective genetic algorithms [24]. M. Mossolly, K.Ghali, N.Ghaddar have used Matlab to optimize control strategy for an air-conditioning system [25]. HVAC system optimization results have been published by Lu Lu, Wenjian Cai, Lihua Xie, Shujiang Li, Yeng Chai Soh [26]. TRNSYS and GenOpt thermal comfort has been optimized by Laurent Magnier, Fariborz Haghighat [27]. Research on the optimal supply air temperature of VAV systems has been published by Fredrik Engdahl, Dennis Johansson [28]. The combination of Excel and Matlab for calculating building retrofit strategies has been suggested by Ehsan Asadi, Manuel Gameiro da Silva, Carlos Henggeler Antunes, Luķs Dias [29]. Single and multi-objective approaches for the overall energy efficiency of the building façade have been demonstrated by Giovanni Zemella, Davide De March, Matteo Borrotti, Irene Poli [30]. Possibilities of energy conservation in buildings have been studied by V. Siddharth, P.V. Ramakrishna, T. Geetha, Anand Sivasubramaniam with DOE-2.2 and genetic algorithms [31]. Multi-parameter thermal optimization (APACHE software) has been done by A. Saporito, A.R. Day, T.G. Karayiannis, F. Parand [32]. A comprehensive study of the energy consumption of a building and indoor environment optimization has been done by Mohamed Hamdy, Ala Hasan, Kai Siren (Matlab + IDA ICE combination) [33]. In 2004 Micheal Wetter stated the following: "discussions with IDA ICE developer showed that IDA-ICE might indeed be a promising tool for use with our optimization algorithms (GenOpt). However, without extensive numerical experiments and code analysis, it is not possible to conclude that IDA-ICE satisfies our requirements" [34]. In the current dissertation a combination of IDA ICE and

GenOpt is presented. This combination has already been used by Ala Hasan, Mika Vuolle and Kai Siren [35], but here a façade optimization has been carried out.

1.3 Indoor climate in school buildings

According to previous regulations in Estonia, which were enforced by the Ministry of Social Affairs, the maximum allowed CO_2 concentration in schools was 1000 ppm [36]. It is still commonly known as good construction practice. In most cases this figure is not achievable without bigger investments into and higher life cycle costs on ventilation systems.

Investigations have discovered diseases, headache and lethargy in patients in case CO_2 concentrations exceed 10 000 ppm [37].

Studies in Europe also refer to problems related to CO_2 concentrations in schools. The studies carried out in Dutch schools show that in some cases the CO_2 level is more than 5000 ppm at the back of a classroom. 7 schools had CO_2 levels between 1500 – 3700 ppm [38]. A comprehensive study of 141 schools [39] done by Wim Zeiler, Gert Boxem gives the following results, Table 1:

Table 1. Dutch studies: CO_2 levels

Study	**No. schools**	**CO_2 levels [ppm]**	
		Average	**Range**
1984	11	1000	500-1500
1990	6	1290	950-1950
1995	6	1320	700-2700
1997	96	990	425-2800
2004	5	1220	480-2400
2004	11	1580	450-4700
2005	6	1355	550-3000

A study in the United Kingdom (UK) in 2 different classrooms shows the average CO_2 concentration of 1638 ppm and 2086 ppm by the outdoor concentration of 593-709 ppm [40]. Table 2 presents the weekly average results of the study in primary schools in the UK in 2001.

Table 2. UK studies: CO_2 levels

School	**CO_2 levels [ppm]**
	Range
1	200-1300
2	300-2000
3	300-3500

School	CO_2 levels [ppm]
	Range
4	310-2830

In the UK studies in most cases the CO_2 range during the occupation of the classrooms was above 1000 ppm.
The overall air quality in educational buildings is usually worse than the normative allows. A similar situation can also be found in Estonian schools.
In Estonia the internal climate in educational buildings has been studied and analyzed in different investigations [41, 42, 43, 44, 45, 46, 47, 48, 49].
A comprehensive theoretical analysis of the air change rate and CO_2 levels generated by occupants and level prediction possibilities with simulation calculations has been carried out [50] by T. Lu, A. Knuutila, M. Viljanen, X. Lu.
An interesting study of natural ventilation possibilities in schools has been conducted in the UK [51]. The results are in Table 3.

Table 3. Natural ventilation: CO_2 levels during 8:40-15:00

Weekday	CO_2 levels [ppm]	
	Average	Range
Monday	1504	601-2804
Tuesday	1303	489-2718
Wednesday	735	296-1770
Thursday	691	341-1940
Friday	1208	345-2608

The figures are promising but in reality they are achieved by opening the windows. There are also several other parameters of indoor climate that affect the indoor air quality and thermal comfort negatively. Therefore this solution should not be recommended for educational buildings. It is also necessary to carry out a study throughout a year. Furthermore, the Sick Building Syndrome (SBS) caused by insufficient air change is very dangerous in children's institutions [52, 53, 54].
It is commonly known that the indoor climate and the CO_2 levels depend on the type of ventilation and its functioning [55], Table 4.

Table 4. CO_2 levels for different types of ventilation

Room	CO_2 levels, [ppm]		Ventilation type
N^o	Average	Max	
1.1	960	1857	Natural
1.2	1054	1725	Natural
2.1	789	1047	Mechanical
2.2	733	880	Mechanical
3.1	853	1472	Hybrid
3.2	1100	1615	Mechanical

Room Nº	CO_2 levels, [ppm] Average	Max	Ventilation type
4.1	1801	4016	Natural
4.2	1255	2676	Natural
5.1	1536	3181	Natural
5.2	2636	5567	Natural
6.1	1185	2570	Natural
6.2	1391	2585	Natural
7.1	1972	2530	Natural
7.2	1778	3109	Natural
8.1	932	2578	Natural
8.2	1031	2488	Natural
9.1	1695	3359	Natural
9.2	1199	2590	Natural

1.4 Heat pumps for district heating and cooling

The European Union 20-20-20 targets emphasize the implementation of renewable energy sources in the energy balances of the member states. Sea water is a large renewable energy source, which can be combined with reversible heat pump technology to produce both thermal and cooling energy. The working principle is similar to geothermal energy production, but sea water allows better utilization of free cooling during the spring and autumn periods. The heat pump technology is studied widely around the world. A comprehensive review of the implementation possibilities of heat pump systems in different fields and also recent improvement with the coefficient of performance (COP) has been presented [56] by K.J. Chua, S.K. Chou and W.M.Yang. The rapid growth of heat pump technology in 2005-2010 has been documented [57, 58]. The feasibility of the technology of the sea water heat pump is compared with conventional district heating, in case the network radius is less than 5 km [59]. The calculation includes the losses of electricity production in coal-fired plants and the pumping costs. When electricity is produced from natural gas, the radius decreases. The feasibility of different production options of district heating and cooling has been studied [60] by Haiwen Shu, Lin Duanmu, Chaohui Zhang and Yingxin Zhu. The life cycle costs are included (installation, system operating, maintenance costs). Sea water district heating and cooling is 1.5 times more expensive in China, due to the relatively low price of coal-produced electrical energy. All economic calculations should be carried out separately for each project. Indirect sea water cooling for Japanese commercial buildings has been researched [61] by Young-hak Song, Yasunori Akashi and Jurng-Jae Yee. A thermal storage tank of 4500 m^3 is used. The storage tank covers 32% of the peak load of cooling. The difference of water temperature utilized is 7K (5-12 ^oC). The cooling capacity of chillers is 2.3 MW. Bigger benefit was received by reducing maintenance costs (not suggestable) and slight saving was achieved by lowering the initial cost. The boiler plant and heat pump technologies were compared using the quasi-dynamic energy-saving calculation [62]. The static calculations that the authors presented earlier the same year (2010) underestimated the feasibility of sea water district heating and cooling by 20%. A similar study has been carried out in Japan [63]. Compared to conventional systems (the cooling tower and heating boiler plant) a saving of 29% was achieved for district cooling and 5% for district heating. In Sweden the short and long term impacts of heat pump technology have been compared with district heating systems [64]. In total 6 TWh of thermal energy was produced in Sweden in 2007. The energy optimization tool MODEST was used for systems modelling. In the total thermal energy balance of Sweden, although heat pump systems for district heating will be developed on a small scale, combined heat and power from renewable energy resources (CHP) is preferred. Nevertheless, in the case of Estonia the share of cooling energy of the selected buildings is higher than that of thermal energy. Therefore in certain coastal areas free cooling from sea water could be feasible and ecologically friendly. In Germany de-nuclearization as a process has been started [65]. Storage and transportation possibilities of renewable energy have been presented in the article. The problems have been laid on the table, but solutions are still fully open. In Greece the demand for cooling largely dominates over the heating demand [66]. The proposed systems are the opposite of our solutions – extra cooling towers are used to cover peak cooling loads. Heat pumps have been suggested to meet the average demand for heating and cooling buildings. Groundwater open loop heat pump systems have been researched [67]. The water storage tank is used either on the side of chilled water or groundwater. On the side of chilled water a 10% saving was achieved due to a better COP. A study of environmental impacts of different heat sources (the coal boiler, gas boiler and heat pump with different COP) has been presented [68]. All the heat pumps with the COP > 2.5 are more environmentally friendly to install than gas boilers. Coal boilers should be avoided. Low temperature heating will give a better COP [69]. In our case of sea water district heating and cooling new buildings will have low temperature heating and in the existing buildings high temperature district heating will be combined with the heat pump system. Different connection possibilities have been presented in the research on combining the existing district heating and the new heat pump technology [70]. The optimization study of heat pump heat exchangers [71] gives a comprehensive overview of the selection principles of the heat exchanger. Different new implementation options and heat pump refrigerants have been presented in exhaustive articles [72, 73, 74, 75, 76, 77, 78]. The feasibility and technical possibilities are closely related to different boundary parameters: - the temperature profile and salinity of sea water; - outdoor climatic conditions;

- the geology of the coastal area;
- the possibilities of constructing sea water and district network pipelines;
- the heating and cooling loads of the connectable buildings;
- the temperature regimes of the pipelines;
- secure energy supply.

2. The calculation methods of energy consumption

2.1 Degree day calculations

The current method for the energy auditing of typical residential buildings belongs to the field of thermal engineering and construction [79]. The method is mainly used as a simplified way of calculating energy consumption. Variable degree-days and specific heat losses are used to determine the energy consumption for heating. The balance temperature is determined by a package of measures. The free heat load of a residential building is determined by the factor of free heat utilization, which depends on the control level of the heating system. The method suits well for typical apartment buildings. Due to different window areas in other types of residential buildings the proportion of free heat from solar radiation varies, therefore template calculations cannot be applied.

Determination of free heat in a residential building

The sources of free heat in the building are people, electric devices, electric lighting and solar radiation.
The main components of the free heat load are calculated using the formula (1).

$$\Phi_{AFH} = \Phi_{PEOP} + \Phi_{LIGHT} + \Phi_{EQUIP} + \Phi_{SOLAR}, \qquad (1)$$

where Φ_{AFH} is the average free heat load, [kW]; Φ_{PEOP} is the average effective free heat load from people, [kW]; Φ_{LIGHT} is the average effective free heat load from electric lighting, [kW]; Φ_{EQUIP} is the average effective free heat load from equipment, [kW]; Φ_{SOLAR} is the average effective free heat load from solar radiation, [kW].

The respective free heat loads Φ_{free} are determined by the amounts of free heat energy Q_{free}
and the duration of the respective period τ (2)

$$\Phi_{free} = 1000 \cdot Q_{free}/\tau \qquad (2)$$

where Q_{free} is the free heat energy of the building, [MWh]; τ is the duration of the period, [h].

Determination of the balance temperature on the basis of free heat

On the basis of degree days it is possible to calculate the heat requirements for heating a building using the formula (3)

$$Q_k = H \cdot S \cdot 24 \cdot 10^{-3} \quad (3)$$

where S is the number of degree-days corresponding to the balance temperature of the building; 24 is the number of hours in a day; H is the specific heat losses, [kW/K], determined by the formula (4).

Specific heat losses of the building

$$H = \sum_{i=1}^{n} U_i \cdot A_i + L \cdot c \cdot \rho \quad (4)$$

where U_i is the U-value of envelope element i, [W/(m^2·K)]; A_i is the area of envelope element i, [m^2]; n is the number of different envelope elements; L is the air change, [m^3/s]; c is the specific heat of the air, [J/(kg·K)]; ρ is the density of the air, [kg/m^3].

To show the heat conservation obtained by renovation more precisely, it is expedient to use the degree days with a variable balance temperature.
In renovating a building (e.g. insulating the envelope elements) the specific heat losses decrease and thus affect the balance temperature.
The internal air temperature of a building is made up of the heat provided by the heating system and free heat (5)

$$t_{int} = t_{ext} + \Delta t_{heat} + \Delta t_{fh} \quad (5)$$

Balance temperatures can be calculated using the formula (6)

$$t_B = t_{int} - \Delta t_{fh} \quad (6)$$

where t_{int} is the internal air temperature; t_{ext} is the external air temperature; t_B is the balance temperature; Δt_{fh} is the rise in the temperature due to free heat playing a role in the heat balance of the building.

The rise in the temperature due to free heat can be calculated applying the formula (7)

$$\Delta t_{fh} = 1000 \cdot \Phi_{free} / H \quad (7)$$

The useful free heat load needed to determine the balance temperature is determined by the formula (8)

$$\Phi_{free}=\Phi_{dfree}*\eta \qquad (8)$$

where Φ_{dfree} is the design free heat load, [W]; *H* is the utilization factor.
The value of the utilization factor depends on the control level of the heating system. (e.g. if the temperature of the flow water of the heating systems is controlled by the external air temperature and the heat output of the radiators is controlled, we can make more use of free heat than if we control only the temperature of the flow water).
Calculations show that following complex renovation of apartment buildings the use of the balance temperature makes it possible to specify the saving calculations considerably well. This can be seen in the duration graph of the external air temperature Fig. 1.

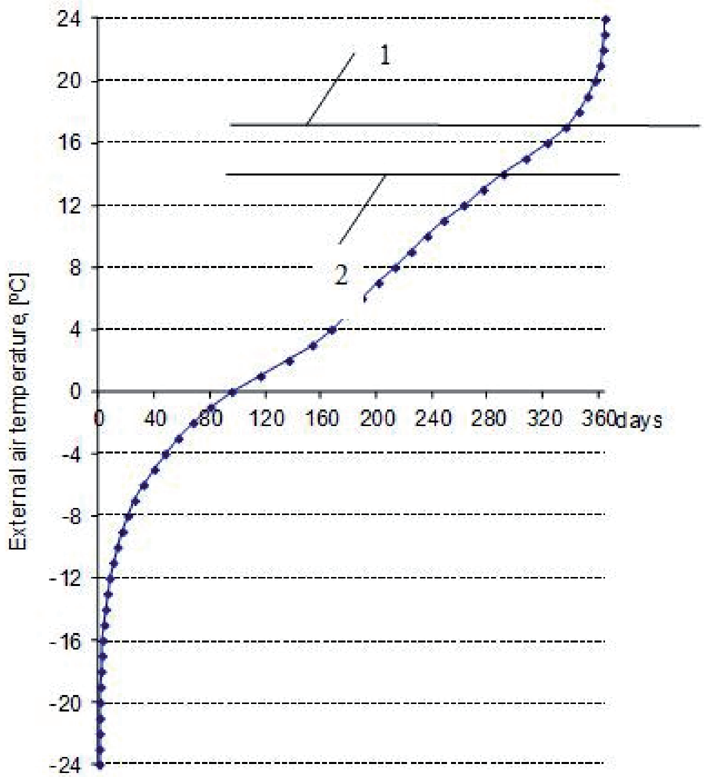

Fig. 1. Duration diagram of external air temperature in Tallinn and different balance temperatures: 1-tb=17°C; 2- tb=14°C

The diagram in Fig. 1 shows that a decrease in the balance temperature brings about a decrease in the area between the balance temperature and the external air temperature, which is proportional with the heat requirements of a building.
The analysis carried out showed that the calculation method based on free heat is more precise than the graphic one [80].
It is simple to consider the joint effect of the saving measures and to assess the amount of minimum investment of the saving package necessary from the standpoint of the construction of the building and indoor climate in typical apartment buildings.

2.1.1 Comparison of degree day calculation and dynamic simulations

The following presents a comparison of two different calculation methodologies: the degree-day method and calculation of energy demand with dynamic simulation tools for apartment buildings.
In 2009 research on energy consumption was conducted for apartment buildings in the major cities of Estonia. Real measuring of energy consumption has been compared with the calculation methods. As calculation methods both degree-day and dynamic simulations were carried out. In total 12 apartment buildings in the towns of Tallinn, Tartu and Narva were studied. Energy consumption of real measurements and dynamic simulations was compared.
Theoretical original condition and two renovation packages were calculated with both calculation methods. Dynamic simulations were carried out using software BV^2.

- Package 0 contains an original typical Soviet apartment building. The thermal conductivities of the envelope have not been changed. The air change rate is 0.45 [1/h] in theoretical calculations.
- Package A contains the following renovations – the heating system has been replaced and equipped with thermostatic valves. The side walls and roof of the building have additional thermal insulation. The windows and doors have been replaced with modern ones. The calculated air change rate is 0.6 [1/h].
- Package B includes all package A renovations. In addition, the front walls have additional thermal insulation.

The calculation results can be seen in Fig. 2. The results do not include the energy consumption of domestic hot water heating.

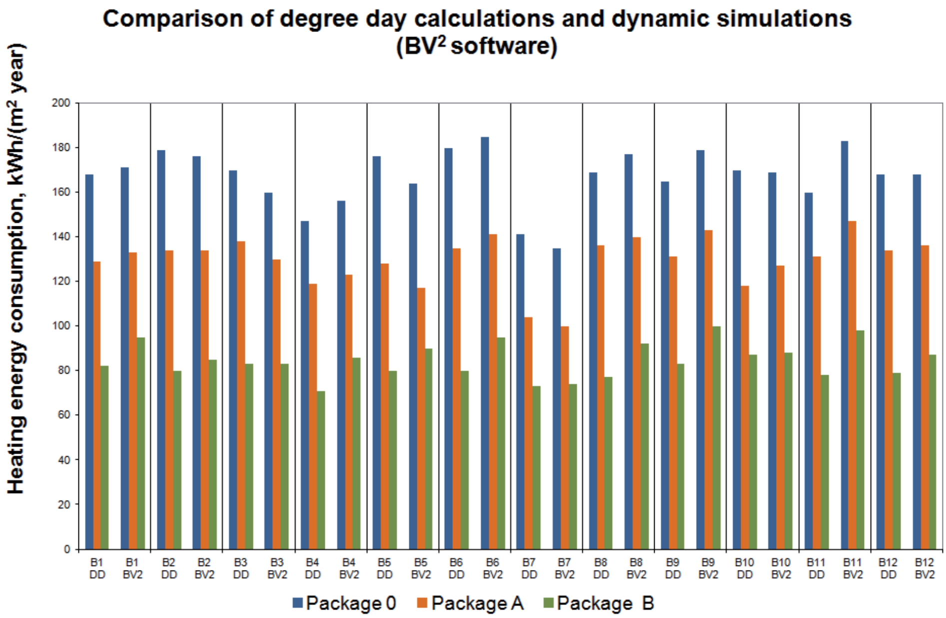

Fig. 2. Calculated and measured heating energy consumption

The results show sufficient accuracy between degree day and dynamic simulation calculations, but there are some major issues to be kept in mind with using the degree-day method:

- the selection of buildings was among typical Soviet prefabricated panel apartment buildings;
- only a few different window sizes were included in the calculations, so the degree-day method cannot be applied for different window areas (e.g. for new apartment buildings);
- the degree-day method cannot be applied to detached houses either due to different window areas and internal heat gains compared to the researched buildings;
- the degree-day method is well applicable for retrofit estimations of old apartment buildings;
- if the solar heat gain and window relation can be presented in more detail, the degree-day calculations can also be well fitted for new apartment buildings and detached houses. Currently the effect of solar heat gain is under research.

2.2 Dynamic simulations

The calculation method to verify the conformity of buildings to energy performance requirements in Estonia is the dynamic simulation. The regulation on the minimum energy performance requirements of buildings came into effect in Estonia in 2007

(EGo ordinance no. 258, 2007). It applies to new buildings as well as significantly reconstructed existing buildings. Compliance with the requirements for a building is checked when the building permit is issued by the local government. The minimum energy performance requirements are expressed as an energy performance value: the EP-value, [kWh/(m^2 year)]. Besides the energy performance value, summer indoor temperatures should be checked to see if they fulfil the requirements. The EP-value is calculated applying the formula (9):

$$\text{EP-value}=\frac{1000}{A_H}\cdot\left(Q_H\cdot C_H+Q_C\cdot C_C+Q_V\cdot C_V+Q_{HW}\cdot C_{HW}+Q_{EL}\cdot C_{EL}\right),$$

kWh/(m^2 year) (9)

where Q_H and Q_C are annual energy consumption for heating and cooling, Q_V is annual energy consumption for ventilation, Q_{HW} is annual energy consumption for hot water, Q_{EL} is annual electricity consumption (lighting, equipment, ventilators, pumps, etc.) and C_H, C_C, C_V, C_{HW}, and C_{EL} are coefficients which take into account the effectiveness of primary energy production and the impact of a particular source on the environment (e.g. wood-based fuels 0.75, district heating 0.9, natural gas 1, electricity 1.5). In Estonia these factors have been determined by political, economic and technical aspects. A_H is the size of the heated floor space.

The energy performance value is calculated for buildings in standardized use (certain indoor temperatures, internal heat gains and their profiles, ventilation, etc.). Calculations for EP-values should be done using dynamic simulation software. Dynamic simulation tools have to allow including data on outdoor weather, indoor temperatures, building envelope, different building systems, building utilization profiles, etc. to make it possible to carry out the annual calculation.

According to the previous regulation on the minimum energy performance requirements of buildings, the EP-values in apartment buildings should not exceed 150 [kWh/(m^2 year)] for new buildings and 200 [kWh/(m^2 year)] for significantly reconstructed buildings. During the summer period the upper limit for the duration of 27ºC is 150 degree-hours [ºCh]. In this study energy performance is analyzed for typical apartment buildings to determine a possible change in the EP-values in Estonia.

The analysis of energy performance requirements for apartment buildings

Hereby, the simulation results of significantly reconstructed five-storey apartment buildings are presented. Dynamic simulations have been done with IDA Indoor Climate and Energy 4,0 software. Estonian Test Reference Year [81] is used for outdoor climate. The simulation model is validated with the energy consumption figures of the last three years and the data on indoor climate measurements. The measured weather dependent energy consumption is corrected with the simple degree-day's method (balance temperature $t_{bal} = 17$ ºC).

Dynamic simulation cases

Solutions of different structure and building systems are calculated to find out the reliability of energy performance values for apartment buildings (Table 5.):

Version A. An existing validated building (envelope not corresponding to contemporary requirements – poorly insulated walls, roof; un-insulated basement floor; windows, balcony doors partly replaced; external doors replaced; no thermostatic valves installed to heating radiators; natural ventilation);

Version B. A partly renovated building in standard-use conditions (insulated side walls, roof; windows, balcony doors replaced; thermostatic valves installed to heating radiators; mechanical exhaust ventilation);

Version C. A fully renovated building in standard-use conditions (insulated walls, roof; windows, balcony doors replaced; thermostatic valves installed to heating radiators; de-centralized mechanical ventilation with heat recovery of exhaust air);

Version D. Building structures meet the requirements according to Estonian standard EVS 837-1:2003.

Version E. A low energy consuming building in standard-use conditions.

Table 5. Building structures and systems

	Version				
	A	**B**	**C**	**D**	**E**
Thermal conductivity U, [W/(m^2·K)]					
External wall	1.0	0.3	0.3	0.24	0.1
Roof	0.8	0.27	0.27	0.19	0.08
Floor	0.6	0.6	0.6	0.31	0.13
Windows	2.5	1.7	1.7	1.2	0.6
Exterior doors	0.8	0.8	0.8	0.6	0.4
Balcony doors	1.7	1.7	1.7	1.7	0.6
Air tightness of building envelope q_{50}, [m^3/(h·m^2)]	4	3	3	3	0.6
Ventilation air change rate, [l/(s m^2)]	0.3	0.42	0.42	0.42	0.42
Heat recovery temperature efficiency, [%]	0	0	60	60	85
Exhaust air min temperature, [ºC]	-	-	5 °C	5 °C	0 °C

2.2.1 Energy performance requirements for apartment buildings

Annual specific energy consumption was simulated for each version. The calculations of the EP-values were based on the efficiency of heating systems and coefficients for primary energy consumption, see Fig. 3.

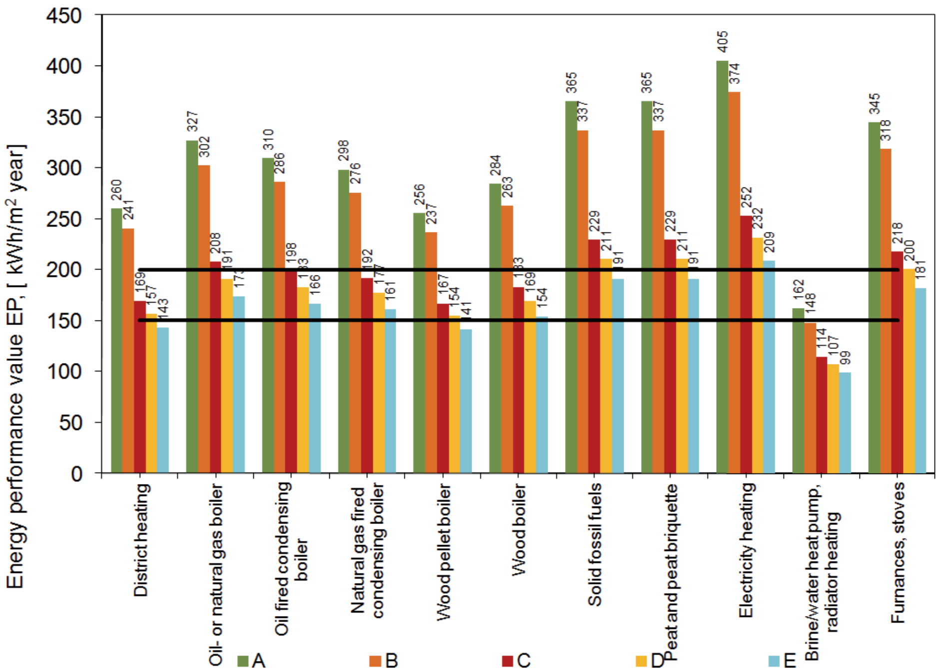

Fig. 3. Results of the EP-value for apartment buildings (horizontal lines represent EP-requirements for new and existing buildings 150 and 200 [kWh/(m^2 year)])

The results of dynamic simulation show that in Estonia the limits of the EP-values for new and significantly renovated buildings are achievable, but a little challenging for the existing apartment buildings.

For new apartment buildings whose building envelope (U-values) meets the requirements according to the Estonian standard EVS 837-1:2003 and the heating energy of which is provided by a district heating network, the EP-value is very close to the requirement value (157 and 150 [kWh/(m^2 year)] respectively). Supply and exhaust ventilation with heat recovery is necessary for new apartment buildings to fulfil the limit of the EP-values. Heat recovery efficiency of 0.6 was used in these simulations. As the EP-value was very close to the requirement value, a more efficient ventilation system could be used.

For significantly reconstructed apartment buildings a ventilation system with heat recovery is technically possible. Decentralized ventilation systems and heat pump solutions are available nowadays.

There is a great difference in the EP-values between heat pumps and other heating systems. It is caused by the low weighting factor for electricity. Therefore the factor 1.5 will be changed to 2.0.

2.3 Combination of dynamic simulations and optimization

In this section the dynamic of the window area, the solar factor versus cooling and heating energy consumption in different cardinal directions are described. Due to the fact that the energy consumption of the façade is evaluated, other building envelope parameters and internal heat gains are handled as constants.

Hendrik Voll and Teet-Andrus Kõiv have published an article about the principles of estimating the demand for cooling power and the relations between different parameters for commercial buildings [82], but energy consumption has not been researched earlier.

Many researchers describe building simulation software as a tool for the calculation process. IDA Indoor Climate and Energy, TRNSYS, Energy Plus, eQuest, DOE-2, etc. are well-known software used to create building models and to perform the necessary simulations of energy consumption and indoor climate condition. These tools have been tested and validated through real experimental cases. The simulation tools are usually used to perform limited numbers of single runs to give an overview and conclusions of a defined task. As these kinds of software are used to conduct hourly based calculations throughout a whole year, sufficiently accurate results of energy consumption are achieved. The probability for these results to run across the optimum solutions of Pareto frontier is actually very low. One possibility to find an optimal solution is to use a 'brute force' search. This method needs huge calculation resource due to the fact that all possible combinations are evaluated [82].

A reasonable approach to achieving an optimal solution is to combine building simulation tools and optimization software. Optimization software can be customized for a particular research. Another possibility is to use an existing solution such as Lawrence Berkeley National Laboratory branded GenOpt or Matlab's Optimization Toolbox.

Different optimization algorithms are implemented in the optimization software. Generally the algorithms are divided into single and multi-objective. The selection of the algorithm depends on the constraints and/or the number of functions to be optimized. Multi-objective functions can be solved, for example, with the Matlab Optimization Toolbox, single objective functions with GenOpt.

Technically it is most challenging to combine simulation and optimization tools. All earlier studies indicate problems with computational hardware power – the calculation time is related to the number of variables and functions.

Our research is focused on the strategies of heating and cooling energy consumption for office buildings. Early stages of design affect future energy consumption for the building most. The objective of this research is to develop quick selection charts for different cardinal directions in relation to the window area and other envelope parameters.

2.3.1 Optimization of office building façades

A theoretical office building model with conventional use and contemporary building systems has been developed for façade optimization in continental climate. Wall, glazing area and window parameters were taken as the main variables. The objective function of the optimization task described in this dissertation is the minimization of cooling and heating energy consumption. Optimization of office building façades was carried out using the combination of IDA Indoor Climate and Energy 4.5 and GenOpt. The process is described in detail so that the approach may be emulated. A hybrid multidimensional optimization algorithm GPSPSOCCHJ was used in the calculation process. The optimization results are presented in four quick selection charts to assist architects, designers and real estate developers in making suitable early stage decisions on façade selection.

The building model

An approach for the building shape was created in the IDA Indoor Climate and Energy 4.5 environment. A square shaped three floor model (floor height 3.0m) is shown in Fig. 4.

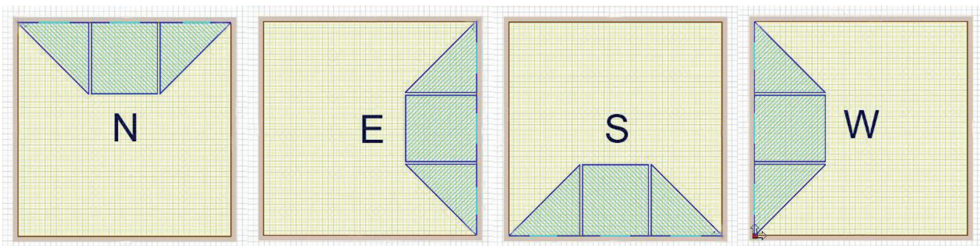

Fig. 4. Shape of the theoretical calculation model

A typical office building is very often a multi-storey compact structure. Therefore, calculations were done in this case for the first floor to eliminate the physical effects of the ground and roof. The outdoor climate is based on the data of Table 6, but with an accuracy of one hour. Indoor climate requirements and conventional use of office buildings are shown in Table 7, Fig. 6.
Table 8 includes the data on the main envelope and HVAC systems for the model.

IDA ICE 4.5 and GenOpt combination

As the first step, the IDA ICE mathematical model run creates a substantial ida_lisp.ida file with all defined data and relations between the parameters. The main structure of ida_lisp.ida consists of files, constants, tables, modules, connections, boundaries, start values, integration and log. To understand the relationships between the different parameters is technically challenging. The whole logic has to be understood and tested. For example, an increase in the window area must decrease the same face wall area and vice versa in the optimization calculations. The solar factor and shading coefficients also have mathematical correlation. To create the base IDA ICE model file for optimization calculations we renamed the ida_lisp.ida file as templ.ida and modified the envelope parameters mostly in the modules section. The basic scheme of optimization is shown in Fig. 5.

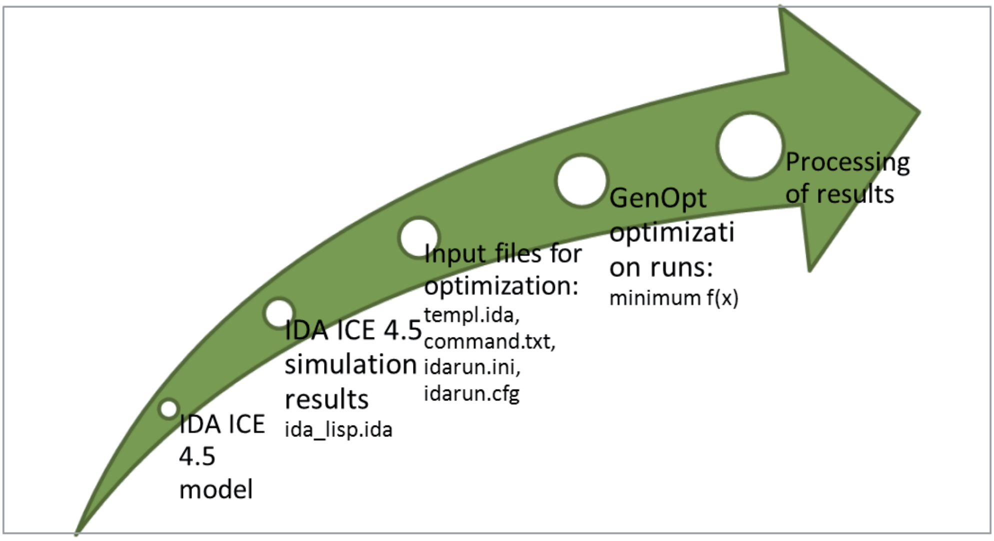

Fig. 5. IDA ICE and GenOpt simulation-optimization process

Convenient search and study of certain parameters in the ida_lisp.ida file can be achieved by giving clearly identified parameter values in the IDA ICE model to a particular module (glass, wall, etc.). Understanding of the total ida file puzzle is time-consuming, but unavoidable for the optimization of IDA ICE calculation results with optimization tools.

The second step is to create a command.txt file and define variables for the optimization process. GenOpt can handle discrete and continuous variables [83].

Preprocessing relations between different building parameters are also described in the command.txt file. For the current paper the correlations between the wall-window and solar factor-shading coefficients were defined (see the following code).

```
Vary { Parameter { Name = A1win; Min = 1.2; Ini = 1.2; Max = 10.8; Step = 1.2; }
Function { Name = A1wall;   Function = "subtract (12.0, %A1win%)";}
Function { Name = A2wall;   Function = "subtract (11.124, %A1win%)"; }
Parameter { Name = sfGl;   Min = 0.2;   Ini = 0.2;   Max = 0.8;   Step = 0.2; }
Function  { Name = tGl;   Function = "multiply (0.87, %sfGl%)"; }}
```

Furthermore, the command.txt file must also contain information about the optimization algorithm.

The actual optimization process was carried out with the GPSPSOCCHJ algorithm [85]. GPSPSOCCHJ is a hybrid multidimensional optimization algorithm, which uses generalized pattern search (GPS) for the first stage search and particle swarm optimization (PSO) Hooke Jeeves algorithm as a fine search for the solution of a defined discrete and continuous variable function.

The configuration file idarun.cfg is written only once and it describes the IDA ICE simulation run parameters.

The third essential file idarun.ini contains information about the locations of the template, input, log, output, configuration and optimization files. The most important idarun.ini information is the objective function (in our case the minimization function) definition. Constraints can be set to the optimization function, if necessary. The first stage of postprocessing is also done here. For the different cardinal directions, our study uses the following IDA ICE templ.ida related code:

```
Name1  = Energ_kWh;      Function1   = "add(%Cool_kWh%, %Heat_kWh%)";
Name2  = negCool_kWh;    Delimiter2  = "Emeterloccool.Totenergy";
Name3  = Cool_kWh;       Function3   = "multiply(%negCool_kWh%, -1)";
Name4  = Heat_kWh;       Delimiter4  = "Emeterlocheat.Totenergy";
Name5  = WinN_SF;        Function5   =  %sfGl% ;
Name6 = Win_m2;          Function6  =  %A1win% ;
Name7 = Wall_m2;         Function7  =  %A1wall% .
```

Our minimization leading function min f(x) is the minimization sum of cooling and heating energy related to external wall-glass parameters. Delimited energy information is recorded separately; therefore we can also present the balance between cooling and heating separately.

Outdoor climate

Test reference years are widely used for energy performance calculations and indoor climate analysis. Hourly based outdoor climate data (dry-bulb air temperature, relative humidity, wind speed, direct solar radiation and diffuse radiation on horizontal surfaces for 12 months) were used to create the mathematical model for IDA ICE 4.5 calculations. Comparison of the current study results for other climatic areas can be done through average monthly and yearly parameters, which are indicated in Table 6.

Table 6. Test reference year parameters

Month	Air temperature [°C]	Relative humidity [%]	Wind speed [m/s]	Direct solar radiation [MJ/m^2]	Diffuse radiation on horizontal surface [MJ/m^2]
Jan	-3.0	90	5	35.0	39.2
Feb	-5.2	89	4	93.4	82.0
Mar	-0.1	76	4	308.1	144.2
Apr	4.0	77	4	254.4	190.2
May	11.2	70	4	493.3	269.6
Jun	14.1	73	3	497.8	306.1
Jul	17.2	77	3	606.1	290.8
Aug	15.7	81	3	453.6	229.7
Sep	10.8	82	4	259.0	161.3
Oct	5.8	87	4	143.8	82.9
Nov	-0.1	91	4	68.2	37.0
Dec	-2.5	86	5	49.7	20.8
Avg.	***5.7***	***81***	***4***	***271.9***	***154.5***

Indoor environment and comfort

Category II requirements of EN 15251:2007 were taken as the basis for defining indoor climate in the simulation-optimization models. This category is considered as the normal expectation for new buildings and renovations according to reasonable indoor climate and energy efficiency levels [84].
Table 7 includes the indoor climate parameters used for the calculations.

Table 7. Indoor climate criteria

Indoor environment parameters	Constraints
Thermal conditions in winter for energy calculations	20-24 °C [21 °C]
Thermal conditions in summer for energy calculations	23-26 °C [25 °C]
Personnel insulative clothing	~0.5 [clo] summer ~1.0 [clo] winter
Personnel activity level	~1,2 met
Airflow to zones	7 l/s person [1.4 l/s m^2]
CO_2 level (outdoor 350 ppm)	< 850 [ppm]
Relative humidity	25 – 60 [%]
Allowed parameter deviation (working hours)	*3[%]*

Conventional use of an office-building

Internal heat gains in an average office area are presented in Fig. 6 [85]. The profile and detailed loads for occupants, equipment and lights were used for calculations in the IDA ICE 4.5 mathematical model. The profile is used from Monday to Friday –

in the theoretical calculations internal heat gains were not estimated for the weekend.

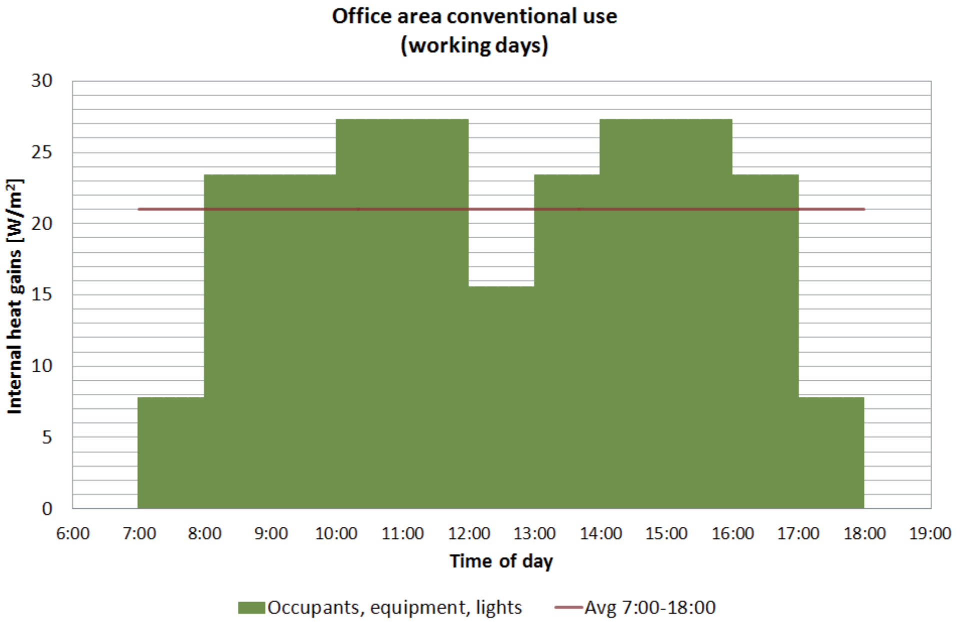

Fig. 6. Internal heat gains of a typical office area

Building envelope and technical services

The U-values of the building enclosure were selected to be challenging but possible to achieve in the construction practice for a "low energy building" [86]. Typical thermal bridge values have been used in the calculations (the effect of thermal bridges on the heat loss achieves more importance in case superb heat transfer coefficients are utilized). HVAC systems and other IDA ICE 4.5 simulation input parameters are indicated in Table 8.

Table 8. Building envelope and HVAC systems parameters

Heat transfer coefficient of the external wall U_w	0.14 [W/(m^2 K)]
Heat transfer coefficient of window glass U_{wg}	0.8 [W/(m^2 K)]
Heat transfer coefficient of the window frame U_{wf}	2.0 [W/(m^2 K)]
External wall/ external wall thermal bridge	0.08 [W/K/(m joint)]
External window or door perimeter thermal bridge	0.03 [W/K/(m perimeter)]
Infiltration q_{50}	1.0 [m^3/(h m^2)]
Building wind exposure	Semi-exposed (pressure coefficients)
Heat recovery of the air handling unit (AHU)	80 [%]
AHU SFP	1.7 [kW/(m^3/s)]
AHU t_{supply} to zone ($t_{AHU\ supply}$ = 16°C)	18 [°C]

Optimization of the case and results

In Table 9 below the optimization parameters are defined.

Table 9. Optimization parameters

Variable	Type	Value
Window area	Continuous	10-90%, step 10%
Glass solar factor	Continuous	0.2-0.8, step 0.2
Cardinal directions	-	North, East, South, West

Four optimization runs were carried out.

GenOpt optimization solver calculated a total of 658 iterations during four optimization runs for different façade directions. The calculation and post-processing results are presented in the following 4 figures (Fig. 7, Fig. 8, Fig. 9, Fig. 10).

Total energy consumption is found from the graphs as the average net energy demand of the four selected façades [kWh/(m^2 year)].

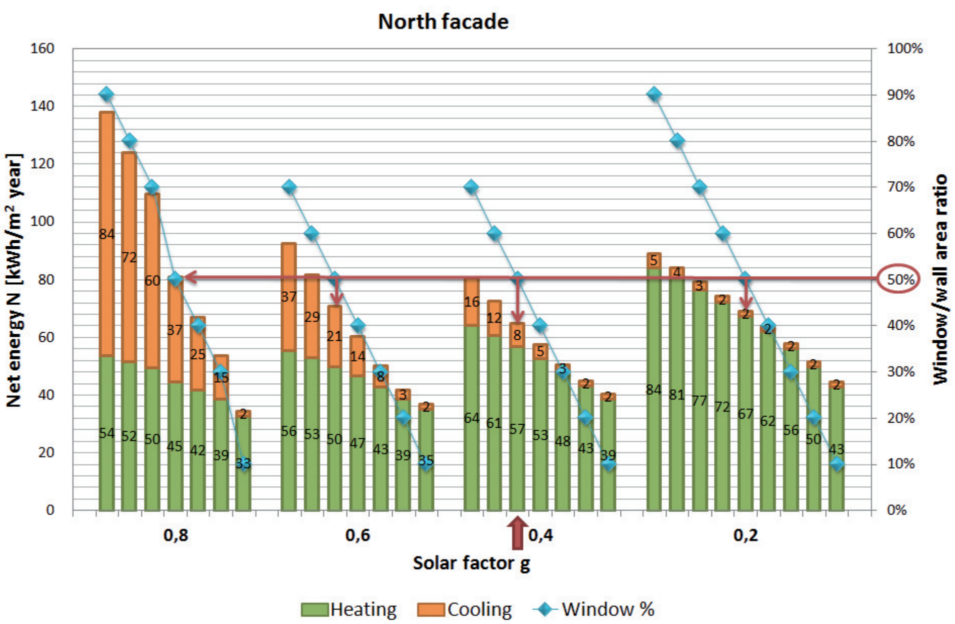

Fig. 7. Optimization results of the northern façade

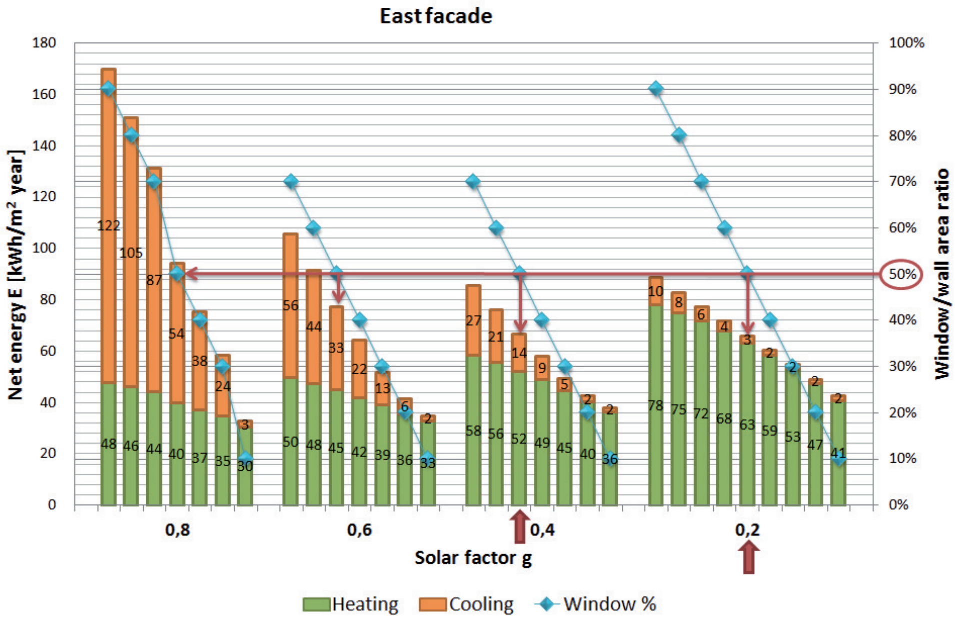

Fig. 8. Optimization results of the eastern façade

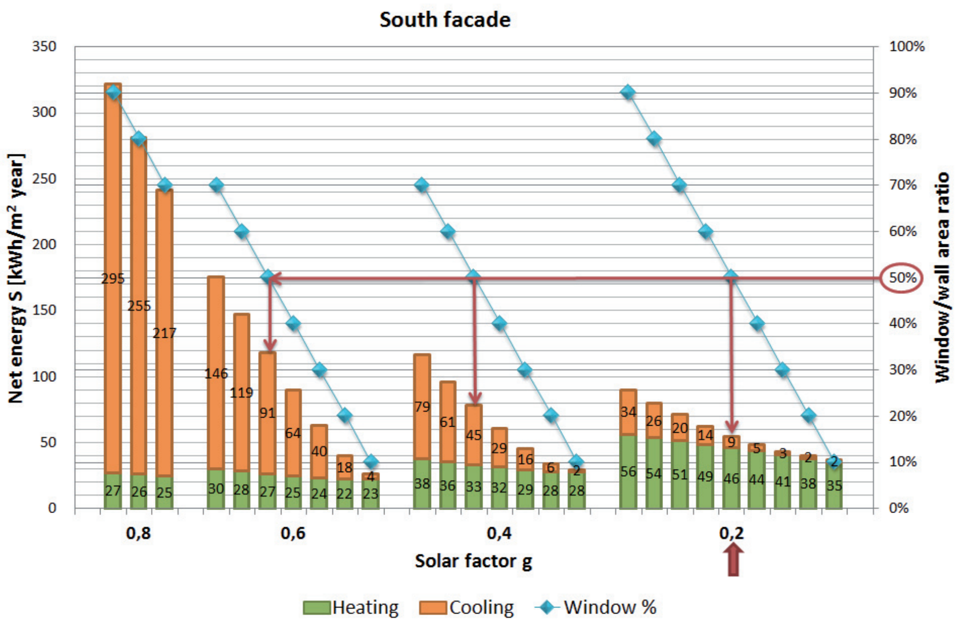

Fig. 9. Optimization results of the southern façade

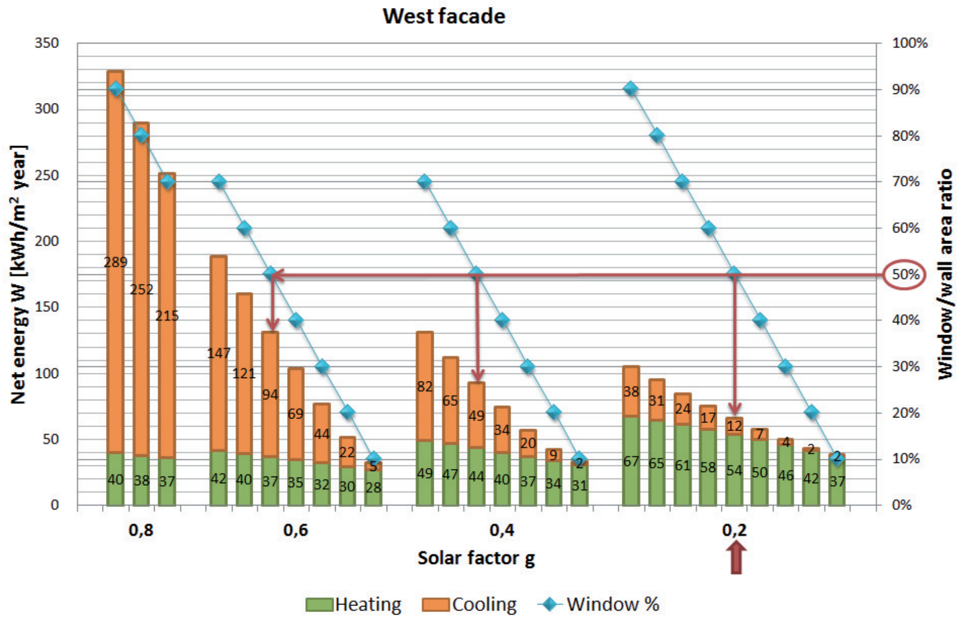

Fig. 10. Optimization results of the western façade

The window/wall area ratio (indicated in the secondary axis) will be the primary directive selection parameter. Energy consumption is directly related to the window/wall ratio and window glass parameters.

In continental climate conditions with warm summers the solar factor of 0.4 can be suggested for northern and eastern façades due to higher heat energy demand. Southern and western façades must have as good a solar factor as possible (in our case 0.2). High solar factor values must be prevented for all cardinal directions of the façade even in a cold climate.

These quick selection figures (Fig. 7, Fig. 8, Fig. 9, Fig. 10) can be used by building architects and developers to make the first quick-selection of the energy consumption of the building façades. According to the Energy Performance of Buildings Directive (EPBD) the EU member states must define nearly zero energy building levels. For new buildings it will be a challenging task to achieve these levels by 2020, therefore, the current selection charts provide additional information for early stage estimation of the energy consumption of buildings. .

To study the sensitivity of the above results some single runs for a double skin façade were carried out. The same principles are applicable for different cardinal directions. The internal envelope must be thermally well insulated for current climate conditions. The total solar factor (for both internal and external glazing) will also have the suggested values. For double skin façades the U-value of windows has a direct effect on the energy consumption for windows.

Furthermore, Tobias Rosencrantz [87] has published the calculation results of heating net energy for façades in different cardinal directions for similar climatic conditions in Sweden and there is only slight deviation from our results.
Several IDA ICE single runs showed acceptable indoor climate with the solar factors of 0.2 and 0.4.

3. Investigation of energy consumption and building services

3.1 Residential buildings

3.1.1 Energy consumption in apartment buildings

In total thermal and electrical energy consumption of 40 buildings (2006-2010) was collected and analyzed. Detailed analysis of energy balance was carried out for 14 buildings. Information about reconstruction, heating source, internal air temperature, air change rate and domestic hot water production is presented in Table 10.
The following abbreviations are used: DH - district heating; WB - wood fired boiler; GB - gas fired boiler; DHW - domestic hot water; ACH - air change rate; HS - heating substation; EL - electrical heaters; win – windows (shows the percentage of replaced windows); bal - balancing work; full - full reconstruction.

Table 10. Main information about researched buildings

Bld.	County	Reconstruction		Heating source	$T_{int\ avg}$	ACH	DHW
		Envelope	Heating system		[°C]	[1/h]	
A1	Pärnu	-	-	DH	20.0	0.40	HS
A2	Harju	2010 roof 300mm, <2010 win 86%	2007 HS, 2008 bal	DH	20.0	0.40	HS
A3	Saare	2006 roof 400mm, 2007 win 66%	2000 HS	DH	22.5	0.27	HS
A4	Tartu	2001 win 100%	2001 HS	DH	23.0	0.25	HS
A5	Harju	<2010 win 85%	-	GB	20.0	0.30	HS
A6	Ida-Viru	<2010 win 54%, walls 100mm 36%	2003 HS, 2007 bal	DH	20.5	0.20	HS

Bld.	County	Reconstruction		Heating source	$T_{int\ avg}$	ACH	DHW
		Envelope	**Heating system**		**[^{o}C]**	**[1/h]**	
A7	Harju	2009 roof 200mm, <2010 win 93%	1997 HS, bal	DH	21.0	0.40	HS
A8	Viljandi	<2009 win 89%	2008 full	DH	21.0	0.33	HS
A9	Jõgeva	-	-	DH	19.0	0.35	EL
A10	Põlva	-	-	DH	23.0	0.24	EL
A11	Ida-Viru	<2008 win 47%	-	DH	19.0	0.31	EL
A12	Valga	<2008 win 63%, doors	-	DH	22.0	0.30	EL
A13	Harju	<2009 win85%	<2009 HS	DH	21.0	0.20	HS
A14	Tartu	<2009 win 77%	-	DH	19.5	0.20	EL

During the actual research, energy audits prepared by professional auditors were evaluated. In numerous cases systematic errors were found. DHW is prepared with decentralized electrical heaters, but the auditors have calculated once again the DHW energy consumption in the heating energy balance, which is not correct. In the current energy balance calculations all the mistakes have been corrected. Furthermore, the packages of saving measures did not include ventilation reconstruction measures. This leads to the fact that in the studied audits no ventilation improvement was done (2006-2010). The problems of ventilation reconstruction should be discussed at future auditor training sessions. Solutions with heat recovery (decentralized room or apartment based ventilation, and exhaust air heat pump) are available for use in reconstruction projects. In the following Fig. 11 and Fig. 12 the energy balances, specific gross consumption and average specific consumption of 14 apartment buildings are presented.

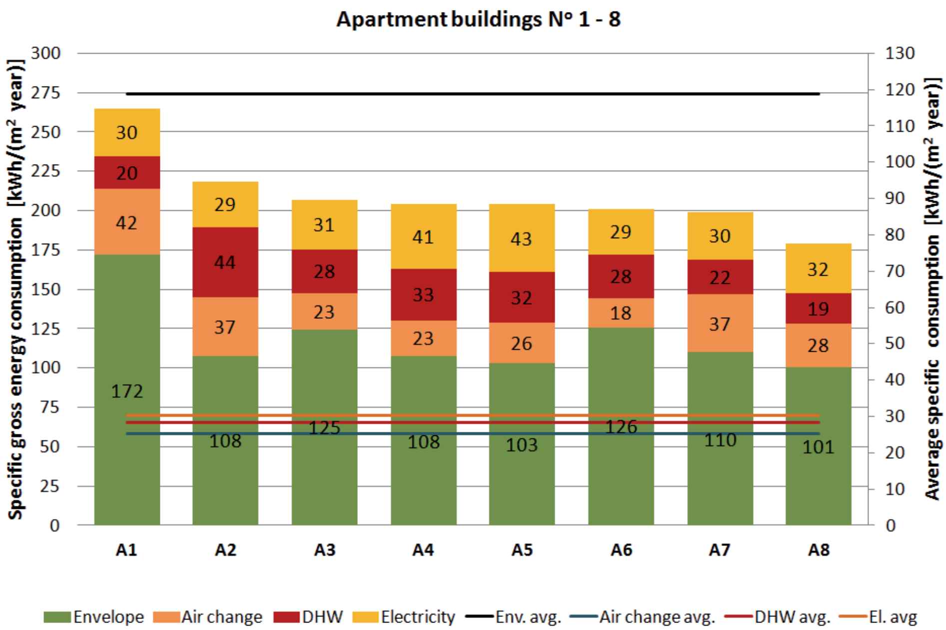

Fig. 11. Dynamics of energy balance and specific energy consumption in the analyzed buildings (DHW heated in substation)

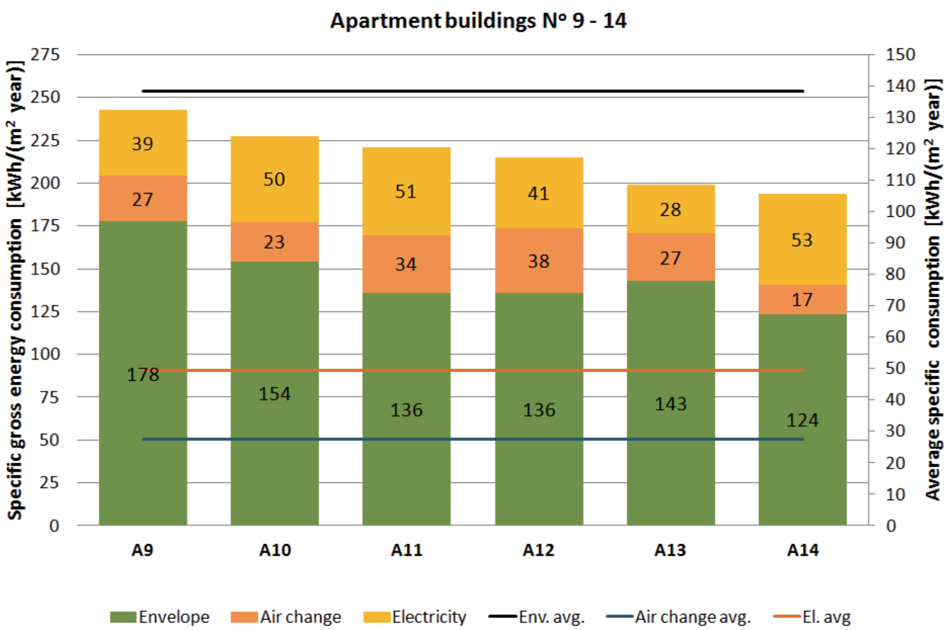

Fig. 12. Dynamics of energy balance and specific energy consumption in the analyzed buildings (DHW heated with electrical heaters in apartments)

Fig. 11 and Fig. 12 average specific energy consumption:
- heating 120-140, kWh/(m^2_{heated} year);
- air change and infiltration 20-30, kWh/(m^2_{heated} year);
- domestic hot water 30, kWh/(m^2_{heated} year);
- electricity 30 without electrical heaters, kWh/(m^2_{heated} year);
- electricity 50 with electrical heaters, kWh/(m^2_{heated} year);
- TOTAL 200 – 250, kWh/(m^2_{heated} year).

The **heated area m²** is the basis for specific energy consumption values.
Earlier studies [88] have indicated average specific heating energy consumption of 185 kWh/(m^2 year). The results of the current analysis gave 180 – 185 kWh/(m^2 year) without electrical energy consumption.
Fig. 13 presents the dispersion of specific thermal and electrical energy consumption for the analyzed 40 apartment buildings.

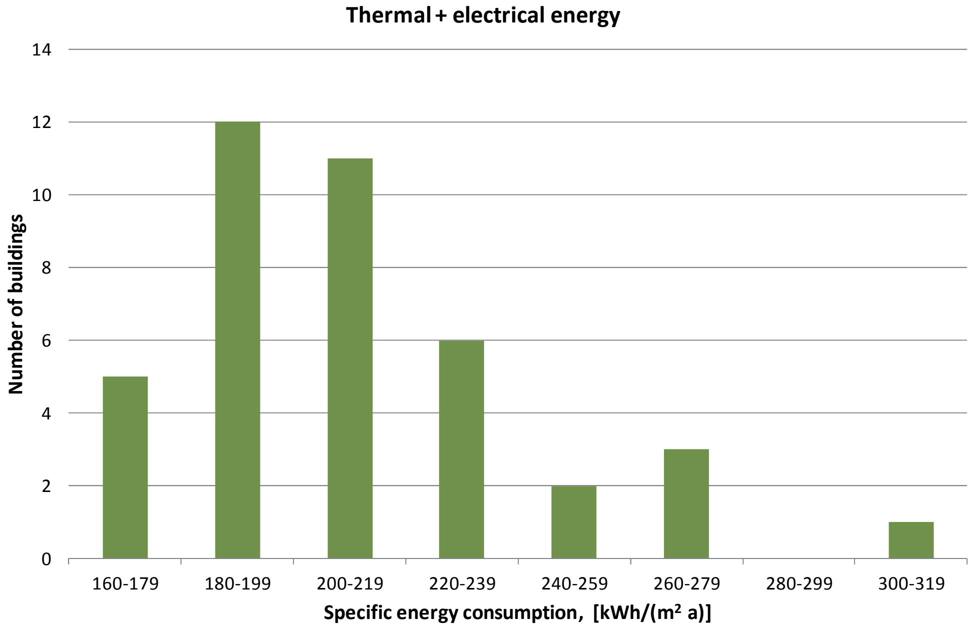

Fig. 13. Dispersion of specific energy consumption of apartment buildings

The energy consumption of the majority of apartment buildings varies between 180-220 kWh/(m^2 year)

The following observations can be made about residential buildings:

- Reconstruction has usually been carried out without ventilation improvement. To maintain normal energy consumption heat recovery ventilation must be designed;
- energy auditors' energy balance calculations occasionally include errors in DHW handling;

- energy consumption for DHW heating is lower with electrical heating compared to district heating. Nevertheless, electrical energy is more expensive;
- in several cases slight under-heating appears (t_{int}=20 °C).

Reconstruction work has decreased energy consumption to 180-220 kWh/(m^2 year) on average.

3.2 Educational institutions

3.2.1 Energy consumption in school buildings

Thermal and electrical energy consumption of a total of 7 school buildings (2009-2011) was collected and analyzed. Heat energy consumption is normalized with the reference year. The following Fig. 14 presents the specific energy consumption of the studied buildings.

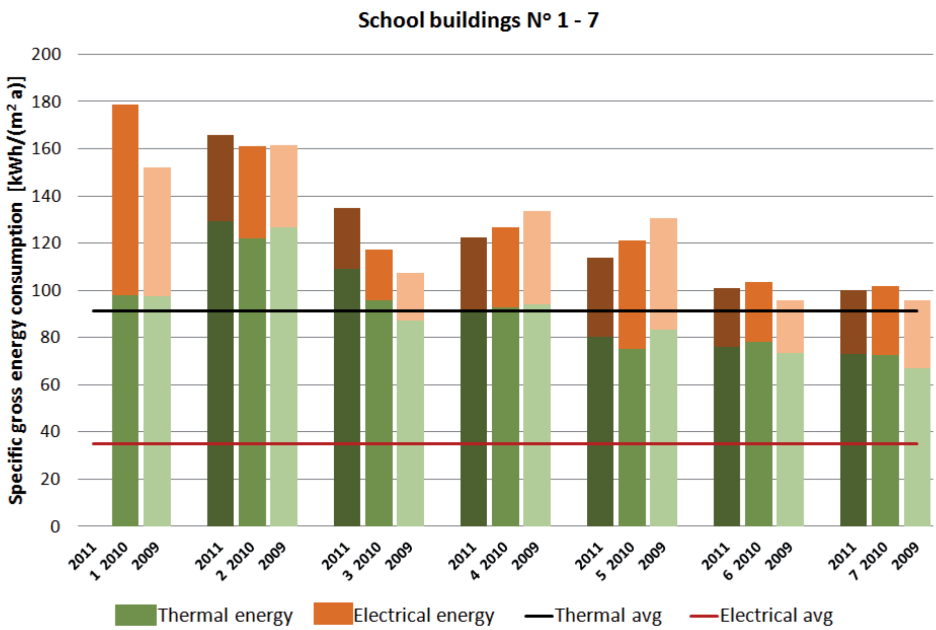

Fig. 14. Specific energy consumption in the analyzed educational buildings

The **net area m²** is a basis for specific energy consumption values.

- The average specific thermal energy consumption (includes DHW) is 90 [kWh/(m^2_{net} year)];
- The average specific electrical energy consumption is 35 [kWh/(m^2_{net} year)];
- TOTAL ~ 125 [kWh/(m^2_{net} year)].

The specific consumption value is relatively low, but during 3 months of the year the usage of school buildings is nearly zero. Also, the net area in typical school buildings is ca 1.5 times bigger than the heated area [89]. Furthermore, the current allocation of resources to schools supports low energy consumption, but the poor indoor climate aspects should also be considered [90].

The following observations can be made about educational buildings:
- information about the heated area m^2 is usually not available. In further research this information should be collected. Based on the net area the energy consumption values are relatively low;
- the ventilation systems are not working properly due to the lack of maintenance knowledge and control possibilities;
- on several occasions the investment model for schools leads to extreme energy saving. Poor indoor climate or opening the windows, which is energy inefficient (air change without heat recovery), are the results;
- simple building management systems for heating substations and ventilation systems are suggested;
- more attention should be paid to the energy efficient use and reconstruction of educational buildings .

3.2.2 Indoor climate in school buildings

The correlation between carbon dioxide level and room air change

There is a well proven theoretical formula for estimating the CO_2 concentration in indoor conditions [42, 50] with natural ventilation. Suppose that the initial carbon dioxide concentration in the air of a classroom before the beginning of a class is C_o. As the class starts, carbon dioxide begins to generate intensively. Air change in the classroom is relatively low. The distribution of temperature in classrooms is uniform (conditions are isothermal), supply and exhaust airflows are equal. The carbon dioxide concentration in the inflow air is C_v and in the outflow air C (the distribution of carbon dioxide in classrooms is uniform). We can write the balance equation:

$$m \cdot d\tau + L \cdot C_v \cdot d\tau - L \cdot C \cdot d\tau - V \cdot dC = 0 \qquad (10)$$

From equation (10)

$$dC = -d\left(\frac{m}{L} + C_v - C\right) \qquad (11)$$

By integration of equation (11)

$$\frac{L}{V} \cdot \tau = -\ln \frac{\frac{m}{L} + C_v - C}{\frac{m}{L} + C_v - C_o} \qquad (12)$$

where
m - carbon dioxide generation in the classroom, L - air change in the classroom, V - volume of the room, C_v - carbon dioxide concentration in external air (in supply air), C - carbon dioxide concentration in the classroom air (in exhaust air), C_o- carbon dioxide concentration in the air of the classroom at the beginning of the class, τ - time.

From equation (12) we can express the basic equation for carbon dioxide concentration C at the time moment τ

$$C = C_v + \frac{m}{L} - \left(C_v + \frac{m}{L} - C_o \right) \cdot \left(e^{-\frac{L}{V} \cdot \tau} \right) \tag{13}$$

It is possible to determine the air change in a room applying the formula (12 or 13) and taking into account the carbon dioxide concentration (in external air, in the classroom air at the beginning of a class and in the classroom air at the time moment of τ), the carbon dioxide generation rate in the classroom and the parameters of the room, .

Fig. 15 presents a theoretical rise in carbon dioxide during a 45 minute class (outside air 400 ppm) in a normal Estonian school with classroom volume of about 240 m^3 and 25 students.

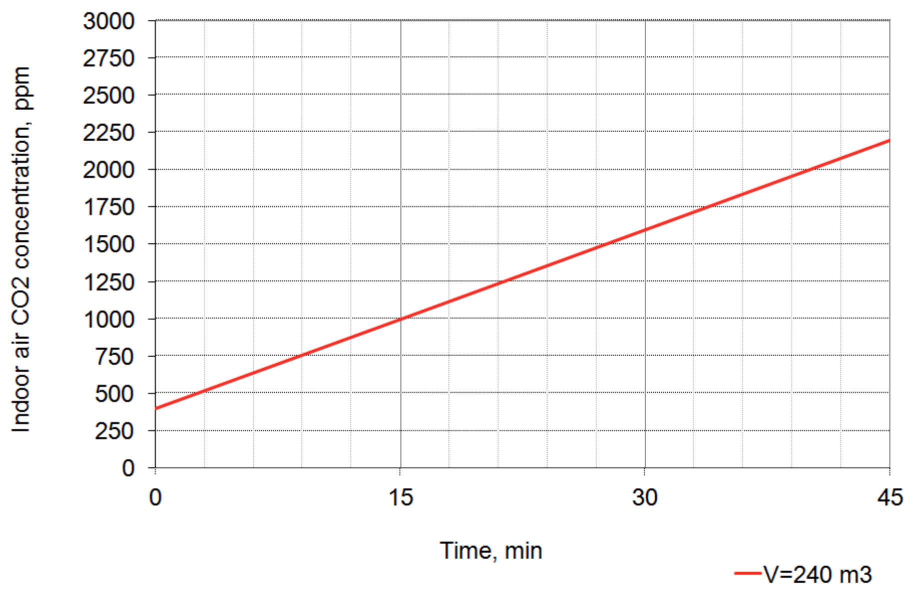

Fig. 15. Calculated change in CO_2 concentration in a typical Estonian classroom (natural ventilation)

The normative [91] defined 1000 ppm as a maximum level for CO_2 concentration in classrooms. Unacceptable conditions will be reached during the first 15 minutes of the class.

Nevertheless, full ventilation renovation programs are not affordable for all Estonian schools. Furthermore, there are technical difficulties of building balanced centralized ventilation systems due to lack of space for technical rooms and especially for ventilation ducts. There is also a problem with the energy consumption of centralized units as not all classrooms are used simultaneously.

Experimental measurements

A case study was made in three different classrooms in a school located near Tallinn (Fig. 16).

All classrooms had a physical volume of 240m^3.

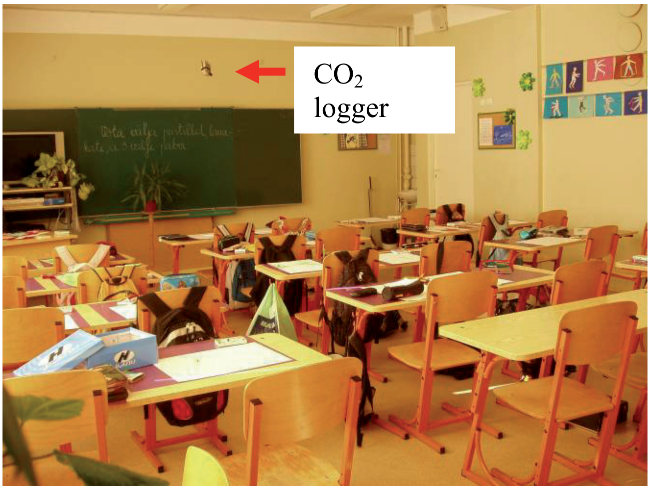

Fig. 16. Logger position in the classroom

The results of the measurements in classrooms with natural ventilation are presented in Fig. 17 and Fig. 18.

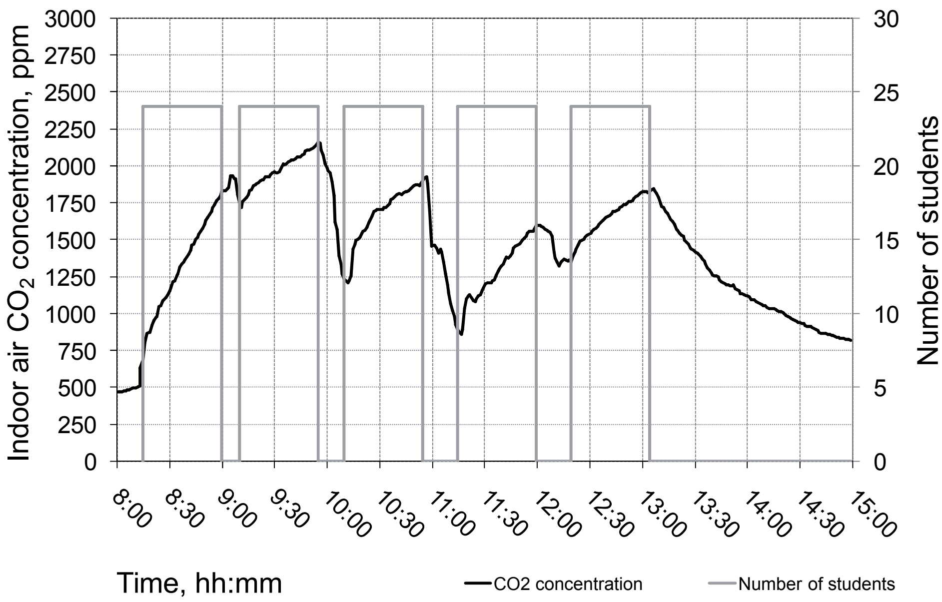

Fig. 17. Measured CO_2 concentration change in a classroom (natural ventilation)

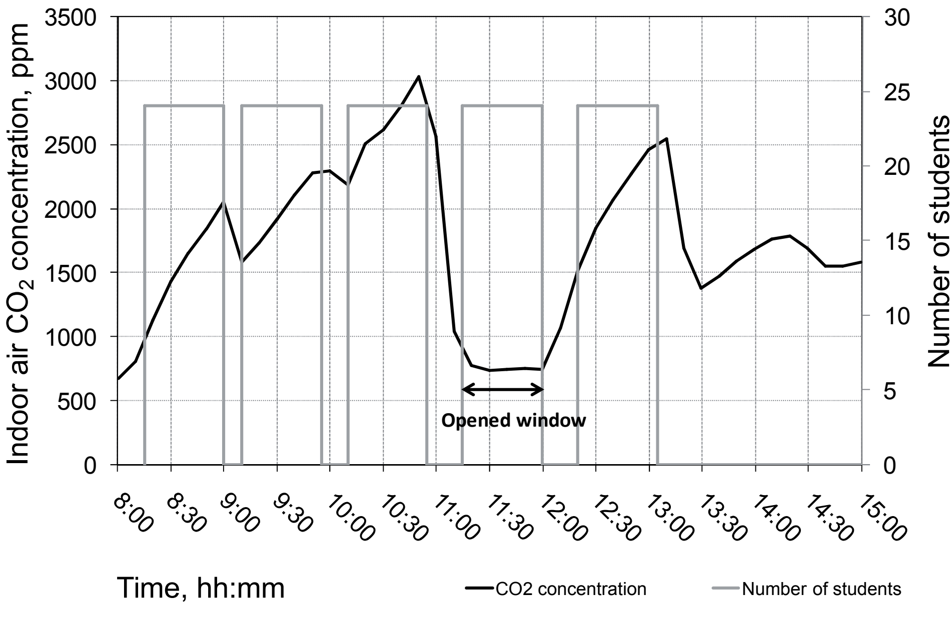

Fig. 18. Measured CO_2 concentration change in a classroom (natural ventilation)

The overview of Fig. 17 and Fig. 18 shows rapid rise in CO_2 concentration during the first class and there is a remarkable correlation with Fig. 15 that presents the calculation results.
Other measurements were carried out in a classroom with a mechanical supply and exhaust ventilation system. These systems usually give good air change results in case they are designed, built and balanced properly. In most cases problems appear with unbalanced systems or not properly completed balancing of the ventilation system. The CO_2 measurement results can be found in figures Fig. 19 (at 12:00-13:00 the ventilation unit was switched off) and Fig. 20.

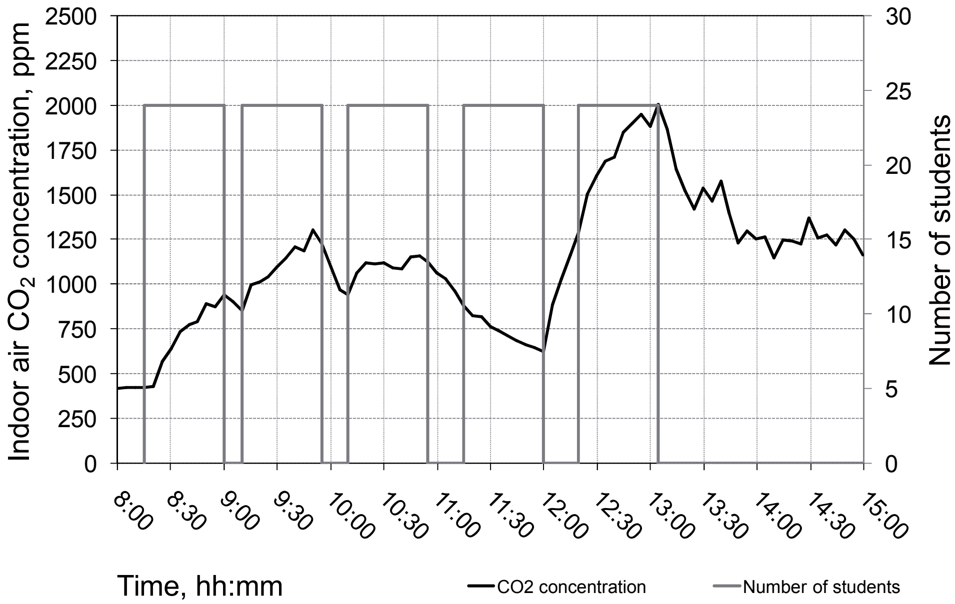

Fig. 19. Measured change in CO_2 concentration in a classroom with mechanical centralized ventilation

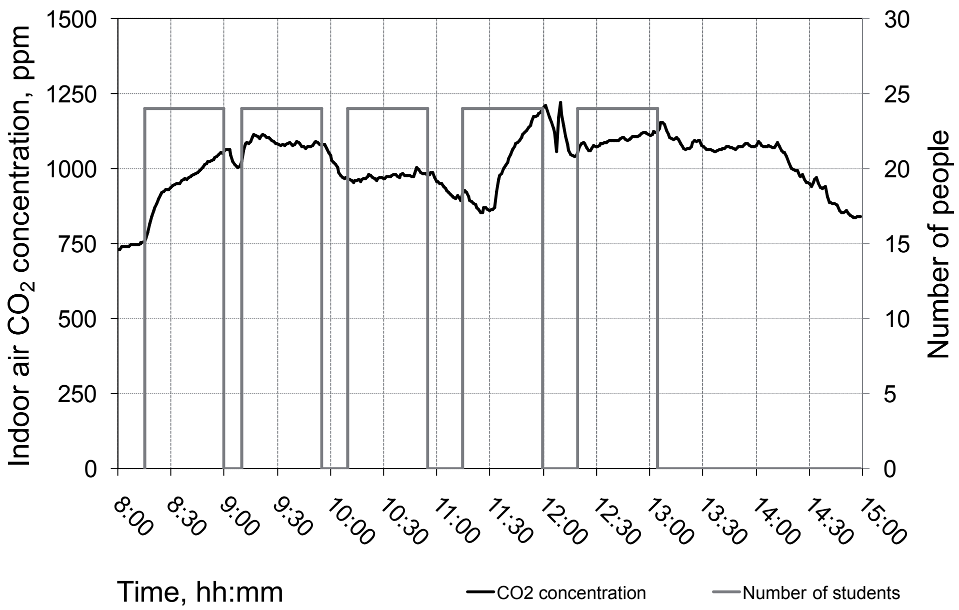

Fig. 20. Measured change in CO_2 concentration in a classroom with mechanical centralized ventilation

Carbon dioxide levels in the previous figures still exceed the normative of 1000 ppm several times during the school day. EN15251:2007 III category can be achieved on average.

Ventilating with room units

Five M-WRG room units were installed below the windows in one of the classrooms.

The technical parameters of M-WRG unit installation are:

- Air volumes 15 – 100 m^3/h per unit;
- Crossflow plate heat exchanger with heat recovery ca 75%;
- Optional electrical heating 3.8 – 34 W (not used in the current case);
- Air filtering G4;
- Sound level 15.5 – 46.5 dB(A)
- EC or DC fans;
- Frost protection;
- Condensate removal to outdoors.

Classes start as at 8:00 as in the previous cases. Children usually appear 15 minutes earlier. Three CO_2 data loggers were spread in the classroom as follows:

above the board, in front of the external wall (near the windows) and the internal wall (near the corridor).
In the following Fig. 21 the installation principle of room ventilation units is presented.

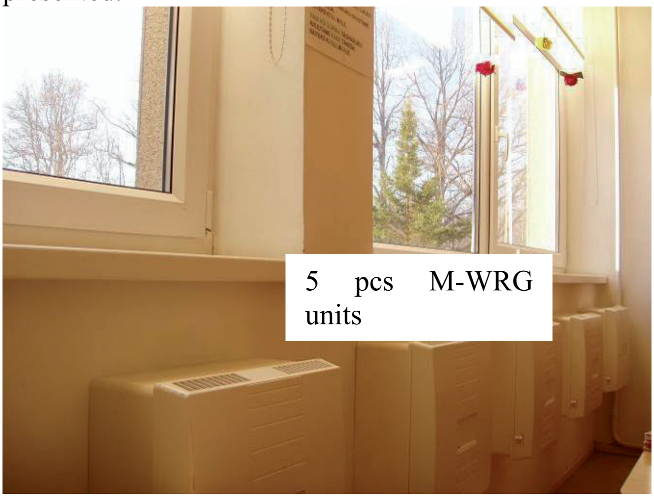

Fig. 21. Locations of room units

Some deviations in the measurements can appear due to teachers tuning the speeds of the M-WRG units to a lower level during the class.
Fig. 22, Fig. 23, Fig. 24, Fig. 25 present the measurement results in correlation with the number of students.

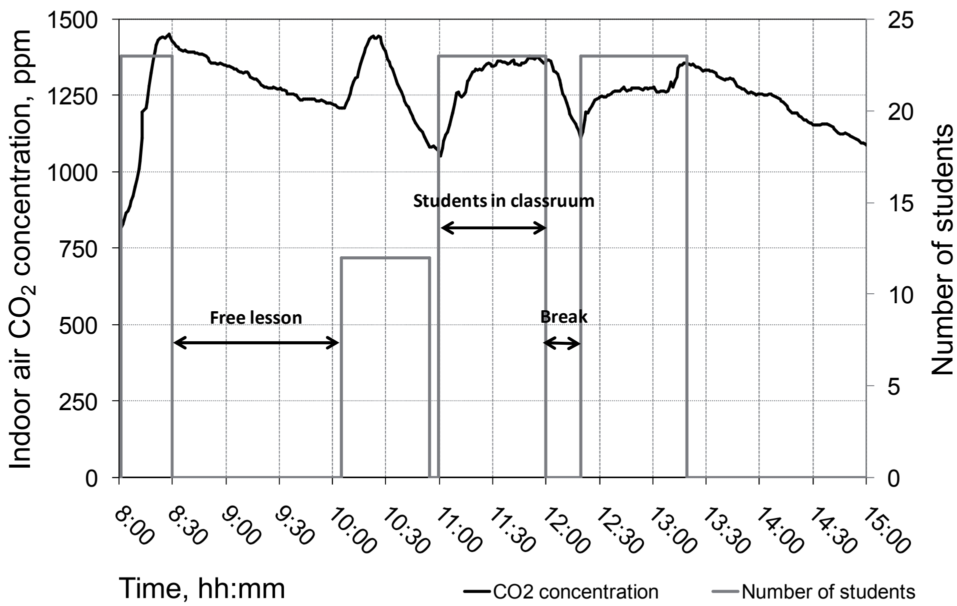

Fig. 22. Measured change in CO_2 concentration in a classroom (ventilation with room units)

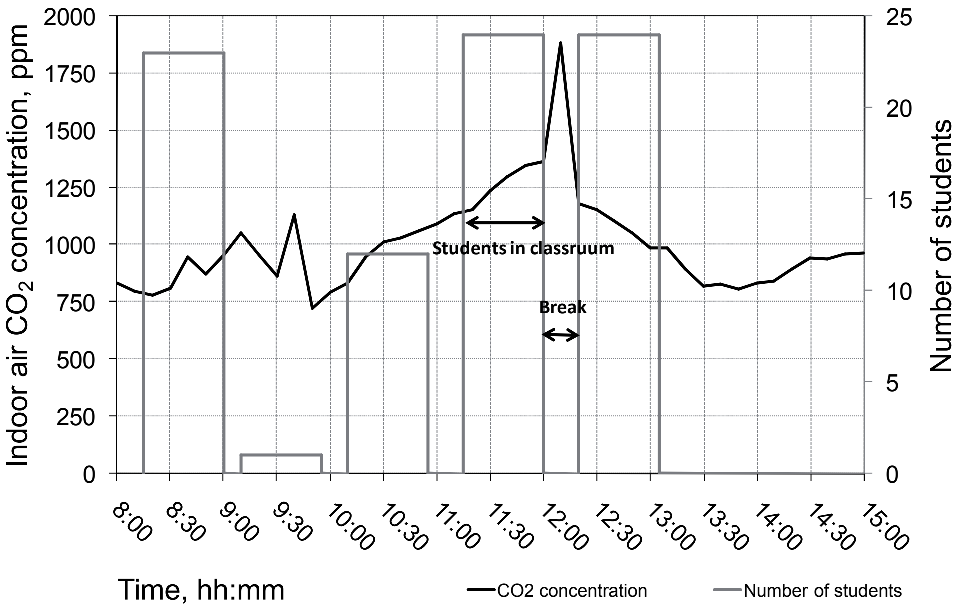

Fig. 23. Measured change in CO_2 concentration in a classroom (ventilation with room units)

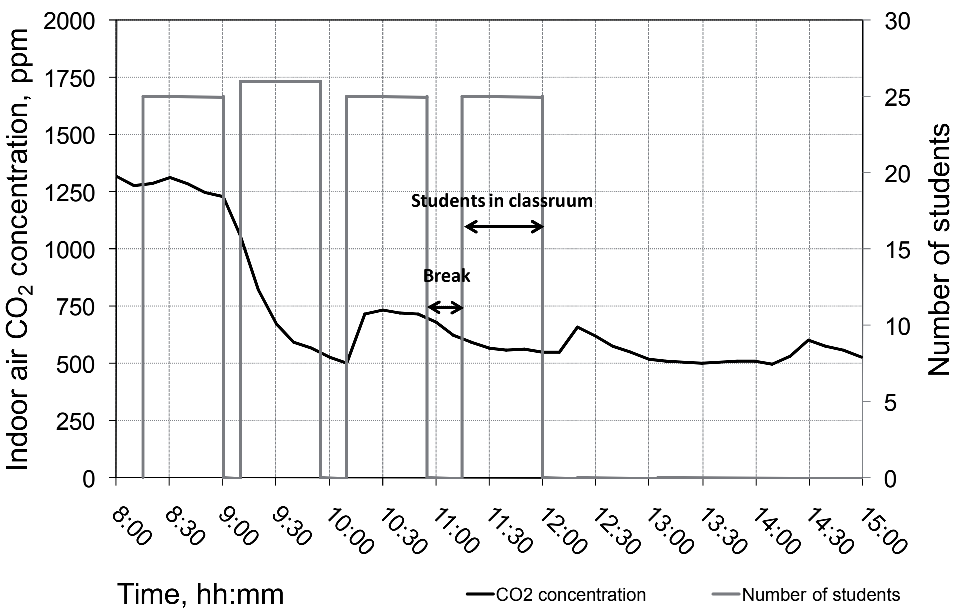

Fig. 24. Measured change in CO_2 concentration in a classroom (ventilation with room units)

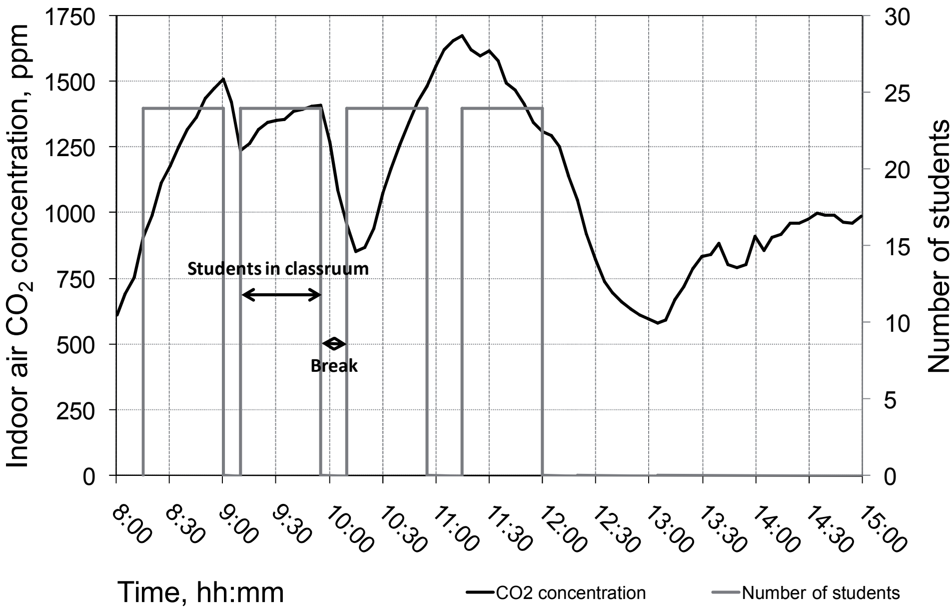

Fig. 25. Measured change in CO_2 concentration in a classroom (ventilation with room units)

Indoor climate and different ventilation solutions

Fig. 26 presents a comparison of the changes in the CO_2 concentration with different ventilation systems based on the research.

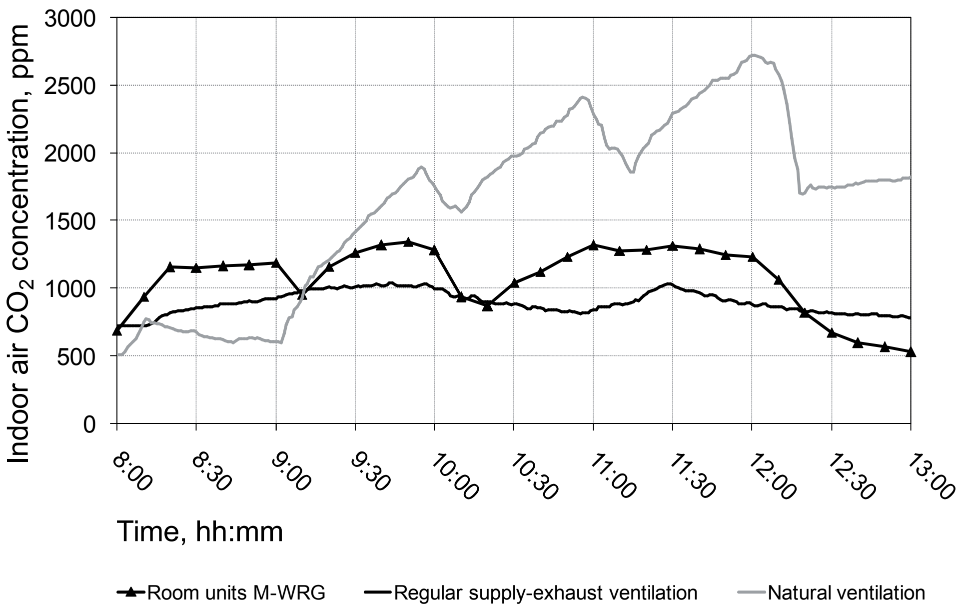

Fig. 26. Indoor air CO_2 concentration in the observed ventilation systems

The cumulative duration figure (Fig. 27) presents indoor carbon dioxide levels with room unit based ventilation.

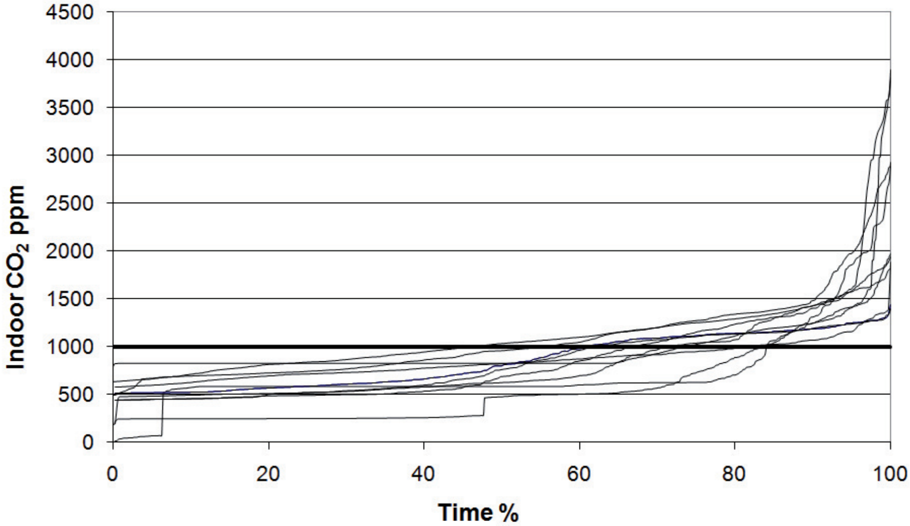

Fig. 27. Duration graph of indoor air CO_2 concentration (room based units)

On average 80% of the measured period satisfies the 1000 ppm normative. It is recommendable to add one more room based unit to one classroom to lower carbon dioxide concentration and the sound level of the units.

Centralized mechanical ventilation generally gives good results to ensure proper indoor climate, but there can also be problems. Energy consumption will be high if classroom usage profiles are not taken into consideration. Also the balancing of the centralized systems has not been done properly in many cases. VAV systems are a way to solve the problem, but in reality these systems are noisy, more expensive and hard to maintain.

Ventilation based on room units is flexible and energy efficient. The main shortcomings are higher noise levels at some speeds (must be taken into account in the design process) and human interference into the adjustment of fan speeds. The solution can be used in the renovation of educational buildings, but the control of the systems should be carefully planned. Centralized control systems that measure CO_2 are suggested to control the units. Still it is preferable to install room unit ventilation in apartment buildings and old people's homes.

3.3 Public buildings

3.3.1 Energy consumption in public buildings

Analysis of 44 public buildings

Thermal and electrical energy consumption of a total of 44 public buildings (2009-2011) was collected and analyzed. In addition, the electrical energy balance of one typical new ten-storey office building was analyzed in more depth.
It is more complicated to develop energy saving measures for the public building sector than for residential buildings. The national heritage board has imposed justified restrictions on the envelope and finishing of public buildings. Internal insulation cannot be added due to climatic conditions. Change of windows is either expensive or not allowed. Reconstruction of the heating system is more complicated as well (employees and equipment have to be moved; valuable finishing materials can be destroyed; more expensive heating elements are required by the architect, etc). Usually roof insulation is the easiest saving measure to be applied.
The current analysis is based on the thermal and electrical energy consumption of 44 public buildings. Heat energy consumption is normalized with the reference year. The **net area m²** is a basis for specific energy consumption values.
The following Fig. 28, Fig. 29, Fig. 30 present thermal and electrical energy consumption of 22 office buildings, 18 court houses and 4 police departments.
The electrically heated buildings are excluded from average calculations.

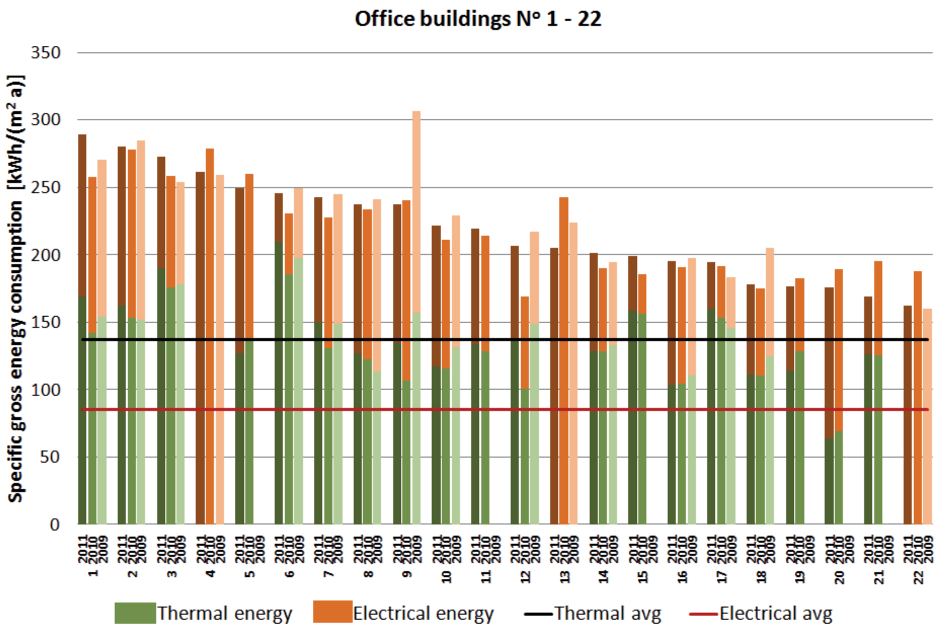

Fig. 28. Specific energy consumption of office buildings

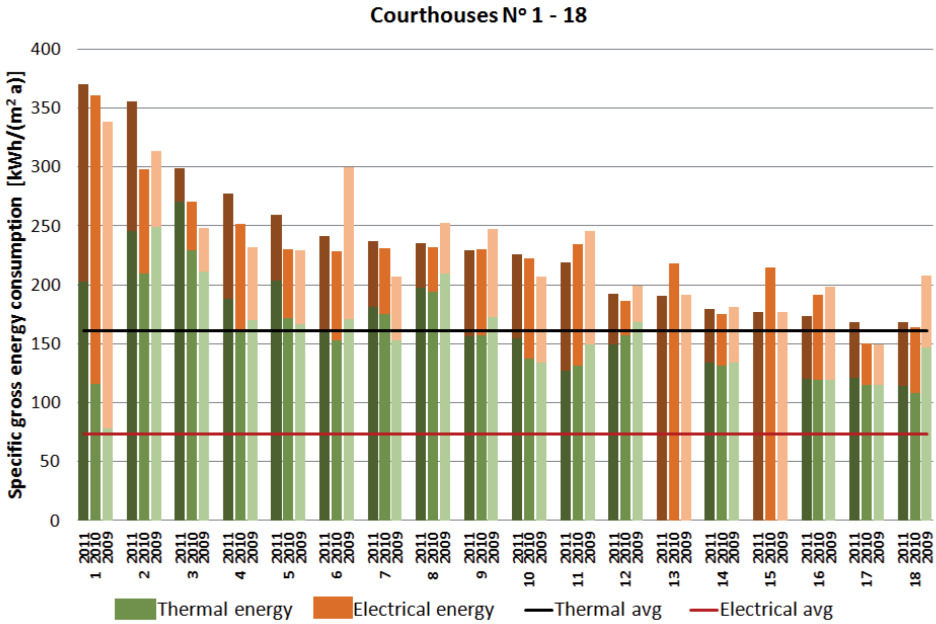

Fig. 29. Specific energy consumption of court houses

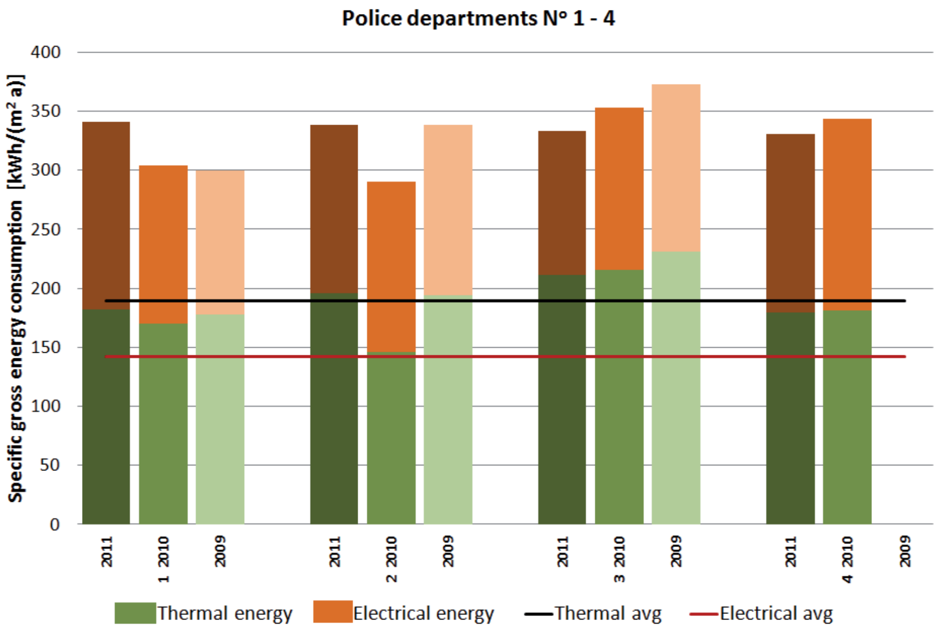

Fig. 30. Specific energy consmuption of police departments

In the following Fig. 31 the dispersion of specific energy consumption of the analysed buildings is presented.

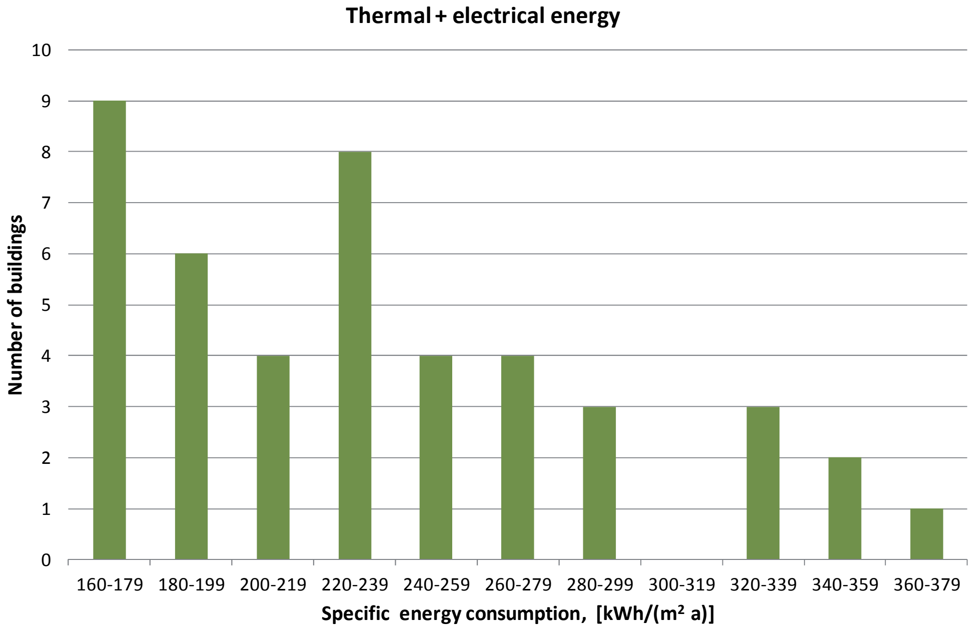

Fig. 31. Dispersion of specific energy consumption of public buildings

Energy consumption of public buildings varies widely and energy saving measures can only be worked out case by case.

In the following Table 11 the results of the analysis of thermal and electrical specific energy consumption for office buildings, court houses and police departments are presented. Furthermore, there are also shares of thermal and electrical energy consumption.

Table 11. Results of the analysis of energy consumption in public buildings

Type of public building	Average specific thermal energy consumption kWh/(m^2 year)	Average specific electrical energy consumption kWh/(m^2 year)	Total average specific energy consumption kWh/(m^2 year)
Office buildings	137.1	85.5	222.7
Share	61.6%	38.4%	
Courthouses	161.3	73.0	234.3
Share	68.8%	31.2%	
Police departments	189.5	141.9	331.4
Share	57.2%	42.8%	

Office buildings and court houses have ordinary 8:00 – 18:00 use during working days, while police departments are partly used 24/7.

Measured energy balance of an office building

The importance of electrical energy consumption in new office buildings is frequently underestimated in our climate. The following Fig. 32 represents the energy balance of a ten-storey office building. The measurements are based on the energy consumption in 2011.

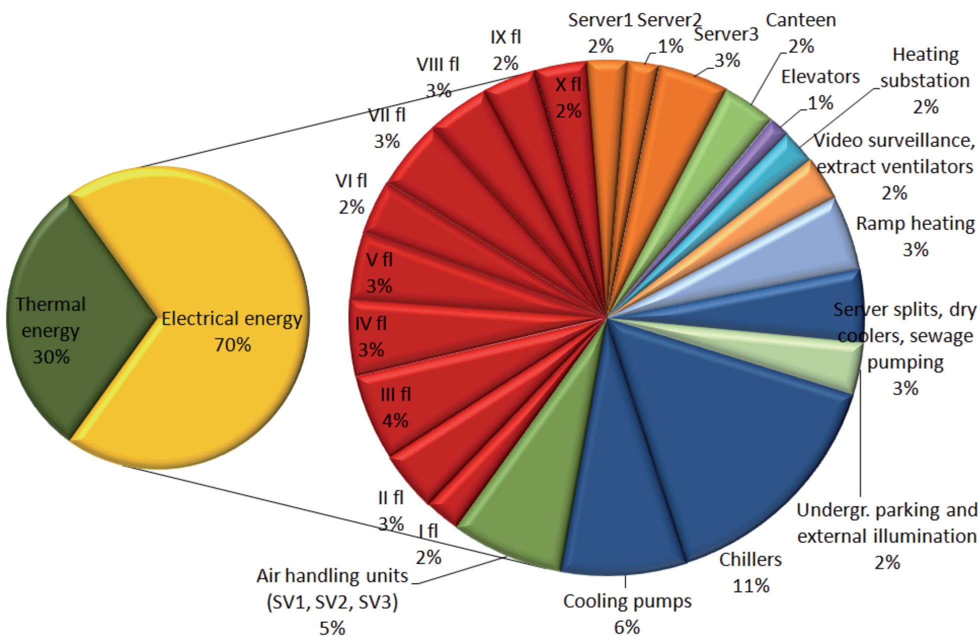

Fig. 32. Measured energy balance of a ten-storey office building

The division of electrical energy balance (100%):
- Lighting and electrical equipment (10 floors) 42.2%;
- Cooling (chiller unit, pumps, dry-coolers, split-units) 27.6%;
- Servers 8.9%;
- Ventilation (fans, heating pumps, heat recovery wheel) 7.0%;
- External el. heating (ramp heating, rainwater gullies) 4.7%;
- External and parking area lighting 3.3%;
- Technical rooms and video surveillance 2.8%;
- Heating substation (boilers, pumps) 2.2%
- Elevators 1.3%.
- Due to variable balance temperature during the year the degree-day calculation method cannot be used for energy balance calculations. Dynamic simulation with validated consumption values is suggested.

Variation in the specific energy consumption of public buildings is wide. Therefore systematic monitoring of energy consumption and an energy saving plan for each building is suggested.

The following observations can be made about public buildings:

- there are mainly two types of buildings: very old cultural heritage buildings and new office buildings;
- for old cultural heritage buildings the envelope reconstruction measures can almost be excluded (in some cases window, door replacement and roof insulation can be suggested);
- heat recovery ventilation has been installed in most cases;
- in the new office building the electrical energy consumption was 70% of the total energy consumption. The biggest electrical energy consumers were the cooling system and server rooms. The set parameters of ramp heating should also be adjusted. In the design phase the air change rates of ventilation must be selected conservatively, but the capacity of air handling units and main ducts should be selected with reservations. Furthermore, the location of meeting rooms should be well considered and VAV systems designed.

Parameter adjustment of free cooling according to real room temperatures should be carried out.

In Appendix A sea water district heating and cooling preliminary research is presented. This approach could be one possibility to serve efficiently Tallinn coastal area cooling and heating demand for office buildings.

4. Summary, final conclusions and recommendations for further research

4.1 Summary

The current dissertation gives an overview of calculation methods of energy consumption for buildings. In addition, energy consumption of different building types (residential, educational and public) is analyzed.

The literature review covers scientific research of the last 10 years on the following topics related to building and HVAC systems:

- the possibilities of reducing energy consumption in buildings;
- combining simulation and optimization tools for energy calculations;
- indoor climate conditions in school buildings;
- the possibilities of the sea water based heat pump for district heating and cooling.

In the first section of the research work the following calculation methods are described:

- degree-day calculations;
- validated dynamic simulations;
- the combination of dynamic simulation and optmimization.

Firstly, simple degree-day calculations can be used in cases where the balance temperature of buildings is relatively constant (typical Soviet apartment buildings). The effect of solar heat gain is low due to small window sizes.

Secondly, the dynamic simulation model must be validated on the basis of real measured values of energy consumption. After the validation process different energy saving scenarios can be created by manually altering the parameters of the model.

Thirdly, the process of altering the parameters manually in dynamic simulation software can be automated using the optimization process. Nevertheless, advanced understanding of some dynamic simulation files is necessary. The advantage of this principle is maximizing the usage of computational power and minimizing manual interaction in the calculation process.

In the second section of the dissertation the following topics are presented:

- analysis of energy consumption for residential, educational and public buildings;
- research on the indoor climate in educational buildings;

The analysis of energy consumption in residential buildings is based on 40 apartment buildings. Detailed energy balances for thermal and electrical energy are presented for 14 apartment buildings. Six of these buildings have DHW heating with electrical heaters in apartments, therefore also DHW consumption is reduced. Generally, energy consumption has decreased in the last years. Unfortunately, ventilation reconstruction has not started with the necessary speed.

In general, energy consumption in schools is quite low (divided into net area), but in addition to this fact, indoor climate is very poor. Natural and centralized mechanical ventilation with heat recovery are the main system principles used in existing schools. The current dissertation also includes real indoor climate measurements in one school. All different ventilation systems (natural, centralized mechanical and room unit based) were available. The room unit based system was analyzed in depth. The results show the possibility of using the system in school buildings, but the system is preferred for apartment buildings and old people's homes.
The selection of public buildings included 44 buildings. The average share of thermal energy consumption was 60%, and of electrical energy 40%. The dispersion of energy consumption varies widely – therefore it is necessary to do thorough research on all buildings case by case. In one modern 10-storey building detailed energy balance was measured. The share of thermal energy consumption was only 30%. Therefore attention should be paid to electrical energy consumption. Cooling, server rooms and ventilation are the biggest electrical energy consumers, if not to take into account lighting an office equipment.
As the heat pump technology is increasingly more used as an energy source of buildings, the current dissertation Appendix A includes research on sea water district heating and cooling based on heat pumps. The open loop system is presented although it is problematic in the Gulf of Finland due to the relatively conservative depth of the sea. The temperatures vary remarkably during the year in the depth of 20-25m which worsens the conditions for heat pump technology. But on the other hand the sea water district heating and cooling is economically more feasible near the coast (ca 500m) in Gulf of Finland.

4.2 Final conclusions

The intention of the author of the dissertation was to find and present possibilities of ensuring good indoor climate conditions in buildings in an energy efficient way. The possibilities of using energy calculation tools have been analysed and optimization results presented. Also various results of monitoring and calculating energy consumption have been indicated.

4.3 Recommendations for further work

Energy consumption of apartments has been well researched, but the consumption of educational and public buildings should be analyzed and monitored in further studies. Also indoor climate conditions in educational buildings would need more research and constant monitoring due to poor conditions. In a number of cases the ventilation rates of public buildings exceed the demand. Therefore technical possibilities of reconstructing centralized ventilation systems to demand based ventilation systems would be a serious task. In the current dissertation single objective building optimization has been carried out. The next step would be a multiobjective approach. Finally, possibilities of using renewable energy sources in urban areas should be developed further.

Kokkuvõte

Käeolev dissertatsioon annab ülevaate meetoditest hoonete energiaarvutuste koostamiseks. Lisaks on välja toodud erinevate hooneliikide (elamud, haridusasutused ja ühiskondlikud honed) energiatarbe analüüs.

Kirjandusülevaade annab ülevaate viimase 10 a teadusuuringutest hoonete ning nende tehonsüsteemide teemadel:

- Energiatarbe vähendamise võimalused;
- simulatsiooni ja optimeerimise kombinatsioonid hoonete energiaarvutusteks;
- koolihoonete sisekliima uuringud;
- merevee kasutusvõimalused Tallinna rannaalal sooljuspumbal põhineval kaugküttel ja –jahutusel.

Esimeses töö pooles on kästiletud alljärgnevaid energiaarvutuste meetodeid:

- Kraadpäevadega arvutused;
- valideeritud dünaamilised simulatsioonid;
- simulatsioonide ning optimeerimise tarkvarade kombineerimine.

Esiteks, lihtsad kraadpäevadega energiaarvutused sobivad hästi hoonetele, kus hoone tasakaalutemperatuur aasta lõike on suhteliselt püsiv (tüüpilised nõukogudeaegsed korruselamud). Vabasoojuste päikese osakaalu mõju on tänu tagasihoidlikele aknasuurustele väiksem.

Teiseks, reaalsete energiatarbimisandetega põhjal valideeritakse dünaamilise simulatsiooni mudel. See mudel võimaldab käsitsi läbi mängida erinevaid hoone energiatarbimise stsenaariumeid sõltuvalt füüsikaliste parameetrite muutmisest.

Kolmandaks, käsitsi pidevat parameetrite muutmise protsessi saab lihtsustada optimeerimistarkvara abiga. Detailne simulatsioonitarkvara failide tundmine ning toimivusloogikast arusaamine on optimieerimisprotsessi aluseks. Antud lähenemise eeliseks on maksimaalne arvutijõudlise ärakasutamine minimaalse inimese osalusega.

Teises dissertatsiooni osas kästiletakse järgnevaid teemasid:

- Elamute, haridusasutuste ning ühiskondlikute hoonete energiatarbe analüüs;
- sisekliima probleemid haritusasutustes;

Elamute energiatarbe analüüs põhineb 40 korruselamul. Detailsed soojuse– ja elektrienergia bilansid on välja toodud 14 hoonele. Viimatimainitute hulgas on kuus hoonet, kus sooja tarbevee vamistamine toimub korteripõhiste elektriboileritega. Sellest tulenevalt on sooja tarbevee tarbimine nendes hoonetes väiksem võrreldes tsenraalse soojavee tootmisega. Uuringutulemused näitavad pidevat energiatarbe vähenemist elamute sektoris. Kahjuks on vähe rõhku pandud ventilatsiooni rekonstrueerimisele.

Üldiselt on koolide energiatarbimine suhteliselt madal. See on tihti tingitud ebarahuldavast õhuvahetusest. Loomulik ventilatsioon ning mehaaniline tsentraalne soojustagastusega ventilatsioon on põhilisemad lahendused koolides. Antud töös on ühe kooli jaoks välja toodud sisekliima reaalsed mõõtmistulemused. Selles hoones

olid olemas kolm ventilatsioonisüsteemide lahendust (loomulik, mehaaniline ning soojustagastusega ruumiagregaatidel põhinev ventilatsioonisüsteem). Ruumiagregaatidel põhinevat süsteemi on käsitletud detailemalt. Tulemuselt põhinedes võib välja tuua, et süsteem on koolihoonetes kasutatav, kuid paremini sobib ruumiagregaatidega lahendus elamutele ning vanadekodudele.
Ühiskondlike hoonete valim käsitleb ka 44 hoonet. Soojusenergia osakaal uuritud hoonetes oli 60%, elektrienergia 40%. Energia eritarbimiste jaostus ühiskondlike hoonete puhul on väga lai – seetõttu tuleb hooneid detailselt käsitleda üksikult. Mõõdetud on kaasaegse kümnekorruselise büroohoone detailne energiabilanss. Soojuse osakaal energiabilansist oli antud hoones ainult 30%. Seetõttu tuleb tähelepanu pöörata uute büroohoonete puhul elektrienergiatarbimisele. Suurimad eraldi elektrienergia tarbijad on jahutussüsteem, serveriruumid ning ventilatsioonisüsteem, kui mitte arvestada korruste valgustuse ja bürooseadmete elektritarbimisi.
Kuna soojuspumpasid kasutatakse järjest rohkem hoonete energiatarbe katmiseks, siis antud töö lisas A on käsitletud mereveel põhinevat soojuspumpade lahendust kaugkütteks ja –jahutuseks. 21 hoonet on arvestatud liituma võrguga. Esitatud on merevee kasutamiseks avatud lahendus, kuigi uurida tuleks edaspidi ka suletud ringiga süsteemi lähtuvalt Soome lahe problemaatilisest sügavusest rannikualal. Merevee temperatuurkõigub sügavuses -25m liiga palju. See on Soome lahes sügavus, mis asub majanduslikult mõistlikus kauguses rannast (ca 500 m).

Lõppjäreldused

Toodud töö eesmärk oli leida ja esitada võimalusi hea sisekliima tagamiseks energiaefektiivsete lahendustega. Energiaarvutuste tööriistastade analüüs ning fassaadide energiatarbe optimeerimine on käsitletud. Lisaks esitati ka erinevate hoonetüüpide energiatarbimise jälgimise ning arvutuste tulemused.

Soovitused edaspidisteks uuringuteks

Elamute energiatarve ning sisekliima on uuritud pikaajaliselt, kuid haridusasutused ning teised avalik-ühiskondlikud hooned vajavad edasis monitoorimist ning analüüsi. Olukorrast tulenevalt peab lasteaedades ning õppeasutustes pidevat sisekliiima monitooringut läbi viima, analüüsima suuremas mahus. Paljudel juhtudel uute avalike hoonete ventilatsiooni õhuvooluhulgad on liiga suured võrreldes vajadusega. Sellest tulenevalt tuleb rõhku panna tarbimisest sõltuva ventilatsiooni toimivate lahenduste uurimiseks ning väljaehitamiseks. Käesolevas töö on käsitletud ühe muutujafunktsiooniga energiatarbe minimeerimist. Järgmine samm oleks kasutada mitme muutujafunktsiooniga energiatarbe ja sisekliima optimeerimist. Lisaks tuleb linnatingimustesse edasi uurida taastuvenergiaallikate kasutusvõimalusi.

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Bibliography

Papers presented by the candidate

Hani, A.; Koiv, T.-A. (2012). Optimization of office building façades in a warm summer continental climate. Building Services Engineering Research and Technology, 3(3), 222 – 230.

Hani, A.; Koiv, T.-A. (2012). Energy consumption monitoring analysis for residential, educational and public buildings. Smart Grid and Renewable Energy, 3(3), 231 – 238.

Hani, A.; Koiv, T.-A. (2012). The preliminary research of sea water district heating and cooling for Tallinn coastal area. Smart Grid and Renewable Energy, 3(3) 246 – 252.

Hani, A.; Koiv, T-A.; Mikola, A. (2011). Ventilating with Room Units in Educational Institutions . International Journal of Energy and Environment, 5, 629 – 636.

Hani, A.; Kõiv, T.-A.; Mikola, A. (2011). Carbon Dioxide Levels in Educational Institutions. In: Recent Researches in Energy & Environment: 6th IASME / WSEAS International Conference on Energy & Environment (EE 11). (Eds.) Brindusa Covaci, Alexandru T. Bogdan, George Lazarolu. Cambridge, UK: WSEAS, 2011, 359 – 364.

Hani, A.; Britikovski, I.; Voll, H.; Kõiv, T-A. (2010). Sea Water District Cooling Feasibility Analysis for Tallinn. In: 12th International Symposium on District Heating and Cooling : September 5th–September 7th, 2010 Tallinn, ESTONIA: (Eds.) Aadu Paist, Andres Siirde. Tallinn:, 2010.

Hani, A.; Kõiv, T.-A.; Voll, H.;.Tali, M (2009). "Energy efficiency in Residential Buildings. The Comparison between Degree Day Calculation and Simulations. In: Proceedings of the 2nd International Scientific "Energy and Climate Change" Conference: 2nd International Scientific "Energy and Climate Change" Conference, 8,9 October 2009, Athens (Greece). (Eds.) Mavrakis, D.. Athens: Energy Policy and Development Centre KEPA, 2009, 209 – 213.

Hani, H; Kalamees, T; Kõiv, T-A (2009). Determination of energy performance requirements for apartment buildings in Estonia. In: Proceedings of Healthy Buildings 2009: Healthy Buildings 2009, Syracuse, NY, USA, September 13-17. (Eds.) Santanam, S.; Bogucz, E.A.; Zhang, J.S.; Ezzat Khalifa, H.. Syracuse:, 2009, Paper 409.

Hani, A.; Kõiv, T.-A. (2008). Energy auditing of residential buildings. In: Proc. of the 2nd Scientific-Technical Conference „Heating and ventilation in agriculture and industry” in Tlen, Poland:, 2008, 41 – 47.

Papers in which the candidate was involved

Kõiv, T.-A.; Voll, H.; Hani, A. (2010). Domestic hot Water Consumption in Educational Premises, Apartment and Office Buildings. WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT, 6, 54 - 64.

Kõiv, T.-A.; Toode, A.; Hani, A. (2009). The influence of domestic hot water maximum consumption on the district heating network dimensioning. WSEAS TRANSACTIONS on ENVIRONMENT and DEVELOPMENT, 5, 104 - 108.

Kõiv, T.-A.; Voll, H.; Hani, A. (2009). Domestic hot water consumption and consumption profiles in education premises. Proceedings of the 3rd WSEAS Int. Conf. on Energy Planning, Energy Saving, Environmental Education, Tenerife, Canary Islands, Spain, July 1-3, 2009 (84 - 88).WSEAS

Toode, A.; Kõiv, T.-A.; Hani, A. (2008). Domestic hot water consumption, consumption profiles for schools, children's institutions and office buildings. In: Proc. of the 2nd Scientific-Technical Conference „Heating and ventilation in agriculture and industry” in Tlen, Poland: (Eds.) Žarski, K.., 2008, 187 - 195.

Inventions

Method for energy auditing of residential buildings; Owner: Tallinn University of Technology ; Authors: Teet-Andrus Kõiv, Teet Tark, Villu Vares, Allan Hani; Priority number: P200800058; Priority date: 12.09.2008

Calculation method of district heating network; Owner: Tallinn University of Technology ; Authors: Teet-Andrus Kõiv, Alvar Toode, Allan Hani; Priority number: P200800046; Priority date: 10.07.2008

List of references

[1] Luis Pe´rez-Lombard, Jose´ Ortiz, Christine Pout, “A review on buildings energy consumption information,“ *Energy and Buildings,* Vol. 40, 2008, pp. 394-398.

[2] B. Howard, L. Parshall, J. Thompson, S. Hammer, J. Dickinson, V. Modi, “Spatial distribution of urban building energy consumption by end use,“ *Energy and Buildings,* Vol. 45, 2012, pp. 141–151.

[3] M. Kolokotroni, X. Ren, M. Davies, A. Mavrogianni, “London's urban heat island: Impact on current and future energy consumption in office buildings,“ *Energy and Buildings*, Vol. 47, 2012, pp. 302–311.

[4] Ruchi Choudhary, „Energy analysis of the non-domestic building stock of Greater London,“ *Building and Environment*, Vol. 51, 2012, pp. 243-254.

[5] He Xiao, Qingpeng Wei, Yi Jiang, “The reality and statistical distribution of energy consumption in office buildings in China,“ *Energy and Buildings,* Accepted Manuscript.

[6] Jing Zhao, Yajuan Xin, Dingding Tong, “Energy consumption quota of public buildings based on statistical analysis,” *Energy Policy*, Vol. 43, 2012, pp. 362–370.

[7] R. Saidur, “Energy consumption, energy savings, and emission analysis in Malaysian office buildings,” *Energy Policy,* Vol. 37, 2009, pp. 4104–4113

[8] Ove Morck, Kirsten Engelund Thomsen, Jųrgen Rose, „The EU CONCERTO project Class 1 – Demonstrating cost-effective low-energy buildings – Recent results with special focus on comparison of calculated and measured energy performance of Danish buildings,“ *Applied Energy,* Article in press.

[9] K.E. Thomsen, J.M. Schultz, B. Poel, „Measured performance of 12 demonstration projects - IEA Task 13 “advanced solar low energy buildings,” *Energy and Buildings*, Vol. 37, 2005, pp. 111–119.

[10] Paul Raftery, Marcus Keane, Andrea Costa, „Calibrating whole building energy models: Detailed case study using hourly measured data,“ *Energy and Buildings*, Vol. 43, 2011, pp. 3666–3679.

[11] Elisabeth Gratia, Andre De Herde, “Design of low energy office buildings,” *Energy and Buildings*, Vol. 35, 2003, pp. 473-491.

[12] Kevin K.W. Wan, Danny H.W. Li, Dalong Liu, Joseph C. Lam, “ Future trends of building heating and cooling loads and energy consumption in different climates,“ *Building and Environment*, Vol. 46, 2011, pp. 223-234.

[13] Danny H.W. Li, Tony N.T. Lam, S.L. Wong, Ernest K.W. Tsang, „Lighting and cooling energy consumption in an open-plan office using solar film coating,“ *Energy*, Vol. 33, 2008, pp. 1288-1297.

[14] Guy R. Newsham, Sandra Mancini, Benjamin J. Birt, „Do LEED-certified buildings save energy? Yes, but. . .,“ *Energy and Buildings,* Vol. 41, 2009, pp. 897–905.

[15] William J. Fisk, Douglas Black, Gregory Brunner, „Changing ventilation rates in U.S. offices: Implications for health, work performance, energy, and associated economics," *Building and Environment,* Vol. 47, 2012, pp. 368-372.
[16] Daniel Tuhus-Dubrow, Moncef Krarti, "Genetic-algorithm based approach to optimize building envelope design for residential buildings," *Building and Environment*, Vol. 45, 2010, pp. 1574–1581.
[17] Youssef Bichiou, Moncef Krarti, "Optimization of envelope and HVAC systems selection for residential buildings," *Energy and Buildings,* Vol. 43, 2011, pp. 3373–3382.
[18] K.F. Fong, V.I. Hanby, T.T. Chow, "HVAC system optimization for energy management by evolutionary programming," *Energy and Buildings,* Vol. 38, 2006, pp. 220–231.
[19] Hanna Jedrzejuk, Wojciech Marks, "Optimization of shape and functional structure of buildings as well as heat source utilisation example," *Building and Environment,* Vol. 37, 2002, pp. 1249 – 1253.
[20] Gianluca Rapone, Onorio Saro, "Optimisation of curtain wall facades for office buildings by means of PSO algoritm," *Energy and Buildings,* Vol. 45, 2012, pp. 189–196
[21] Natasa Djuric, Vojislav Novakovic, Johnny Holst, Zoran Mitrovic, "Optimization of energy consumption in buildings with hydronic heating systems considering thermal comfort by use of computer-based tools," *Energy and Buildings,* Vol. 39, 2007, pp. 471–477.
[22] V. Sambou, B. Lartigue, F. Monchoux, M. Adj, "Thermal optimization of multilayered walls using genetic algorithms," *Energy and Buildings,* Vol. 41, 2009, pp. 1031–1036.
[23] Jingran Ma, Joe Qin, Timothy Salsbury, Peng Xu, "Demand reduction in building energy systems based on economic model predictive control," *Chemical Engineering Science,* Vol. 67, 2012, pp. 92–100.
[24] Weimin Wang, Radu Zmeureanu, Hugues Rivard, "Applying multi-objective genetic algorithmsin green building design optimization," *Building and Environment,* Vol. 40, 2005, pp. 1512–1525.
[25] M. Mossolly, K.Ghali, N.Ghaddar, "Optimal control strategy for a multi-zone air conditioning system using a genetic algorithm," *Energy,* Vol. 34, 2009, pp. 58–66.
[26] Lu Lu, Wenjian Cai, Lihua Xie, Shujiang Li, Yeng Chai Soh, "HVAC system optimization in building section," *Energy and Buildings,* Vol. 37, 2005, pp. 11–22.
[27] Laurent Magnier, Fariborz Haghighat, "Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network," *Building and Environment,* Vol. 45, 2010, pp. 739–746.
[28] Fredrik Engdahl, Dennis Johansson, "Optimal supply air temperature with respect to energy use in a variable air volume system," *Energy and Buildings,* Vol. 36, 2004, pp. 205–218.

[29] Ehsan Asadi, Manuel Gameiro da Silva, Carlos Henggeler Antunes, Luķs Dias, "Multi-objective optimization for building retrofit strategies: A model and an application," *Energy and Buildings,* Vol. 44, 2012, pp. 81–87.
[30] Giovanni Zemella, Davide De March, Matteo Borrotti, Irene Poli, "Optimised design of energy efficient building facades via Evolutionary Neural Networks," *Energy and Buildings,* Vol. 43, 2011, pp. 3297–3302.
[31] V. Siddharth, P.V. Ramakrishna, T. Geetha, Anand Sivasubramaniam, "Automatic generation of energy conservation measures in buildings using genetic algorithms," *Energy and Buildings,* Vol. 43, 2011, pp. 2718–2726.
[32] A. Saporito, A.R. Day, T.G. Karayiannis, F. Parand, "Multi-parameter building thermal analysis using the lattice method for global optimisation," *Energy and Buildings,* Vol. 33, 2001, pp. 267–274.
[33] Mohamed Hamdy, Ala Hasan, Kai Siren, "Impact of adaptive thermal comfort criteria on building energy use and cooling equipment size using a multi-objective optimization scheme," *Energy and Buildings,* Vol. 43, 2011, pp. 2055–2067.
[34] Michael Wetter, "BuildOpt - a new building energy simulation program that is built on smooth models," *Building and Environment,* Vol. 40, 2005, pp. 1085–1092.
[35] Ala Hasan, Mika Vuolle, Kai Siren, "Minimisation of life cycle cost of a detached house using combined simulation and optimisation," *Building and Environment,* Vol. 43, 2008, pp. 2022–2034.
[36] "Health-protection Ordinance for Educational Institutions", Ministry of Social Affairs in Estonia.
[37]http://en.wikipedia.org/wiki/File:Main_symptoms_of_carbon_dioxide_toxicity.svg
[38] Hens Hugo S.L.C., De Meulenaer, "Schools: All problem buildings?," *Proceedings of Clima 2007 WellBeing Indoors,* 2007.
[39] Wim Zeiler, Gert Boxem, "Ventilation of Dutch schools; an integral approach to improve design," *Proceedings of Clima 2007 WellBeing Indoors*, 2007.
[40] Zs. Bako-Biro, N. Kochhar, D.J. Clements-Croome, H.B.Awbi and M. Williams, "Ventilation in Schools and Learning Performance," *Proceedings of Clima 2007 WellBeing Indoors,* 2007.
[41] T. A. Koiv, M. Rebane, P. Parre, "Indoor climate and improvement possibilities in educational premises," *Proceedings of Clima 2007 WellBeing Indoors,* 2007.
[42] T. A. Koiv, "Indoor climate and ventilation in Talllinn school buildings," *Proceedings of Estonian Academy of Sciences. Engineering,* Vol.13(1), 2007, pp. 17-25.
[43] T. A. Koiv, "Indoor climate and energy efficiency of apartment and educational buildings in Estonia," *Proceeding of 3rd WSEAS International Conference on Engineering Mechanics, Structures, Engineering Geology,* Corfu Island, Greece, July 22-24, 2010, pp. 196-199.
[44] T. A. Koiv, H. Voll, M. Rebane, "Indoor climate in educational and residential buildings," *Journal of Chonqqing University (English edition),* December 08, 2009, pp. 35-38.

[45] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, "Indoor Climate and Energy Consumption in residential buildings," *Proceeding of 3rd International Conference on Energy and Development-Environment-Biomedicine,* WSEAS Press 2009, pp. 82-86.
[46] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, "Indoor Climate and Energy Consumption in residential buildings," *Proceeding of 3rd International Conference on Energy and Development-Environment-Biomedicine,* WSEAS Press 2009, pp. 82-86.
[47] A. Hani, T. Kalamees, T. A. Koiv, "Determination of energy performance requirements for apartment buildings in Estonia," *Proceeding of Healthy Buildings,* Syracuse NY, 2009, Paper 409.
[48] T. A. Koiv, H. Voll, M. Rebane, "Indoor climate in educational and residential buildings," *International Conference on Sustainable Development in Building and Environment,* Chonqquing, 2009, 2.
[49] P. Tint, Ü. Kask, T.A. Koiv, T. Vinnal, K. Reinhold, "Improvement of environmental and health issues in educational institutions," *Safety and Reliability for Managing Risks,* Estoril, Portugal, 18-22 September 2006, pp. 835-840.
[50] T. Lu, A. Knuutila, M. Viljanen, X. Lu, "A novel methodology for estimating space air change rates and occupant CO_2 generation rates from measurements in mechanically ventilated buildings," *Building and Environment* Vol. 45, 2010, pp. 1161-1172.
[51] M. Griffits, M. Eftekhari, "Control of CO_2 in naturally ventilated glassroom, *Energy and Buildings,* Vol. 40, 2008, pp. 556-560.
[52] K. Andersson, "Epidemiological approach to indoor air problems," *Indoor Air,* Vol. 4, 1998, pp. 32-39
[53] H. B. Awbi, AJ. Pay, "A study of the air quality in glassroom," *Proceeding of 2nd international conference on indoor air quality, ventilation and energy conservation in buildings,* Montreal Canada, 1995.
[54] DJ. Clements-Croome, "Creating the productive workplace," Spon-Rouledge, 2000.
[55] D. Mumovic, J. Palmer, M. Davies, M. Orme, I. Ridley, T. Oreszczyn, C. Judd, R. Critchlow, H. A. Medina, G. Pilmoor, C. Pearson, P. Way, "Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England," *Building and Environment,* Vol. 44, 2009, pp. 1466-1477.
[56] K.J. Chua, S.K. Chou, W.M.Yang, "Advantages in heat pump systems: A review," *Applied Energy,* Vol. 87, 2010, pp. 3611–3624.
[57] John W. Lund, Derek H. Freeston, Tonya L. Boyd, "Direct application of geothermal energy: 2005 Worldwide review," *Geothermics,* Vol 34, 2005, pp. 691–727.
[58] John W. Lund, Derek H. Freeston, Tonya L. Boyd, "Direct utilization of geothermal energy 2010 worldwide review," *Geothermics*, Vol 40, 2010, pp. 159–180.

[59] Shu Haiwen, Duanmu Lin, Li Xiangli, Zhu Yingxin, "Energy-saving judgment of electric-driven seawater source heat pump district heating system over boiler house district heating system," *Energy and Buildings*, Vol 42, 2010, pp. 889–895.
[60] Haiwen Shu, Lin Duanmu, Chaohui Zhang, Yingxin Zhu, "Study on the decision-making of district cooling and heating systems by means of value engineering," *Renewable Energy*, Vol 35, 2010, pp. 1929–1939.
[61] Young-hak Song, Yasunori Akashi, Jurng-Jae Yee, "Effects of utilizing seawater as a cooling source system in a commercial complex," *Energy and Buildings*, Vol 39, 2007, pp. 1080–1087.
[62] Shu Haiwen, Duanmu Lin, Li Xiangli, Zhu Yingxin, "Quasi-dynamic energy-saving judgment of electric-driven seawater source heat pump district heating system over boiler house district heating system," *Energy and Buildings*, Vol 42, 2010, pp. 2424–2430.
[63] Tomoji Nagota, Yoshiyuki Shimoda, Minoru Mizuno, "Verification of the energy-saving effect of the district heating and cooling system - Simulation of an electric-driven heat pump system," *Energy and Buildings*, Vol 40, 2008, pp. 732–741.
[64] Marcus Eriksson, Lennart Vamling, "Future use of heat pumps in Swedish district heating systems: Short- and long-term impact of policy instruments and planned investments," *Applied Energy*, Vol 84, 2007, pp. 1240–1257.
[65] Carl-Jochen Winter, "SUNRISE - A caesura after nuclear has gone: Energy in Germany (and in other potentially de-nuclearizing countries)," *International Journal of Hydrogen Energy*, Article in press, 2012, pp.1–16.
[66] Z. Sagia, C. Rakopoulos, E. Kakaras, "Cooling dominated Hybrid Ground Source Heat Pump System application," *Applied Energy*, Vol 94, 2012, pp. 41–47.
[67] Stefano Lo Russo, Glenda Taddia, Giorgia Baccino, Vittorio Verda, "Different design scenarios related to an open loop groundwater heat pump in a large building: Impact on subsurface and primary energy consumption," *Energy and Buildings*, Vol 43, 2011, pp. 347–357.
[68] Chen Chengmin, Zhang Yufeng, Ma Lijun, "Assessment for central heating systems with different heat sources: A case study," *Energy and Buildings*, Vol 48, 2012, pp. 168–174.
[69] Vittorio Verda, Giorgia Baccino, Adriano Sciacovelli, Stefano Lo Russo, "Impact of district heating and groundwater heat pump systems on the primary energy needs in urban areas," *Applied Thermal Engineering*, Vol 40, 2012, pp. 18–26.
[70] Wang Ying, Zhang Yufeng, "Analysis of the dilatancy technology of district heating system with high-temperature heat pump," *Energy and Buildings*, Vol 47, 2012, pp. 230–236.
[71] Benjamin David, Julien Ramousse, Lingai Luo, "Optimization of thermoelectric heat pumps by operating condition management and heat exchanger design," *Energy Conversion and Management*, 2012, Article in Press.

[72] Satoru Okamoto, "A heat pump system with a latent heat storage utilizing seawater installed in an aquarium," *Energy and Buildings*, Vol 38, 2006, pp. 121–128.
[73] Kadir Bakirci, Bedri Yuksel, "Experimental thermal performance of a solar source heat-pump system for residential heating in cold climate region," *Applied Thermal Engineering*, Vol 31, 2011, pp. 1508–1518.
[74] Kentaro Hirata, Hiroyuki Kakiuchi, "Energy saving for ethylene process by Adsorption Heat Pump," *Applied Thermal Engineering*, Vol 31, 2011, pp. 2115–2122.
[75] W.E. TeGrotenhuis, P.H. Humble, J.B. Sweeney, "Simulation of a high efficiency multi-bed adsorption heat pump," *Applied Thermal Engineering*, Vol 37, 2012, pp. 176–182.
[76] Brian T. Austin, K. Sumathy, "Transcritical carbon dioxide heat pump systems: A review," *Renewable and Sustainable Energy Reviews*, Vol 15, 2011, pp. 4013–4029.
[77] Kasumi Yasukawa, Shinji Takasugi, "Present status of underground thermal utilization in Japan," *Geothermics*, Vol 32, 2003, pp. 609–618.
[78] Andrew Hall, John Ashley Scott, Helen Shang, "Geothermal energy recovery from underground mines," *Renewable and Sustainable Energy Reviews*, Vol 15, 2011, pp. 916–924.
[79] T-A Koiv, "Estonian degree-days," Tallinn, 2007.
[80] M. Krarti. Energy Audit of Building Systems. An Engineering Approach. Boca Raton, London, New York, Washington D.C., 2000.
[81] Targo Kalamees and Jarek Kurnitski, "Estonian test reference year for energy calculations," *Proc. Estonian Acad. Sci. Eng.* Vol. 12, 1, 2006, pp. 40–58.
[82] Peter G. Ellis, Brent T. Griffith, Nicholas Long, Paul Torcellini and Drury Crawley, "Automated multivariate optimization tool for energy analysis" *IBPSA SimBuild,* 2006.
[82] Hendrik Voll, Teet-Andrus Kõiv, Teet Tark, M. Sergejeva, "Cooling Demand in Commercial Buildings - The Influence of Daylight Window Design," *WSEAS Transactions on Applied and Theoretical Mechanics,* Vol. 1/5, 2010, pp. 101–111.
[83] Michael Wetter, "GenOpt(R) Generic Optimization Program. User Manual. Version 3.0.0.," Lawrence Berkeley National Laboratory, 2009.
[84] EN 15251:2007 – Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics.
[85] Estonian Government Ordinance No. 258. Energiatõhususe miinimumnõuded. (Minimum requirements for energy performance of buildings) (20.12.2007); RT I 2007, 72, 445, 2007.

[86] Jarek Kurnitski, Arto Saari, Mika Vuolle, Jouko Niemelä, Targo Kalamees, "Final report: Cost optimal and nZEB energy performance levels for buildings," July 4, 2011.

[87] Tobias Rosencrantz, "Performance of Energy Efficient Windows and Solar Shading Devices. Evaluation through Measurements and Simulations," ISSN 1651-8136. ISBN 91-85147-13-3, 2005.
[88] A Hani, T-A Koiv, H Voll, M Tali, "Energy efficiency in Residential Buildings. The Comparison between Degree Day Calculation and Simulations," *Proceedings of the 2nd International Scientific "Energy and Climate Change" Conference: 2nd International Scientific "Energy and Climate Change" Conference*, 8-9 October 2009, Athens (Greece), pp. 209 - 213.
[89] T-A Koiv, "Estonian Government ordinance no 258, 2007 Minimum requirements for buildings energy performance additional analysis," Tallinn, 2009.
[90] A Hani, T-A Koiv, A Mikola, "Ventilating with Room Units in Educational Institutions," *International Journal of Energy and Environment,* Vol. 5, 2011, pp. 629 - 636
[91] "Health-protection Ordinance for Educational Institutions", Ministry of Social Affairs in Estonia.
[92] Bror Jonsson, Kristofer Doos, Jonas Nycander and Peter Lundberg, "Standing waves in the Gulf of Finland and their relationship to the basin-wide Baltic seiches," *Journal of Geophysical Research*, Vol. 113, 2008, C03004, doi:10.1029/2006JC003862.
[93] Taavi Liblik, Urmas Lips, "Characteristics and variability of the vertical thermohaline structure in the Gulf of Finland in Summer," *Boreal Environment Research,* Vol 16, 2011, pp. 73–83.

Curriculum Vitae

1. Personal data

First name, surname: Allan Hani
Date of birth, location: 29 March 1979 Võru
Nationality: Estonian

2. Contact data

Address: Särje 51/ Kanarbiku 1, 10922, Tallinn
Telefon: (+372) 52 62 985
E-mail: allan.hani@rkas.ee

3. Education

Institution	Graduation	Programme/Degree
Tallinn University of Technology	2008	Environmental Engineering, Master of Science
Tallinn University of Technology	2001	Thermal Engineering, Bachelor of Science

4. Language skills

Language	Level
Estonian	Native language
English	Intermediate level
Russian	Intermediate level
Finnish	Basic level
German	Basic level

5. Additional courses

Period	Educational or other organisation
11-13 June 2012	Tallinn University of Technology, ”Sustainable and Energy Efficient Building Design and Refurbishment”
10 January 2012	Tallinn University of Technology, ”Simulation and optimisation of indoor climate and energy use of buildings II“
27-29 May 2009	Helsinki University of Technology, Ene-58.5151, Post-graduate seminar on HVAC technology ”Simulation and optimisation of building energy systems – estimation of primary energy and CO2 emissions”

6. Professional employment

Period	Organization	Position
2011-	Riigi Kinnisvara AS	Specialist
2005-2010	Pöyry OÜ	Head of Department

7. Scientific work

Investigation of energy efficiency in buildings and HVAC systems.

8. Defended theses

Energy auditing of buildings. Degree of Master of Science.
Energy sector in AS Rapla Dairy. Degree of Bachelor of Science.

9. Research topics

Natural Sciences and Engineering, Construction and Municipal Engineering (Investigation of energy efficiency in buildings and HVAC systems, production of thermal and cooling energy, simulation and optimization of buildings, the effect of ventilation on indoor climate).

Elulookirjeldus

1. Isikandmed

Ees- ja perekonnanimi:	Allan Hani
Sünniaeg ja -koht:	29.03.1979 Võru
Kodakondsus:	Eesti

2. Kontaktandmed

Aadress:	Särje 51/ Kanarbiku 1, 10922, Tallinn
Telefon:	(+372) 52 62 985
E-posti aadress:	allan.hani@rkas.ee

3. Hariduskäik

Õppeasutus (nimetus lõpetamise ajal)	**Lõpetamise aeg**	**Haridus (eriala/kraad)**
Tallinna Tehnikaülikool	2008	Keskkonnatehnika, Tehnikateaduste magister
Tallinna Tehnikaülikool	2001	Soojustehnika, Tehnikateaduste bakalaureus

4. Keelteoskus (alg-, kesk- või kõrgtase)

Keel	**Tase**
Eesti keel	emakeel
Inglise keel	kesktase
Vene keel	kesktase
Soome keel	algtase
Saksa keel	algtase

5. Täiendõpe

Õppimise aeg	**Õppeasutuse või muu organisatsiooni nimetus**
11-13.06.2012	Tallinna Tehnikaülikool, ”Sustainable and Energy Efficient Building Design and Refurbishment”
10.01.2012	Tallinna Tehnikaülikool, „Simulation and optimisation of indoor climate and energy use of buildings II“
27-29.5.2009	Helsingi Tehnikaülikool, Ene-58.5151, ”Simulation and optimisation of building energy systems – estimation of primary energy and CO2 emissions”

6. Teenistuskäik

Töötamise aeg	Tööandja nimetus	Ametikoht
2011-	Riigi Kinnisvara AS	Spetsialist
2005-2010	Pöyry OÜ	Osakonnajuhataja

7. Teadustegevus

Hoonete ja nende tehnosüsteemide energeetilise efektiivsuse uurimine.

8. Kaitstud lõputööd

Hoonete energeetiline auditeerimine. Tehnikateaduste magistrikraad.
AS Rapla Dairy energiamajandus. Tehnikateaduste bakalaureuse kraad.

9. Teadustöö põhisuunad

Loodusteadused ja tehnika, Ehitus ja kommunaaltehnika (Hoonete ja nende tehnosüsteemide energeetilise efektiivsuse uurimine, soojus- ja külmavarustus, hoonete simulatsioonid ja optimeerimine, hoonete ventilatsioonilahenduste mõju sisekliimale).

Appendix A: Sea water district heating and cooling

The study of sea water district heating and cooling is based on the coastal area of Tallinn.

The parameters of the Gulf of Finland
The water and thermal processes in the Gulf of Finland are continuously monitored in the HELCOM project. Scientific articles [92, 93] have been written about the sea water parameters by Scandinavian and Estonian scientists.
All the measurements reported to HELCOM have to comply with the requirements of the survey program COMBINE. Information about the requirements is available at http://www.helcom.fi/groups/monas/CombineManual/en_GB/main/
Due to the salinity of the gulf water ice formation appears < - 0,4 ^{o}C.
The average ice thickness is 31 cm, very rare thickness > 50-60 cm (absolute maximum 1.2 m once in 150 years).
The temperature and profile of the sea water are analysed for the possibility of a sea water heat pump plant. The average depth profile of the Gulf of Finland is presented in Table 12.

Table 12. Average depth profile of the Gulf of Finland

Distance from coast, m	Depth (sea), m
500	20
1500	25
3200	30
4000	35
5500	40

The depth of the gulf is shallow – on average it increases 5m by an additional distance of 1 km from the coast. Economically it would be efficient to search for deeper locations in the costal area (< 500 m).
In the following Fig. 33 the temperature profile of sea water during the year is presented. The data are based on the information of station F3 monitoring the Gulf of Finland. The monthly average as well as minimum and maximum temperatures are presented in correlation with the sea depth.

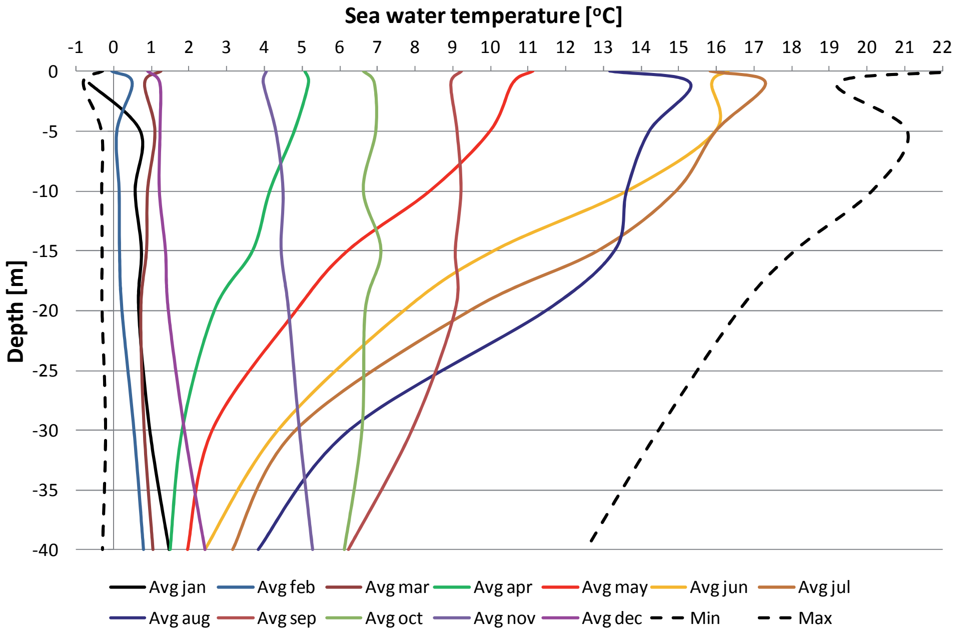

Fig. 33. Measurement results of the monitoring station F3

There is a wide variation of temperature during the year in the whole depth profile. In combination with the distance <500 m and depth -20 m the temperature range is between -0.31°C in winter and 16.6 °C in summer.

Outdoor climatic conditions

Outdoor climatic conditions and other design information of reference buildings is taken as a basis for dimensioning the loads of the sea water district heating and cooling plant. The minimum temperature for calculating the heating load is -22 °C to assure 21 °C in buildings. The design parameters of the cooling load are +27 °C and 50% relative humidity to assure +24 °C in buildings.

Case study

Based on the development plan of the local area 21 buildings (see Table 13) are included in the research from the Port of Tallinn area. There are existing buildings, but a majority are still to be erected. The total network of heating and cooling consumption is planned within the radius of <1 km from the coast.
In the preliminary stage 80 $W/m^2_{public\ area}$ for heating load calculations and 100 $W/m^2_{public\ area}$ for cooling calculations were calculated. These values include transportation losses of 5% for cooling and 10% for thermal energy. 60 $W/m^2_{public\ area}$ is calculated for the cooling demand of Building no 17.

Table 13. Heating and cooling load calculation

Building no	Building height, m	Storeys above ground	Public area, m^2	Cooling demand, kW	Heating demand, kW
1	24	6	8 764	876	701
2	24	6	18 870	1 887	1 510
3	24	6	1 458	146	117
4	24	6	3 564	356	285
5	24	6	5 780	578	462
6	18	5	5 198	520	416
7	11	2	2 340	234	187
8	18	5	8 775	878	702
9	24	6	2 268	227	181
10	24	6	2 430	243	194
11	24	6	10 260	1 026	821
12	24	6	5 049	505	404
13	24	6	4 860	486	389
14	20	5	24 500	2 450	1 960
15	16	4	4 250	425	340
16	19	5	11 200	1 120	896
17	-	4	37 221	2 233	2 978
18	19	5	10 500	1 050	840
19	19	5	2 200	220	176
20	19	5	5 250	525	420
21	22	5	3 700	370	296

A total of 14.3 MW of heating and 16.4 MW of cooling load was calculated. A simultaneous factor of 0.85 is applied to the calculation results. The maximum thermal capacity of the plant is 12 MW and the cooling capacity is 14 MW. The plant will be located at the Gulf of Finland.

The depth profile of the coastal area of Tallinn is presented in the following Fig. 34. The depth of 25m is located 500m from the area. The flow pipe will be directed there. The return pipe can be located near the coast.

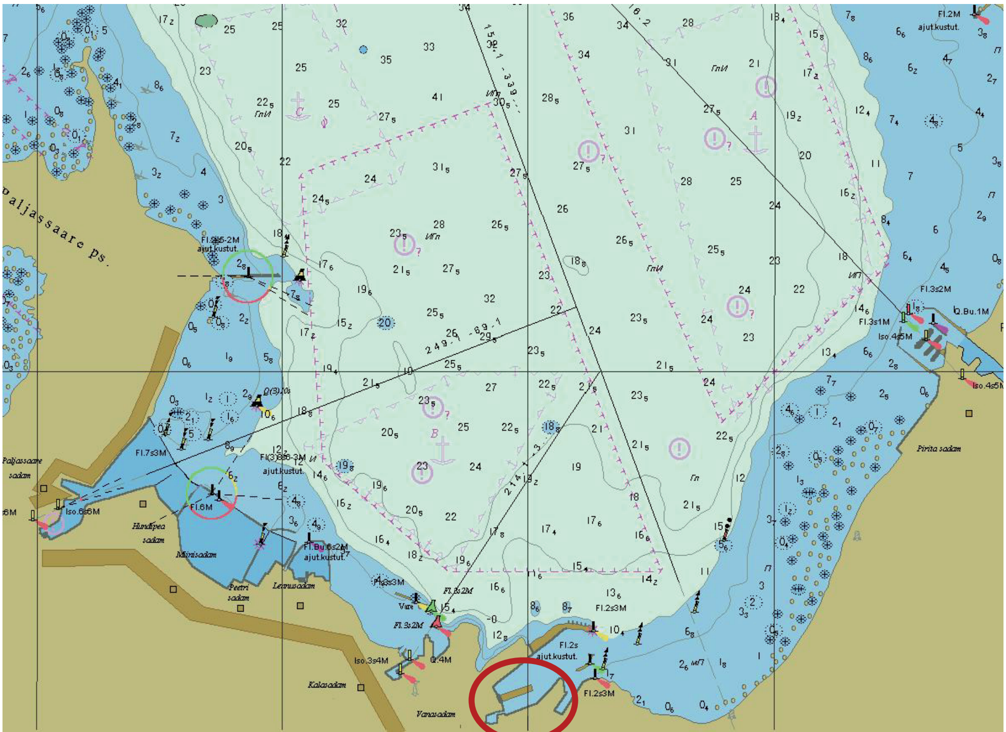

Fig. 34. Sea water profile of the coastal area of Tallinn

Technology

Two industrial heat pumps (e.g. Uniturbo 34FY a´8,0 MW) with high outlet temperatures of condenser water for heating and cooling are considered to cover the heating and cooling demand of the buildings. The principle scheme is presented in Fig. 35.

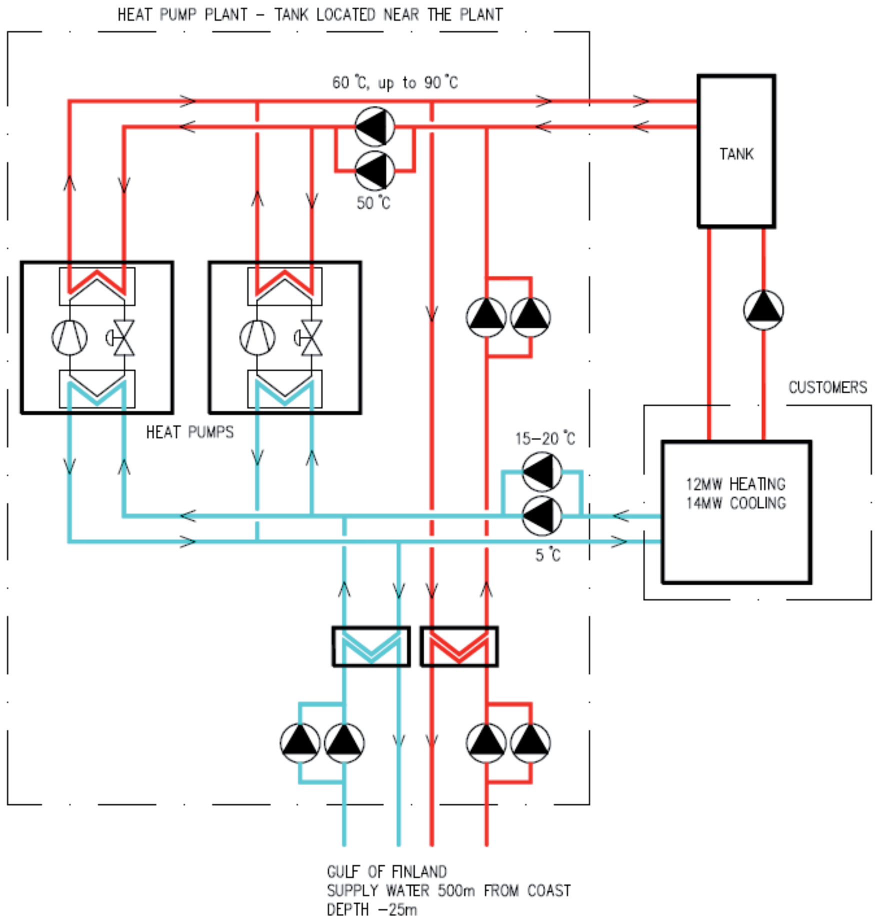

Fig. 35. The principle scheme of the sea water district heating and cooling plant

Heating mode operation:

The temperature of supply water to the district network is 60-90 °C (70 °C).
The temperature of return water from the district network is 50 °C.
The thermal storage tank is to provide temperature stability of the district heating network and prevent freezing of the evaporator side of return sea water. A 3600m^3 tank could provide up to 7 days' thermal energy (dT=20K).
Sea water dT=2K (0/2 °C).
The new buildings must be designed for low temperature heating (55/40 °C) to allow the maximum efficiency of the heat pump plant. For the existing buildings (80/60 or 70/50 °C) a combination of the heat pump plant and district heating will be considered.
The district heating network will be insulated to provide minimum thermal losses of the system.

Cooling mode operation:

The temperature of the supply water to the district network is 5 ^{o}C.
The temperature of the return water from the district network is 15-20 ^{o}C.
Sea water temperature < 4 ^{o}C. Completely free-cooling;
Sea water temperature 4-10 ^{o}C. Pre-cooling with sea water + compressor cooling;
Sea water temperature > 10 ^{o}C. Only compressor cooling (free cooling heat exchangers are equipped with bypasses).
Due to the fact that the soil temperature in summer in the depth of 1.5 m is 10 ^{o}C, it is not necessary to insulate the return pipe of the district cooling network. The supply pipe is insulated with 10 cm of modern heat insulation material.
The titanium heat exchangers allow using soft water in the distribution network while the problematic salty sea water flows through the open central circuit.
In summer mode excess heat can be used for DHW heating in the heating district network.

Comparable research and risk definition

Based on the reference projects studied and referred to in the introduction of the current study, sea water for district heating and cooling is a favourable renewable energy source. Still there are several matters to be considered before a real investment decision could be made.
A study of the environmental impact is required before any projects are executed. In addition to the evaluation of the deep zone cold water pumping, an analysis of recycling sea water back to the lower sea water zone with higher and lower temperatures should be carried out.
The possibilities of using old underground tunnels, etc must be studied to find economically reasonable solutions for district network construction.
It is necessary to optimize the size of the thermal storage tank as it affects both the stability of the district heating network and the economic possibilities of continuing with the design of the plant.
There is a risk to have too low temperatures on the evaporation side during cold winter periods, which will cause the shut-off of the heat pumps. A storage tank helps to overcome this, but cannot fully prevent it if the cold period lasts longer than designed. The design parameters must be carefully considered.
Also minimum altitudes between the heat exchangers and water resource level should be designed.
A centralized district heating and cooling plant, heat exchangers and a pumping station together are normally less expensive than decentralised systems. A centralized system has fewer maintenance problems.
Conventional cooling systems usually use electrical energy, which in Estonia is produced from oil-shale. Sea water is a huge cold water resource, so free cooling can be used.
Optimization of systems and an economic feasibility study should be carried out before continuing with research and real design. Furthermore, it is necessary to research trigeneration versus sea water district heating and cooling.

PAPER I

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Optimization of Office Building Façades in a Warm Summer Continental Climate

Allan Hani, Teet Andrus Koiv

Environmental Department, Tallinn University of Technology, Estonia.
Email: allan.hani@rkas.ee

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ABSTRACT

A typical office building model with conventional use and contemporary building systems was developed for façade optimization in continental climate. Wall, glazing area and window parameters were taken as the main variables. The objective function of optimization task described in this article is the minimization of cooling and heating energy consumption. The office building façades optimization was carried out using a combination of IDA Indoor Climate and Energy 4.5 and GenOpt. The process is described in detail so that the approach may be emulated. A hybrid multidimensional optimization algorithm GPSPSOCCHJ was used in calculation process. The optimization results are presented in four quick selection charts to assist architects, designers and real estate developers make suitable early stage façade selection decisions.

Keywords: Optimization; Envelope Design; Passive Solar Control; Energy Efficiency; Office Building

1. Introduction

Much research describes building simulation software as a tool for calculation process. IDA Indoor Climate and Energy, TRNSYS, Energy Plus, eQuest, DOE-2, etc. are well-known programs used to create building models and to perform the necessary energy consumption and indoor climate condition simulations. These tools have been tested and validated through real experimental cases. The simulation tools are usually used to perform limited numbers of single runs to give an overview and conclusions about a defined task. As these programs are used to conduct hourly based calculations over the full year, sufficiently accurate energy consumption results are achieved. The probability for these results to run across the Pareto frontier optimum solutions is actually very low. A possibility to find optimal solution is to use a "brute force" search. This method needs a huge calculation resource due to the fact that all possible combinations are evaluated [1].

A reasonable approach to achieving the optimal solution is to combine building simulation tools and optimization software. Optimization software can be customized for the particular research. Another possibility is to use an existing solution such as Lawrence Berkeley National Laboratory branded GenOpt or Matlab's Optimization Toolbox.

Different optimization algorithms are implemented in optimization software. Generally the algorithms are divided into: single and multi-objective. Selection of the algorithm depends on the constraints and/or the number of functions to be optimized. Multi-objective functions can be solved, for example, with Matlab Optimization Toolbox, single objective with GenOpt.

Technically the most challenging is to combine simulation and optimization tools. All the earlier studies indicate problems with computational hardware power—the calculation time is in relation to the number of variables and functions.

Daniel Tuhus-Dubrow, Moncef Krarti have used DOE-2, Perl application and Matlab for the optimization of a residential building envelope shape [2,3]. TRNSYS and Matlab calculations were done for cooling system optimization by K. F. Fong, V. I. Hanby, T. T. Chow [4]. Hanna Jedrzejuk, Wojciech Marks used a tailor-made solution for the optimization of the walls and heat source for a building [5]. Gianluca Rapone, Onorio Saro had researched office building shading solutions with a combination of Energy Plus and GenOpt in 2011 [6]. Energy Plus and GenOpt are combined for indoor comfort and hydronic heating optimization by Natasa Djuric, Vojislav Novakovic, Johnny Holst, Zoran Mitrovic [7]. Multilayered walls have been optimized with genetic algorithms by V. Sambou, B. Lartigue, F. Monchoux, M. Adj [8]. Energy Plus and Matlab was used by Jingran Ma, Joe Qin, Timothy Salsbury, Peng Xu to show the demand controlled systems economic efficiency in [9]. Weimin

Wang, Radu Zmeureanu, Hugues Rivard have published green building optimization concept with multi-objective genetic algorithms [10]. M. Mossolly, K. Ghali, N. Ghaddar have used Matlab to optimize control strategy for an air-conditioning system [11]. HVAC system optimization results were published by Lu Lu, Wenjian Cai, Lihua Xie, Shujiang Li, Yeng Chai Soh [12]. TRNSYS and GenOpt thermal comfort has been optimized by Laurent Magnier, Fariborz Haghighat [13]. VAV system optimal supply air temperature research was published by Fredrik Engdahl, Dennis Johansson [14]. Excel and Matlab combination for building retrofit strategies calculation has been carried out by Ehsan Asadi, Manuel Gameiro da Silva, Carlos Henggeler Antunes, Luķs Dias [15]. Single and multi-objective approaches for building façade overall energy efficiency were demostrated by Giovanni Zemella, Davide De March, Matteo Borrotti, Irene Poli [16]. Energy conser vation possibilities in buildings have been studied by V. Siddharth, P. V. Ramakrishna, T. Geetha, Anand Sivasubramaniam with DOE-2.2 and genetic algorithms [17]. Multi-parameter thermal optimization (APACHE software) has been done by A. Saporito, A. R. Day, T. G. Karayiannis, F. Parand [18]. A comprehensive study of building energy consumption and indoor environment optimization was done by Mohamed Hamdy, Ala Hasan, Kai Siren (Matlab + IDA ICE combination) [19].

Micheal Wetter stated in 2004 the following: "Discussions with IDA ICE developer showed that IDA-ICE might indeed be a promising tool for use with our optimization algorithms (GenOpt). However, without extensive numerical experiments and code analysis, it is not possible to conclude that IDA-ICE satisfies our requirements" [20].

The current research is based on a combination of IDA ICE and GenOpt. The IDA ICE and GenOpt combination has already been used by Ala Hasan, Mika Vuolle and Kai Siren [21]. Our paper describes the dynamic of window area, solar factor versus cooling, heating energy consumption in different cardinal directions. Due to the fact that the façade energy consumption is evaluated, other building envelope parameters and internal heat gains are handled as constants.

Hendrik Voll and Teet-Andrus Kõiv have published an article about cooling power demand estimation principles and different parameter relations for commercial buildings [22].

Our research is focused on heating and cooling energy consumption strategies for office buildings. Early stages of design affect future energy consumption for the building the most. The objective of this research is to develop quick selection charts for different cardinal directions in relation to window area and other envelope parameters.

2. Methods

2.1. Simulation-Optimization Approach

The theoretical approach for the building shape was created in the IDA Indoor Climate and Energy 4.5 environment. A square shaped three floor model (floor height 3.0 m) is indicated in **Figure 1**.

A typical office building is very often a multi-storey compact structure. Therefore, calculations were done in this case for the first floor to eliminate ground and roof physical effects.

First step, the IDA ICE mathematical model run creates a substantial ida_lisp.ida file with all defined data and relations between the parameters. The main structure of ida_lisp.ida consists of files, constants, tables, modules, connections, boundaries, start values, integration and log. To understand the relationships between different parameters is technically challenging. The full logic has to be understood and tested. For example, an increase of window area must decrease the same face wall area and vice versa in optimization calculations. As well the solar factor and shading coefficient have mathematical relation between them. To create the base IDA ICE model file for optimization calculations we renamed the ida_lisp.ida file to templ.ida and modified the envelope parameters mostly in the modules section. The basic scheme of the optimization is shown in **Figure 2**.

The convenient search and study of certain parameters in the ida_lisp.ida file can be achieved by giving clearly identified parameter values in the IDA ICE model for the particular module (glass, wall, etc.). Understanding of the total ida file puzzle is time-consuming, but unavoidable for optimization of IDA ICE calculation results with optimization tools.

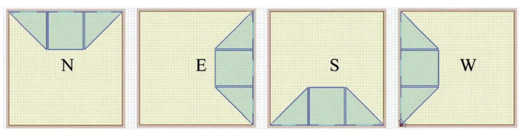

Figure 1. Shape of theoretical calculation model.

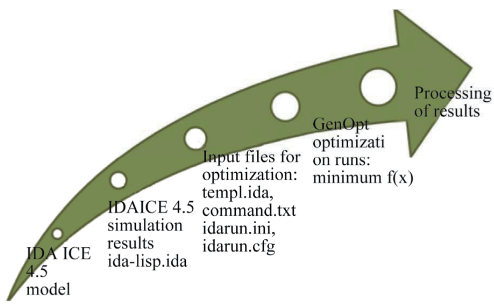

Figure 2. IDA ICE and GenOpt simulation-optimization process.

The second step is to create a command.txt file and define variables for the optimization process. The variables are indicated in **Table 1**. GenOpt can handle discrete and continuous variables.

Pre-processing relations between different building parameters are also described into command.txt file. For the current paper wall-window and solar factor-shading coefficient relations were defined (see following code).

```
Vary { Parameter { Name = A1win; Min = 1.2; Ini = 1.2; Max = 10.8; Step = 1.2; }
Function { Name = A1wall; Function = "subtract (12.0, %A1win%)"; }
Function { Name = A2wall; Function = "subtract (11.124, %A1win%)"; }
Parameter { Name = sfGl; Min = 0.2; Ini = 0.2; Max = 0.8; Step = 0.2; }
Function { Name = tGl ; Function = "multiply (0.87, %sfGl%)"; }
```

Furthermore, the command.txt file must also contain information about the optimization algorithm [23].

The actual optimization process was carried out with GPSPSOCCHJ algorithm. GPSPSOCCHJ is a hybrid multidimensional optimization algorithm which uses generalized pattern search (GPS) for the first stage search and particle swarm optimization (PSO) Hooke Jeeves algorithm as a fine search for the defined discrete and continuous variables function solution.

The configuration file idarun.cfg is written only once and it describes the IDA ICE simulation run parameters. The third essential file idarun.ini contains information about the locations of template, input, log, output, configuration and optimization files. The most important idarun.ini information is the objective function (in our case minimization function) definition. Constraints can be set to the optimization function, if necessary. The first stage of post-processing is also done here. For the different cardinal directions, our study uses the following IDA ICE templ.ida related code:

```
Name1 = Energ_kWh;
Function1 = "add(%Cool_kWh%, %Heat_kWh%)"
Name2 = negCool_kWh:
Delimiter2 = "Emeterlocool.Totenergy";
Name3 = Cool_kWh;
Function3 = "multiply (% neCool_kWh %, -1)"
Name4 = Heat_kWh;
Delimiter4 = "Etelocheat.Totenergy";
Name5 = WinN_SF;
Function5 = %SFG1%;
Name6 = Win_m2;
Function6 = %A1win%;
Name7 = Wall_m2;
Function7 = %A1wall%;
```

Our minimization leading function min f(x) is the minimization sum of cooling and heating energy related to external wall-glass parameters. The delimited energy information is recorded separately; therefore we can also present the balance between cooling and heating individually.

Four optimization runs were carried out.

2.2. Outdoor Climate Conditions

The test reference years are widely used for energy performance calculations and indoor climate analysis. Hourly based outdoor climate data (dry-bulb air temperature, relative humidity, wind speed, direct solar radiation and diffuse radiation on horizontal surfaces for 8784 hours) was used to create the mathematical model for IDA ICE 4.5 calculations [24]. Comparability of current study results for other climatic areas can be done through monthly and yearly average parameters which are indicated in **Table 2**.

2.3. Indoor Environment

Category II requirements from EN 15251:2007 were taken as the basis for defining indoor climate in simulation-optimization models. This category is considered as the normal expectation for new buildings and renovations according to reasonable indoor climate and energy efficiency levels [25].

Table 1. Optimization parameters.

Variable	Type	Value
Window area	Continuous	10% - 90%, step 10%
Glass solar factor	Continuous	0.2 - 0.8, step 0.2
Cardinal directions	-	North, East, South, West

Table 2. Test reference year parameters.

Month	Air temperture ˚C	Relative humidity %	Wind speed m/s	Direct dolar radition MJ/m^2	Diffuse rdiation on hozontal surf. MJ/m^2
Jan	–3.0	90	5	35.0	39.2
Feb	–5.2	89	4	93.4	82.0
Mar	–0.1	76	4	308.1	144.2
Apr	4.0	77	4	254.4	190.2
May	11.2	70	4	493.3	269.6
Jun	14.1	73	3	497.8	306.1
Jul	17.2	77	3	606.1	290.8
Aug	15.7	81	3	453.6	229.7
Sep	10.8	82	4	259.0	161.3
Oct	5.8	87	4	143.8	82.9
Nov	–0.1	91	4	68.2	37.0
Dec	–2.5	86	5	49.7	20.8
Avg	5.7	81	4	271.9	154.5

Indoor climate comfort can be described by two different indexes: PMV and PPD. These take into account the influence of six thermal comfort parameters: clothing, activity, air- and mean radiant temperature, air velocity and humidity. **Table 3** indicates the indoor climate parameters used for the calculations.

2.4. Office-Building Conventional Use

Internal heat gains in the average office area are presented in **Figure 3** [26]. The profile and detailed loads for occupants, equipment and lights were used for calculations in the IDA ICE 4.5 mathematical model. The profile is used from Monday to Friday—in the theoretical calculations internal heat gains were not estimated for the weekend.

Table 3. Indoor climate criteria.

Indoor environment parameters	Constraints
Thermal conditions in winter for energy calculations	20˚C - 24˚C [21˚C]
Thermal conditions in summer for energy calculations	23˚C - 26˚C [25˚C]
Personnel insulative clothing	~0.5 clo summer
Personnel activity level	~1.0 clo winter
Airflow to zones	~1.2 met
CO_2 level (outdoor 350 ppm)	7 l/s person [1.4 l/s m^2] < 850 ppm
Relative humidity	25% - 60%
Allowed parameter deviation (working hours)	3%

2.5. Building Envelope and Technical Services

The building enclosure's U-values were selected to be challenging but possible to achieve in construction practice for a "low energy building" [27]. Typical thermal bridge values have been used in the calculations (the effect of thermal bridges heat loss achieves more importance in case superb heat transfer coefficients are utilized). HVAC systems and other IDA ICE 4.5 simulation input parameters are indicated in **Table 4**.

Table 4. Building envelope and HVAC systems parameters.

External wall heat transfer coefficient U_w	0.14 W/(m^{2}K)
Window glass heat transfer coefficient U_{wg}	0.8 W/(m^{2}K)
Window frame heat transfer coefficient U_{wf}	2.0 W/(m^{2}K)
External wall/ external wall thermal bridge	0.08 W/K/(m joint)
External window or door perimeter thermal bridge	0.03 W/K/(m perimeter)
Infiltration q_{50}	1.0 m^3/(h m^2)
Building wind exposure	Semi-exposed (pressure coefficients)
Air handling unit (AHU) heat recovery	80%
AHU SFP	1.7 kW/(m^3/s)
AHU t_{supply} to zone ($t_{AHU\ supply}$ = 16˚C)	18˚C

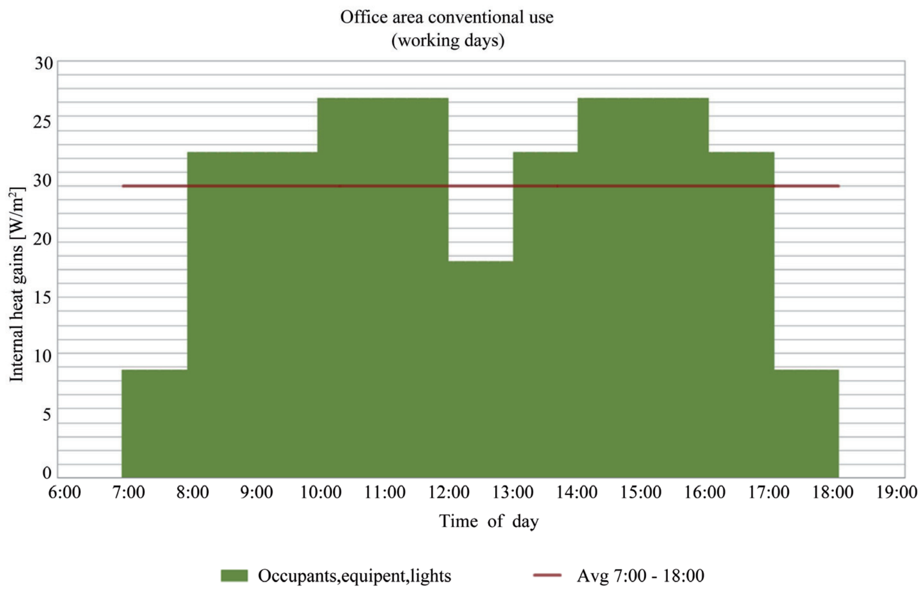

Figure 3. Typical office area internal heat gains.

3. Results

GenOpt optimization solver calculated through a total of 658 iterations during four optimization runs for different façade directions. The calculation and post-processing results are presented in the following 4 figures (**Figures 4-7**).

Total yearly specific energy consumption is the average of four façade selected net energy consumptions (kWh/m^{2}a).

Figures 4-7 detailed explanation: on primary axis net energy consumption for façade heating and cooling is presented. Secondary axis shows the window/wall ratio in percentages. Horizontal axis show glass solar factor (7 - 8 different window/wall ratio cases for each—see the blue dots). The selection of optimum starts from the directive window/wall ratio (e.g. from architect)—four different cases are possible for current cardinal direction related to glass solar factor.

4. Discussion

Window/wall area ratio (indicated in secondary axis) shall be the primary directive selection parameter (daylight window design parameters can be taken as additional constraints to make the first selection for window area [22]). Energy consumption is directly related to window/wall ratio and window glass parameters.

In the warm summer continental climate conditions for North and East façades the solar factor 0.4 can be suggested due to higher heat energy demand. South and West façades must have a solar factor as good as possible (in our case 0.2). High solar factor values must be prevented for all façade cardinal directions even in a cold climate.

These quick selection figures (**Figures 4-7**) can be used by building architects and developers to make a first quick-selection of building façades energy consumption. According to the Energy Performance of Buildings Directions (EPBD) the EU member states must define nearly zero energy buildings levels. For new buildings it will be a challenging task to achieve these levels by 2020, therefore, the current selection charts provide additional information for early stage building energy consumption estimation.

4.1. Sensitivity Analysis

To study the sensitivity of the above results we carried out some single runs for a double skin façade. The same principles are applicable for different cardinal directions. The internal envelope must be well thermally insulated for current climate conditions. Total solar factor (for both internal and external glazing) shall also have the suggested values. For double skin façades the window U-value has a direct effect on energy consumption for windows.

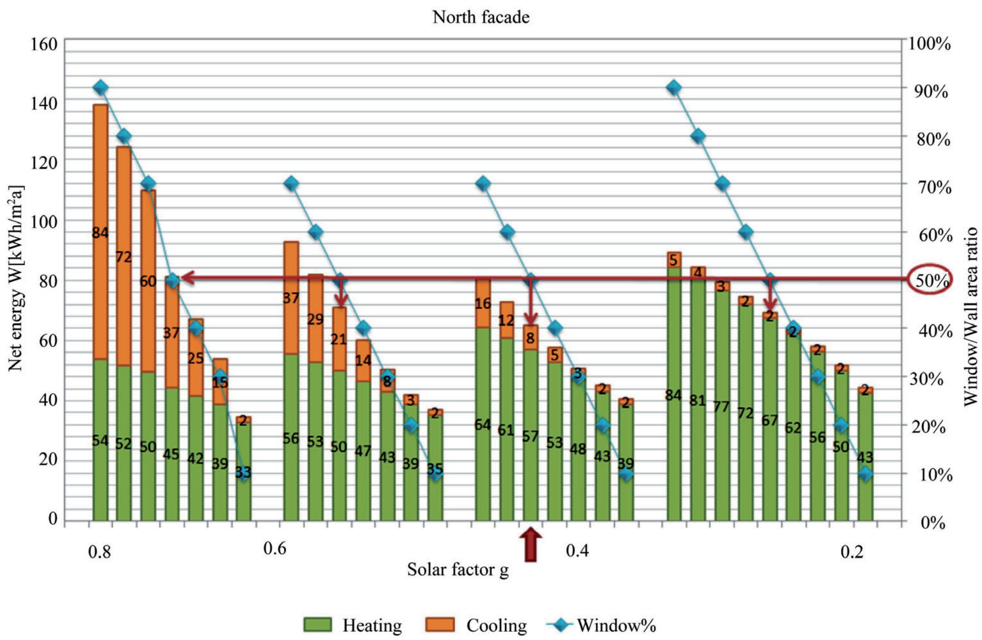

Figure 4. North façade optimization results.

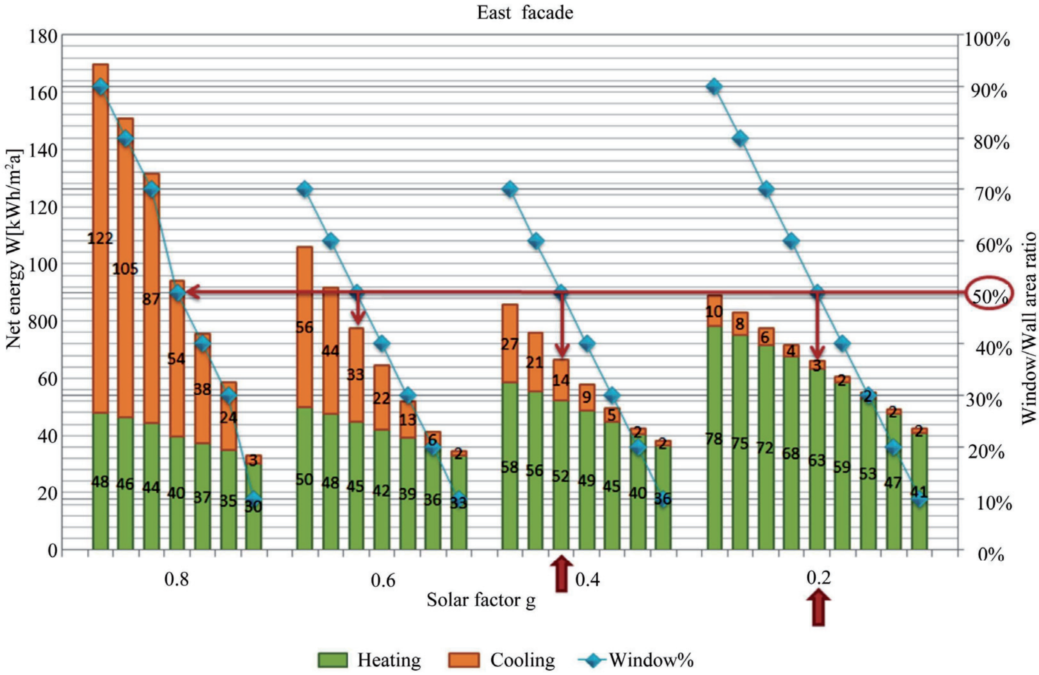

Figure 5. East façade optimization results.

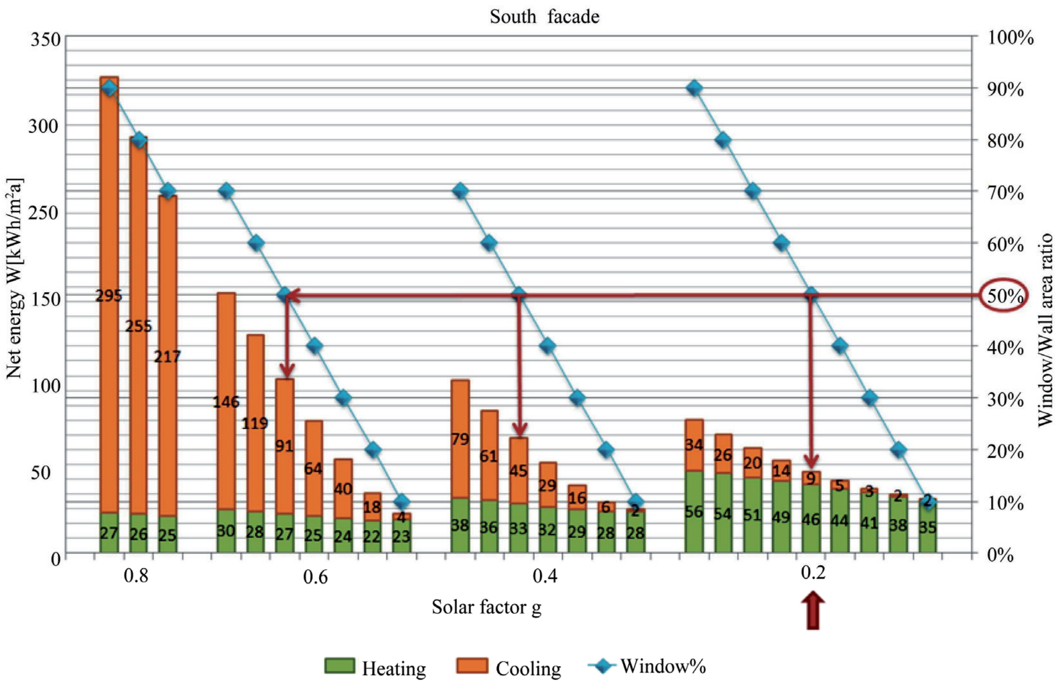

Figure 6. South façade optimization results.

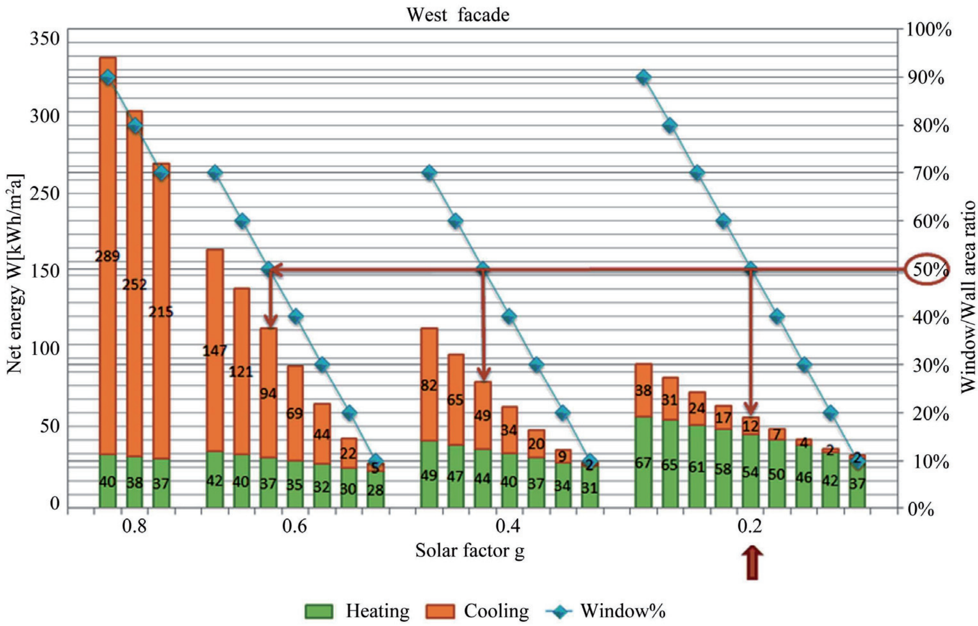

Figure 7. West façade optimization results.

Furthermore, Tobias Rosencrantz [28] has published heating net energy results for façades in the different cardinal directions for similar climatic conditions in Sweden and there is only slight deviation with our results.

Several IDA ICE single runs showed an acceptable indoor climate with solar factor 0.2 and 0.4.

5. Conclusions

The structure and importance of this work is presented as follows:

Creation of theoretical office building simulation model suitable for defining external wall window mathematical problem for optimization. Hourly based test reference year parameters were used for the external climate data. Indoor climate parameters are based on EN15251:2007 and the conventional use of the building [26].

The problem of combining IDA Indoor Climate and Energy building simulation model and the GenOpt optimization tool has been overcome. The main steps of the optimization approach have been described above. In addition, example code for the optimization files has been indicated.

Quick selection charts (**Figures 4-7**) have been developed for different façade directions and the results have been verified. In the quick selection charts heating, cooling net energy consumption for façades, window/wall ratio and window solar factor relationships are indicated.

Future new building solutions will have to follow nearly zero energy buildings legislation in EU member states. The current research helps to select office building façade in the early design stage. Architects often use a lot of glass in conventional office building façades and this will result in high energy consumption and life cycle costs. The energy consumption minimization shall be done based on the **Figures 4-7** in warm summer continental climate as the figures clearly present the relationship of different parameters (cardinal direction, window area, solar factor, specific cooling and heating energy consumption)

Further research topics should be related to other optimization tools. GenOpt, as currently used, solves single objective problems. In future, multi-objective solvers shall be applied to incorporate more detailed indoor environment (PMV, PPD) considerations into the façade investigation which has been dealt with here.

To use different double skin façade parameters, combined with thermal comfort, will be another interesting field of study. Moreover, economical calculations could be included as one of the multi-objective variables in further research.

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REFERENCES

[1] P. G. Ellis, B. T. Griffith, N. Long, P. Torcellini and D. Crawley, "Automated Multivariate Optimization Tool for Energy Analysis," *IBPSA SimBuild Conference*, Cambridge, 2-4 August 2006, 7 p.

[2] D. Tuhus-Dubrow and M. Krarti, "Genetic-Algorithm Based Approach to Optimize Building Envelope Design for Residential Buildings," *Building and Environment*, Vol. 45, No. 7, 2010, pp. 1574-1581. doi:10.1016/j.buildenv.2010.01.005

[3] Y. Bichiou and M. Krarti, "Optimization of Envelope and HVAC Systems Selection for Residential Buildings," *Energy and Buildings*, Vol. 43, No. 12, 2011, pp. 3373-3382. doi:10.1016/j.enbuild.2011.08.031

[4] K. F. Fong, V. I. Hanby and T. T. Chow, "HVAC System Optimization for Energy Management by Evolutionary Programming," *Energy and Buildings*, Vol. 38, No. 3, 2006, pp. 220-231. doi:10.1016/j.enbuild.2005.05.008

[5] H. Jedrzejuk and W. Marks, "Optimization of Shape and Functional Structure of Buildings as Well as Heat Source Utilisation Example," *Building and Environment*, Vol. 37, No. 12, 2002, pp. 1249-1253. doi:10.1016/S0360-1323(01)00100-7

[6] G. Rapone and O. Saro, "Optimisation of Curtain Wall Facades for Office Buildings by Means of PSO Algoritm," *Energy and Buildings*, Vol. 45, 2012, pp. 189-196. doi:10.1016/j.enbuild.2011.11.003

[7] N. Djuric, V. Novakovic, J. Holst and Z. Mitrovi, "Optimization of Energy Consumption in Buildings with Hydronic Heating Systems Considering Thermal Comfort by Use of Computer-Based Tools," *Energy and Buildings*, Vol. 39, No. 4, 2007, pp. 471-477. doi:10.1016/j.enbuild.2006.08.009

[8] V. Sambou, B. Lartigue, F. Monchoux and M. Adj, "Thermal Optimization of Multilayered Walls Using Genetic Algorithms," *Energy and Buildings*, Vol. 41, No. 10, 2009, pp. 1031-1036. doi:10.1016/j.enbuild.2009.05.007

[9] J. Ma, J. Qin, T. Salsbury and P. Xu, "Demand Reduction in Building Energy Systems Based on Economic Model Predictive Control," *Chemical Engineering Science*, Vol. 67, No. 1, 2012, pp. 92-100. doi:10.1016/j.ces.2011.07.052

[10] W. Wang, R. Zmeureanu and H. Rivard, "Applying Multi-Objective Genetic Algorithmsin Green Building Design Optimization," *Building and Environment*, Vol. 40, No. 11, 2005, pp. 1512-1525. doi:10.1016/j.buildenv.2004.11.017

[11] M. Mossolly, K. Ghali and N. Ghaddar, "Optimal Control Strategy for a Multi-Zone Air Conditioning System Using a Genetic Algorithm," *Energy*, Vol. 34, No. 1, 2009, pp. 58-66. doi:10.1016/j.energy.2008.10.001

[12] L. Lu, W. Cai, L. Xie, S. Li and Y. C. Soh, "HVAC System Optimization—In-Building Section," *Energy and Buildings*, Vol. 37, No. 1, 2005, pp. 11-22.

[13] L. Magnier and F. Haghighat, "Multiobjective Optimization of Building Design Using TRNSYS Simulations, Genetic Algorithm, and Artificial Neural Network," *Building and Environment*, Vol. 45, No. 3, 2010, pp. 739-746. doi:10.1016/j.buildenv.2009.08.016

[14] F. Engdahl and D. Johansson, "Optimal Supply Air Temperature with Respect to Energy Use in a Variable Air Volume System," *Energy and Buildings*, Vol. 36, No. 3, 2004, pp. 205-218. doi:10.1016/j.enbuild.2003.09.007

[15] E. Asadi, M. G. da Silva, C. H. Antunes and L. Dias, "Multi-Objective Optimization for Building Retrofit Strategies: A Model and an Application," *Energy and Buildings*, Vol. 44, 2012, pp. 81-87.

[16] G. Zemella, D. De March, M. Borrotti and I. Poli, "Optimised Design of Energy Efficient Building Facades via Evolutionary Neural Networks," *Energy and Buildings*, Vol. 43, No. 12, 2011, pp. 3297-3302. doi:10.1016/j.enbuild.2011.10.006

[17] V. Siddharth, P. V. Ramakrishna, T. Geetha and Anand Sivasubramaniam, "Automatic Generation of Energy Conservation Measures in Buildings Using Genetic Algorithms," *Energy and Buildings*, Vol. 43, No. 10, 2011, pp. 2718-2726. doi:10.1016/j.enbuild.2011.06.028

[18] A. Saporito, A. R. Day, T. G. Karayiannis and F. Parand, "Multi-Parameter Building Thermal Analysis Using the Lattice Method for Global Optimisation," *Energy and Buildings*, Vol. 33, No. 3, 2001, pp. 267-274. doi:10.1016/S0378-7788(00)00091-8

[19] M. Hamdy, A. Hasan and K. Siren, "Impact of Adaptive Thermal Comfort Criteria on Building Energy Use and Cooling Equipment Size Using a Multi-Objective Optimization Scheme," *Energy and Buildings*, Vol. 43, No. 9, 2011, pp. 2055-2067. doi:10.1016/j.enbuild.2011.04.006

[20] M. Wetter, "BuildOpt—A New Building Energy Simulation Program That is Built on Smooth Models," *Building and Environment*, Vol. 40, No. 8, 2005, pp. 1085-1092. doi:10.1016/j.buildenv.2004.10.003

[21] A. Hasan, M. Vuolle and K. Siren, "Minimisation of Life Cycle Cost of a Detached House Using Combined Simulation and Optimisation," *Building and Environment*, Vol. 43, No. 12, 2008, pp. 2022-2034. doi:10.1016/j.buildenv.2007.12.003

[22] H. Voll, T.-A. Kõiv, T. Tark and M. Sergejeva, "Cooling Demand in Commercial Buildings—The Influence of Daylight Window Design," *WSEAS Transactions on Applied and Theoretical Mechanics*, Vol. 5, No. 1, 2010, pp. 101-111.

[23] M. Wetter, "GenOpt(R) Generic Optimization Program, User Manual, Version 3.0.0," Lawrence Berkeley National Laboratory, Berkeley, 2009. doi:10.2172/962948

[24] T. Kalamees and J. Kurnitski, "Estonian Test Reference Year for Energy Calculations," *Proceedings of the Estonian Academy of Science*, *Engineering*, Vol. 12, No. 1, 2006, pp. 40-58.

[25] EN 15251:2007, "Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of

Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics."

[26] Estonian Government Ordinance No. 258, "Minimum Requirements for Energy Performance of Buildings (20. 12.2007)," RT I 2007.

[27] J. Kurnitski, A. Saari, M. Vuolle, J. Niemelä and T. Kalamees, "Cost Optimal and nZEB Energy Performance Levels for Buildings," Final Report, 2011.

[28] T. Rosencrantz, "Performance of Energy Efficient Windows and Solar Shading Devices, Evaluation through Measurements and Simulations," Lund University, Lund, 2005.

PAPER II

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Energy Consumption Monitoring Analysis for Residential, Educational and Public Buildings

Allan Hani, Teet-Andrus Koiv

Environmental Department, Tallinn University of Technology, Tallinn, Estonia.
Email: allan.hani@rkas.ee

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ABSTRACT

In the present article thermal and electrical energy consumptions for different types of buildings are analyzed. The latitude and longitude of the researched area are defined 59˚00'N and 26˚00'E. According to Köppen climate classification the area is located in warm summer continental climate. The study consist 40 residential, 7 educational and 44 public buildings. Three years data for each building type among 2006-2011 was used. Several detailed energy balances are presented for apartment buildings. In addition the different ways of domestic hot water preparation are analyzed for apartment buildings. The school buildings average consumption values are represented in study. Also valuable information of measured electrical energy consumption balance for a new office building is presented. Finally there is included the energy consumption analysis of public buildings.

Keywords: Specific Energy Consumption; Thermal Energy; Electrical Energy; Residential Buildings; Educational Buildings; Office Buildings

1. Introduction

He energy prices are rising continuously in most countries all over the world. Currently the targets are to consume less energy and produce more green energy. The building sector is responsible for approximately 40% consumption from total countries energy balances in EU and USA. In developing countries the value is around 20%. A comprehensive research conclusion is presented in 2007 [1]. The biggest consumers of non-domestic buildings sector are supermarkets, hospitals, restaurants. The research of urban energy consumption distribution in USA [2] shows the variety of residential, public and industrial buildings energy consumption. Also energy balances for residential and public buildings are presented. The electrical energy consumption in public buildings is a concern. London public buildings have been researched [3,4]—the office buildings specific energy consumption values range is wide. In addition, a scenario of energy consumption in London until 2050 is presented. Similar scenarios could be suggested also to other countries. Statistical analysis of Chinese buildings has been carried out in some extent [5,6]. The dispersion diagrams are presented (offices, hotels, governmental buildings). The Malaysian office buildings are compared with other countries [7]. Also the results of electrical motor variable speed drives economical calculation are carried out and the solution can be suggested. The calculated energy consumptions and real measurement result differ 1.2 - 1.5 times in lots of cases [8,9]. The calculation methods must be revised. To have more precise calculation results the iterative calibration process for dynamic simulations is prepared [10]. Already in 2002 an envelope shape and other building parameters based strategies have been suggested for designing low energy office buildings [11]. This information is valuable and can be used by architects, engineers and design companies. In China the trends for heating and cooling energy consumption in different climate areas are researched. The scenario for period 2009-2100 is presented [12]. To lower a cooling load and glaring of the light in buildings the windows can be coated with protective films [13]. The solution suits well for the older buildings. A very interesting research of LEED certification effects to energy consumption is done in North America [14]. Averagely LEED buildings consume 18% - 39% less energy per floor area than others. But 28% - 35% LEED buildings consume more energy per floor area than others. To lower the ventilation air exchange rates reduces energy consumption. A good solution is to use 8 l/s per person and lower the ventilation rate when absent [15]. The energy saving measures shall be selected according to the building.

2. Methods

2.1. The Compensation of External Air Temperature Variety for Different Years Heat Consumption

The degree-days are widely used to eliminate the influence of external air temperature difference for different years to heat energy consumption. The heat energy consumption is reduced to reference year basis. The reference year degree-days in Estonia are selected from 1975-2004 (30-year period) and defined for six different locations (Tallinn, Tartu, Jõhvi, Pärnu, Valga, Ristna).

Determination of degree-day reference year

Following Equation (1) expresses the equation for degree-day reference year creation [16].

$$S = \sum_{i=1}^{n} \left(t_B - t_{\text{EXTi}}\right) \times \delta_i \quad (1)$$

where, S is number of degree-days, $°\text{K} \cdot d$; n is number of days (in a month or a year); t_B is internal air temperature (balance temperature), ˚C; t_{EXTi} is external air temperature of i day, ˚C; $\delta_i = 1$, if $t_B > t_{\text{EXTi}}$; $\delta_i = 0$, if $t_B \le t_{\text{EXTi}}$

Determination of heat energy consumption normalized with reference year

The following Equation (2) is used to eliminate the influence of external air temperature to heat energy.

$$Q_n = \left(Q_{\text{REAL}} - C\right) \times \frac{S_N}{S_{\text{REAL}}} + C \quad (2)$$

where, Q_n is heat consumption normalized with reference year, MWH/year; Q_{REAL} is heat consumption of real year, MWH/year; S_N is degree-days of reference year, $°\text{K} \cdot d$; S_{REAL} is degree-days of real year, $°\text{K} \cdot d$; C is heat consumption where degree-days do not have affect (e.g. hot water), MWH/year.

The actual research heat energy consumption values are normalized according to Equation (2). In addition the electrical energy consumption is added.

2.2. Degree-Day Energy Consumption Calculations with Variable Balance Temperature

The method is also expressed in [16].

Determination of free heat in residential building

The sources of free heat in the building are people, electric devices, electric lightning, and solar radiation. The main components of the free heat load are calculated by the Equation (3).

$$\Phi_{\text{AFH}} = \Phi_{\text{PEOP}} + \Phi_{\text{LIGHT}} + \Phi_{\text{EQUIP}} + \Phi_{\text{SOLAR}} \quad (3)$$

where, Φ_{AFH} is the average free heat load, kW; Φ_{PEOP} is the people average effective free heat load, kW; Φ_{LIGHT} is the electric lighting average effective free heat load, kW; Φ_{EQUIP} is the average effective free heat load of equipments, kW; Φ_{SOLAR} is the average effective free heat load due to the solar radiation, kW.

The respective free heat loads Φ_{free} are determined by the amounts of free heat energy Q_{free} and the duration of the respective period τ (4).

$$\Phi_{\text{free}} = 1000 \cdot \frac{Q_{\text{free}}}{\tau} \quad (4)$$

where Q_{free} is the free heat energy of the building, MWH; τ is the duration of the period, *h*.

Determination of the balance temperature on the basis of free heat

On the basis of the degree days it is possible to calculate the heat requirements for heating the building by Equation (5)

$$Q_k = H \cdot S_N \times 24 \times 10^{-3} \quad (5)$$

where, S_N is the number of degree-days corresponding to the balance temperature of the building; 24 is the number of hours in a day; H is the specific heat losses, kW/ °K , determined by Equation (6).

Specific heat losses of the building

$$H = \sum_{i=1}^{n} U_i \cdot A_i + L \cdot c \cdot \rho \quad (6)$$

where, U_i is the U-value of envelope element i W/(m^2· °K); A_i is the area of envelope element i , m^2; n is the number of different envelope elements; L is the air change, m^3/s; c is the specific heat of the air, J/(kg· °K); ρ is the density of the air, kg/m^3.

To more precisely display the heat conservation obtained by renovation it is expedient to use the degree days with a variable balance temperature.

In renovating the building (e.g. insulating the envelope elements) the specific heat losses decrease and thus affect the balance temperature.

The internal air temperature of the building is made up by the heat provided by the heating system and free heat (7).

$$t_{\text{int}} = t_{\text{ext}} + \Delta t_{\text{heat}} + \Delta t_{fh} \quad (7)$$

Balance temperatures can be found by Equation (8)

$$t_B = t_{\text{int}} - \Delta t_{fh} \quad (8)$$

where, t_{int} is internal air temperature; t_{ext} is the external air temperature; t_B is the balance temperature; Δt_{fh} is the rise in the temperature at the expense of the free heat taking part in the heat balance of the building.

The rise in the temperature at the expense of free heat can be found by Equation (9)

$$\Delta t_{fh} = 1000 \cdot \frac{\Phi_{\text{free}}}{H} \quad (9)$$

The useful free heat load needed in determining the balance temperature is determined by Equation (10)

$$\Phi_{\text{free}} = \Phi_{\text{dfree}} \cdot \eta \quad (10)$$

where, Φ_{dfree} is the design free heat load, W; η is the utilization factor.

The value of the utilization factor depends on the control level of the heating system. (e.g. if the temperature of the heating systems' flow water is controlled by the external air temperature and the heat output of the radiators is controlled, we can acquaint more use of free heat than if we control only the temperature of the flow water). Based on balance temperature degree days the energy consumption balance can be calculated and evaluated with real measurement results. A decrease of the balance temperature brings remarkable savings in the heat requirements of the building. The method is used for apartment buildings thermal energy balance calculations and saving estimations. Nevertheless, for public buildings, where the t_B varies remarkably during the year, dynamic simulations (IDA Indoor Climate and Energy, TRNSYS, Energy Plus, etc.) or real measurements for energy balance determination can be suggested.

3. Results and Discussion

3.1. Residential Buildings

Total 40 buildings thermal and electrical energy consumptions (2006-2010) were collected and analyzed. The detailed energy balance analysis was carried out for 14 buildings. Information about reconstructions, heating source, internal air temperature, air exchange rate and domestic hot water production is presented in **Table 1**.

Following abbreviations are used: DH-district heating; WB—wood fired boiler; GB—gas fired boiler; DHW—domestic hot water; ACH—air exchange rate; HS—heating substation; EL—electrical heaters; win—windows; bal—balancing works; full—full reconstruction.

During actual research the energy audits, prepared by professional auditors, were evaluated. In a numerous cases the systematic errors were found. DHW is prepared with decentralized electrical heaters, but the auditors have calculated once again the DHW energy consumption to heating energy balance and this is not correct. Among current energy balance calculations all the mistakes were corrected. Furthermore the packages of saving measures did not include ventilation reconstruction measures. This leads to the fact that among studied audits no ventilation improvement was done (2006-2010). The ventilation reconstruction problems shall be taken to the focus in further auditor trainings. The solutions with heat recovery (decentralized room or apartment based ventilation, and exhaust air heat pump) are available to use in reconstruction projects. In following **Figures 1** and **2** the energy balances, specific gross consumptions and average specific consumptions of 14 apartment buildings are presented.

The **Figures 1** and **2** the average specific energy consumptions:

Table 1. The main information about researched buildings.

Bld.	County	Reconstructions		Heating source	Tintavg	ACH	DHW
		Envelope	Heating system		[˚C]	[1/h]	
A1	Pärnu	-	-	DH	20.0	0.40	HS
A2	Harju	2010 roof 300 mm, <2010 win 86%	2007 HS, 2008 bal	DH	20.0	0.40	HS
A3	Saare	2006 roof 400 mm, 2007 win 66%	2000 HS	DH	22.5	0.27	HS
A4	Tartu	2001 win 100%	2001 HS	DH	23.0	0.25	HS
A5	Harju	<2010 win 85%	-	GB	20.0	0.30	HS
A6	Ida-Viru	<2010 win 54%, walls 100 mm 36%	2003 HS, 2007 bal	DH	20.5	0.20	HS
A7	Harju	2009 roof 200 mm, <2010 win 93%	1997 HS, bal	DH	21.0	0.40	HS
A8	Viljandi	<2009 win 89%	2008 full	DH	21.0	0.33	HS
A9	Jõgeva	-	-	DH	19.0	0.35	EL
A10	Põlva	-	-	DH	23.0	0.24	EL
A11	Ida-Viru	<2008 win 47%	-	DH	19.0	0.31	EL
A12	Valga	<2008 win 63%, doors	-	DH	22.0	0.30	EL
A13	Harju	<2009 win85%	<2009 HS	DH	21.0	0.20	HS
A14	Tartu	<2009 win 77%	-	DH	19.5	0.20	EL

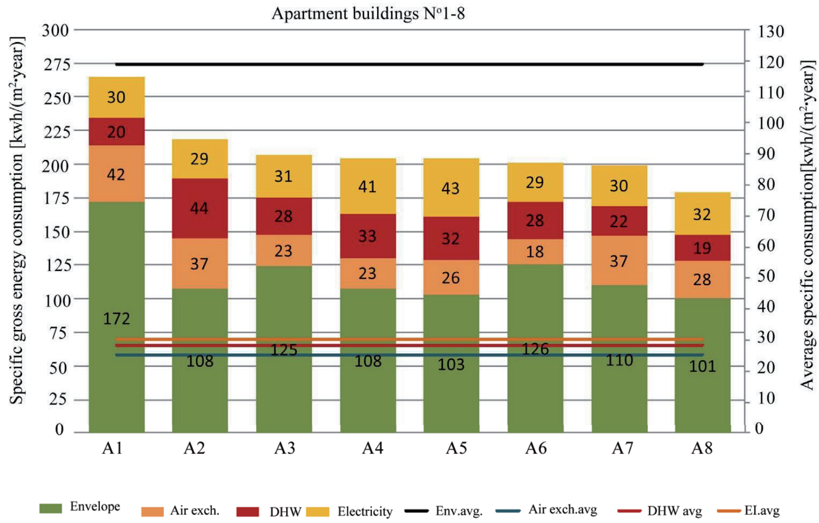

Figure 1. Dynamics of energy balance and specific energy consumption in the analyzed buildings (DHW prepared in substation).

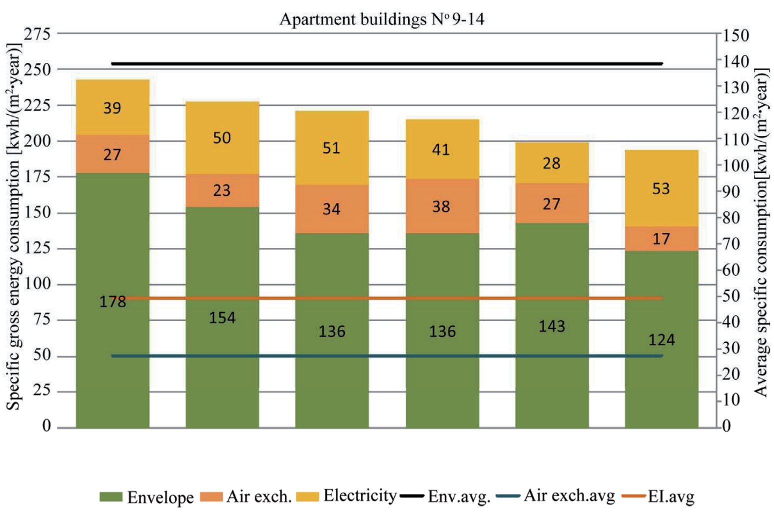

Figure 2. Dynamics of energy balance and specific energy consumption in the analyzed buildings (DHW prepared with electrical heaters in apartments).

1) Heating 120 - 140, kWh/(m^2_{heated} ·year);
2) Air exchange and infiltration 20-30, kWh/(m^2_{heated} ·year);
3) Domestic hot water 30, kWh/(m^2_{heated} ·year);
4) Electricity 30 without electrical heaters, kWh/(m^2_{heated} ·year);
5) Electricity 50 with electrical heaters, kWh/(m^2_{heated} ·year);
6) Total 200 - 250, kWh/(m^2_{heated} ·year).

The **heated area m²** is a basis for specific energy consumption values.

Earlier studies [17] have indicated average specific heating energy consumption of 185 kWh/(m²·year). Current analyse results gave 180 - 185 kWh/(m²·year) without electrical energy consumption.

The **Figure 3** presents dispersion of specific thermal and electrical energy consumption for analyzed 40 apartment buildings.

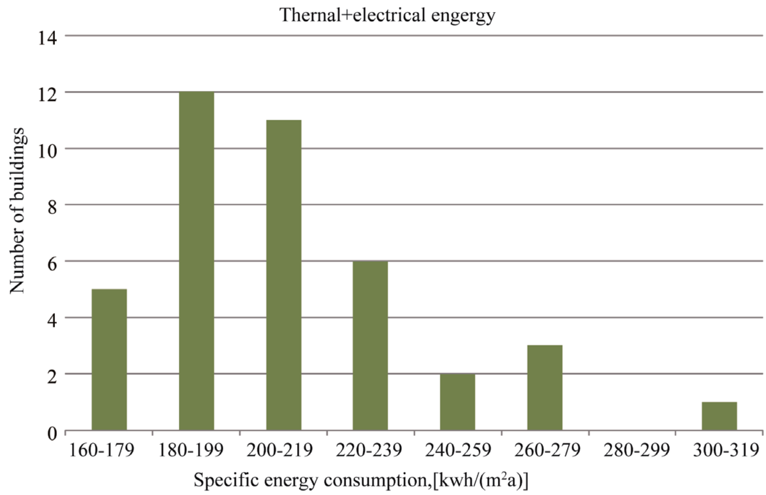

Figure 3. Dispersion of specific energy consumption of apartment buildings.

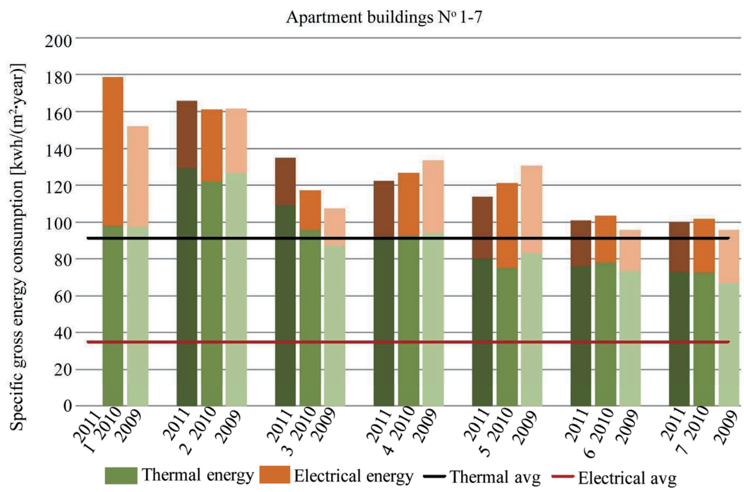

Figure 4. Specific energy consumption in the analyzed educational buildings.

Most of the apartment buildings energy consumption varies between 180-220 kWh/(m²·year).

3.2. Educational buildings

Total 7 school buildings thermal and electrical energy consumptions (2009-2011) were collected and analyzed. The heat energy consumption is normalized with reference year. Following **Figure 4** presents the specific energy consumption of studied buildings.

The **net area m²** is a basis for specific energy consumption values.

1) Average specific thermal energy consumption (includes DHW) is 90 kWh/(m^2_{net} ·year).

2) Average specific electrical energy consumption is 35 kWh/(m^2_{net} ·year).

3)Total ~ 125 kWh/(m^2_{net} ·year).

The specific consumption value is relatively low, but 3 months during the year the usage of school buildings is nearly 0. Also, the net area in typical school buildings is ca 1.5 times bigger than heated area [18]. Furthermore, the current schools investment schematic supports the low energy consumption, but the poor indoor climate aspects shall be considered [19].

3.3. Public Buildings

Total 44 public buildings thermal and electrical energy consumptions (2009-2011) were collected and analyzed. In addition one typical new ten-storey office building electrical energy balance is analyzed more in deep.

Measured energy balance of an office building

The importance of electrical energy consumption in new office buildings is frequently underestimated in warm summer continental climate. Following **Figure 5** represents the energy balance of a ten-storey office building. The measurements base on 2011 energy consumption.

The electrical energy balance (100%) division:

1) Lighting and electrical equipment (10 floors) 42.2%;

2) Cooling (chiller unit, pumps, dry-coolers, split-units) 27.6%;

3) Servers 8.9%;

4) Ventilation (fans, heating pumps, heat recovery wheel) 7.0%;

5) External electrical heating (ramp heating, rainwater gullies) 4.7%;

6) External and parking area lighting 3.3%;

7) Technical rooms and video surveillance 2.8%;

8) Heating substation (boilers, pumps) 2.2%

9) Elevators 1.3%.

The analysis of 44 *public buildings*

It is more complicated to evolve energy saving measures in public building sector than in residential buildings. The national heritage board has grounded restrictions to public buildings envelope and finishing. The internal insulation can not be added due to climatic conditions. Windows change is whether expensive or not allowed. As well the heating system reconstruction is more complicated (employees and equipment have to be moved; valuable finishing materials can be destroyed; more expensive heating elements are required by architect, etc.).

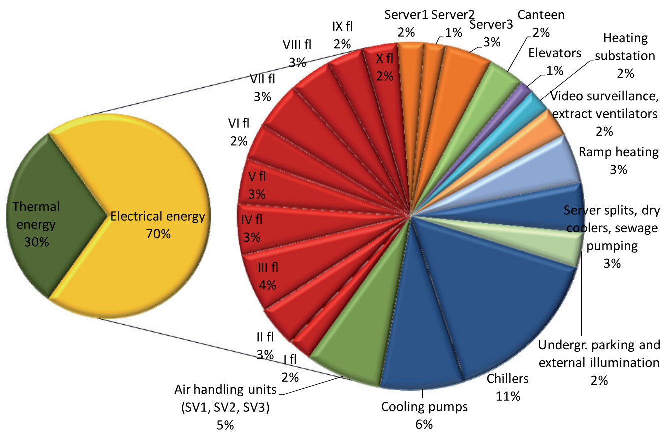

Figure 5. Measured energy balance of a high rise office building.

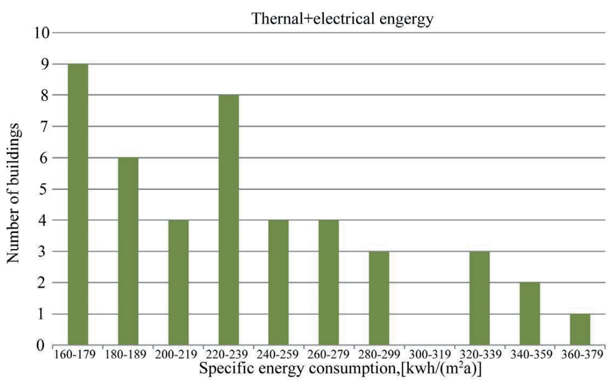

Figure 6. Dispersion of specific energy consumption of public buildings.

Usually roof insulation is the easiest saving measure to be done.

The current analysis is based on 44 public buildings thermal and electrical energy consumption. The heat energy consumption is normalized with reference year. The **net area m²** is a basis for specific energy consumption values. In following **Figure 6** the dispersion of specific energy consumption of analysed buildings is presented.

The energy consumption varies widely and the energy saving measures can be worked out only case by case.

Average share of thermal energy is 60% and electrical 40% in public buildings. In 10 cases the electrical energy consumption was 25%.

Among the study 4 buildings were electrically heated and their energy consumptions rating were in 12^{th}, 28^{th}, 34^{th} and 38^{th} position in a regressive row. Nevertheless, the electrical energy is more expensive than other energy resources.

4. Conclusions

Based on the analysis of the energy consumption of residential, educational and public buildings following findings can be categorized:

Residential buildings

1) Reconstructions have been carried out without ventilation improvement. To maintain normal energy consumption heat recovery ventilation must be designed;

2) The energy balance calculations of energy auditors include occasionally errors in DHW handling.

3) The energy consumption for DHW preparation is lower with electrical heating compared to district heating. Nevertheless, the electrical energy is more expensive.

4) In several cases slight under-heating appears (t_{int} = 20˚C).

5) Reconstruction works have lowered energy cosumption averagely to 180 - 220 kWh/(m^2·year).

Educational buildings

1) The heated area m^2 information is usually not available. In further research this information shall be collected. Based on the net area the energy consumption values are relatively low.

2) The ventilation systems are not working properly due to lack of maintenance knowledge and control possibilities.

3) In several occasions the investment model for schools directs to extreme energy saving. The poor indoor climate or energetically inefficient window opening (air exchange without heat recovery) is the result.

4) Simple building management systems for heating substations and ventilation systems are suggested.

5) More attention must be paid to educational buildings energy efficient use and reconstructions.

Public buildings

1) There are mainly two types of buildings: very old cultural heritage buildings and new office buildings.

2) For old cultural heritage buildings the envelope reconstruction measures can be almost excluded (in some cases window, door replacement and roof insulation can be suggested).

3) Heat recovery ventilation has been installed in most of the cases.

4) In new office building the electrical energy consumption was 70% of total energy consumption. The biggest electrical energy consumers were cooling system and server rooms. The ramp heating set parameters shall be also adjusted. In design phase the ventilation air exchange rates must be selected conservatively, but the capacity of air handling units and main ducts shall be selected with reservations. Furthermore, meeting rooms location selection shall be well considered and VAV systems designed.

5) Free cooling parameter adjustment according to real room temperatures must be carried out.

6) Due to variable balance temperature during the year the degree-day calculation method can not be used for energy balance calculations. Minimally dynamic simulation with validated consumption values is suggested.

7) The variation of public buildings specific energy consumption is wide. Therefore systematic monitoring of energy consumption and energy saving plan for each building shall be suggested.

5. Acknowledgements

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REFERENCES

[1] L. Pérez-Lombard, J. Ortiz and C. Pout, "A Review on Buildings Energy Consumption Information," *Energy and Buildings*, Vol. 40, No. 3, 2008, pp. 394-398. doi:10.1016/j.enbuild.2007.03.007

[2] B. Howard, L. Parshall, J. Thompson, S. Hammer, J. Dickinson and V. Modi, "Spatial Distribution of Urban Building Energy Consumption by End Use," *Energy and Buildings*, Vol. 45, 2012, pp. 141-151. doi:10.1016/j.enbuild.2011.10.061

[3] M. Kolokotroni, X. Ren, M. Davies and A. Mavrogianni, "London's Urban Heat Island: Impact on Current and Future Energy Consumption in Office Buildings," *Energy and Buildings*, Vol. 47, 2012, pp. 302-311. doi:10.1016/j.enbuild.2011.12.019

[4] R. Choudhary, "Energy Analysis of the Non-Domestic Building Stock of Greater London," *Building and Envi-*

ronment, Vol. 51, 2012, pp. 243-254. doi:10.1016/j.buildenv.2011.10.006

[5] H. Xiao, Q. P. Wei and Y. Jiang, "The Reality and Statistical Distribution of Energy Consumption in Office Buildings in China," *Energy and Buildings*, Vol. 50, 2012, pp. 259-265. doi:10.1016/j.enbuild.2012.03.048

[6] J. Zhao, Y. J. Xin and D. D. Tong, "Energy Consumption Quota of Public Buildings Based on Statistical Analysis," *Energy Policy*, Vol. 43, 2012, pp. 362-370. doi:10.1016/j.enpol.2012.01.015

[7] R. Saidur, "Energy Consumption, Energy Savings, and Emission Analysis in Malaysian Office Buildings," *Energy Policy*, Vol. 37, No. 10, 2009, pp. 4104-4113. doi:10.1016/j.enpol.2009.04.052

[8] O. Morck, K. E. Thomsen and J. Rose, "The EU CONCERTO Project Class 1—Demonstrating Cost-Effective Low-Energy Buildings—Recent Results with Special Focus on Comparison of Calculated and Measured Energy Performance of DANISH Buildings," *Applied Energy*, Article in Press, 2012.

[9] K. E. Thomsen, J. M. Schultz and B. Poel, "Measured Performance of 12 Demonstration Projects—IEA Task 13 'Advanced Solar Low Energy Buildings'," *Energy and Buildings*, Vol. 37, No. 2, 2005, pp. 111-119. doi:10.1016/j.enbuild.2004.01.036

[10] P. Raftery, M. Keane and A. Costa, "Calibrating Whole Building Energy Models: Detailed Case Study Using Hourly Measured Data," *Energy and Buildings*, Vol. 43, No. 12, 2011, pp. 3666-3679. doi:10.1016/j.enbuild.2011.09.039

[11] E. Gratia and A. De Herde, "Design of Low Energy Office Buildings," *Energy and Buildings*, Vol. 35, No. 5, 2003, pp. 473-491. doi:10.1016/S0378-7788(02)00160-3

[12] K. K. W. Wan, D. H. W. Li, D. L. Liu and J. C. Lam, "Future Trends of Building Heating and Cooling Loads and Energy Consumption in Different Climates," *Building and Environment*, Vol. 46, No. 1, 2011, pp. 223-234. doi:10.1016/j.buildenv.2010.07.016

[13] D. H. W. Li, T. N. T. Lam, S. L. Wong and E. K. W. Tsang, "Lighting and Cooling Energy Consumption in an Open-Plan Office Using Solar Film Coating," *Energy*, Vol. 33, No. 8, 2008, pp. 1288-1297. doi:10.1016/j.energy.2008.03.002

[14] G. R. Newsham, S. Mancini and B. J. Birt, "Do LEED-Certified Buildings Save Energy? Yes, But…," *Energy and Buildings*, Vol. 41, No. 8, 2009, pp. 897-905. doi:10.1016/j.enbuild.2009.03.014

[15] W. J. Fisk, D. Black and G. Brunner, "Changing Ventilation Rates in U.S. Offices: Implications for Health, Work Performance, Energy, and Associated Economics," *Building and Environment*, Vol. 47, 2012, pp. 368-372. doi:10.1016/j.buildenv.2011.07.001

[16] T.-A. Koiv, "Estonian Degree-Days," Tallinn, 2007.

[17] A. Hani, T.-A. Koiv, H. Voll and M. Tali, "Energy Efficiency in Residential Buildings. The Comparison between Degree Day Calculation and Simulations," *Proceedings of the 2nd International Scientific "Energy and Climate Change" Conference*, Athens, 8-9 October 2009, pp. 209-213.

[18] T.-A. Koiv, "Estonian Government Ordinance No. 258, 2007 Minimum Requirements for Buildings Energy Performance Additional Analysis," Tallinn, 2009.

[19] A. Hani, T.-A. Koiv and A. Mikola, "Ventilating with Room Units in Educational Institutions," *International Journal of Energy and Environment*, Vol. 5, No. 5, 2011, pp. 629-636.

PAPER III

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The Preliminary Research of Sea Water District Heating and Cooling for Tallinn Coastal Area

Allan Hani, Teet-Andrus Koiv

Environmental Department, Tallinn University of Technology, Estonia.
Email: allan.hani@rkas.ee

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ABSTRACT

This paper describes possibilities to utilize sea water for district heating and cooling purposes in Tallinn costal area. The sea water temperature profiles and suitability of heating and cooling generation are studied for continental climatic conditions. The district network study bases on 21 buildings located near to the Gulf of Finland. Industrial reversible heat pump technology is selected to cover heating and cooling loads for the new buildings. Combination of existing district heating and heat pump technology is considered for existing buildings. The results show possibilities, threats and need for further research of the sea water based heat pump district network implementation.

Keywords: District Heating; Cooling; Sea Water; Heat Pump; Renewable Energy; Office Building

1. Introduction

The European Union 20-20-20 targets emphasize implementation of renewable energy sources in member states energy balances. Sea water is a large renewable energy source, which can be combined with reversible heat pump technology to produce both thermal and cooling energy. The working principle is similar to geothermal energy production, but the sea water allows utilization of free cooling during spring and autumn period. The heat pump technology is studied widely around the World. A comprehensive review of heat pump systems implementation possibilities in different fields and also recent improvement with coefficient of performance (COP) is presented [1]. The heat pump technology rapid growth in 2005-2010 is documented [2,3]. The sea water electrically driven heat pump technology feasibility is compared with conventional district heating, in case the network radius is less than 5 km [4]. The calculation includes coal-fired plants electricity production losses and pumping costs. When the electricity is produced from natural gas, the radius degreases. Feasibility of different district heating and cooling production options is studied [5]. The life cycle costs are included (installation, system operating, maintenance costs). The sea water district heating and cooling is 1.5 times more expensive in China, due to relatively low coal-produced electrical energy price. All the economic calculations shall be carried out project by project separately. Indirect sea water cooling for Japan commercial buildings is researched [6]. Thermal storage tank of 4500 m^3 is used. Storage tank covers 32% of the cooling peak load. Difference of water temperature utilization is 7 K (5˚C - 12˚C). Cooling capacity of chillers is 2.3 MW. Large advantage in maintenance costs was found also a slight saving in initial cost was found. Boiler plant and heat pump technology is compared by quasi-dynamic energy-saving calculation [7]. The static calculations authors presented earlier the same year (2010) underestimated the feasibility of sea water district heating and cooling by 20%. Similar study was carried out in Japan [8]. Compared to conventional systems (cooling tower and heating boiler plant) the saving of 29% was received for district cooling and 5% for district heating. In Sweden the short and long term impacts of heat pump technology are compared with district heating systems [9]. Totally 6 TWH thermal energy was produced in Sweden year 2007. Energy optimization tool MODEST was used for systems modelling. In a total thermal energy balance of Sweden, still the heat pump systems for district heating will be developed in small scale, combined heat and power from renewable energy resources (CHP) is preferred. Nevertheless, in our Estonian case the share of cooling energy of selected buildings is higher than thermal energy. Therefore in certain costal areas the free cooling from sea water could be feasible and ecologically friendly. In Germany the de-nuclearization as a process is started [10]. Renewable energy storage and transportation possibilities are presented in the article. The problems are laid on the table, but solutions are still fully open. In Greece the cooling dominates widely over the heating demand [11]. The proposed systems are vice versa to ours solutions—extra cooling towers are used to cover peak cooling loads. Heating and average cooling demand is proposed to be produced with heat pumps. Groundwater open loop heat pump systems are researched [12]. Water storage tank is used either on chilled water or groundwater side. In chilled water side 10% saving was received due to better COP. The study of environmental impacts of different heat sources (coal boiler, gas boiler and heat pump with different COP) [13]. All the heat pumps with COP > 2.5 are more environmentally friendly to install than gas boilers. The coal boilers should be avoided. Low temperature heating will give better COP [14]. In our sea water district heating and cooling case the new buildings shall have low temperature heating and in existing buildings the high temperature district heating will be combined with heat pump system. Different connection possibilities are presented in research of combining existing district heating and new heat pump technology [15]. The heat pump heat exchangers optimization study [16] gives a comprehensive overview of the heat exchanger selection principles. Different new implementation options and heat pump refrigerants are presented in exhaustive articles [17-23].

The feasibility and technical possibilities are closely related to different boundary parameters:

1) Sea water temperature profile and salinity;
2) Outdoor climatic conditions;
3) Coastal area geology;
4) Possibilities to construct the sea water and district network pipelines;
5) Heating and cooling loads of the connectable buildings;
6) Temperature regimes of the pipelines;
7) Secure energy supply.

In current study these different aspects are analysed. The threats and possibilities are presented of the sea water district heating and cooling for Tallinn coastal area.

2. Methods

2.1. Gulf of Finland Parameters

The water and thermal processes in Gulf of Finland are continuously monitored among HELCOM project. Scientific articles [24,25] are written about the sea water parameters by Scandinavian and Estonian scientists.

All the measurements reported to HELCOM have to comply with survey program COMBINE requirements. The information about requirements is available: http://www.helcom.fi/groups/monas/CombineManual/en GB/main/

Due to the salinity of the gulf water the ice formation will appear <–0.4˚C.

Average ice thickness is 31 cm, very rare thickness > 50 - 60 cm (absolute maximum 1.2 m in a 150 years).

The sea water temperature and profile are analysed for the sea water heat pump plant possibility. The average depth profile of Gulf of Finland is presented in **Table 1**.

Depth of the gulf is shallow—averagely it will increase 5 m by additional distance of 1 km from the coast. Economically it would be efficient to search deeper locations in costal area (<500 m). In following **Figure 1** the sea water temperature profile during the year is presented. The data bases on Gulf of Finland monitoring station F3 info. Monthly average as well minimum and maximum temperatures are presented in correlation of sea depth.

There is a wide variation of temperature during the year in a whole depth profile. In combination of distance <500 m and depth –20 m the temperature range will be between –0.31˚C in winter to 16.6˚C in summer.

2.2. Outdoor Climatic Conditions

Tallinn area external air duration diagram is presented in **Figure 2**.

In our case outdoor climatic conditions and other reference buildings design information is taken as a basis for dimensioning the sea water district heating and cooling plant loads. Minimum temperature for heating load calculation is –22˚C to assure 21˚C in buildings. Cooling load design parameters are +27˚C and 50% relative humidity to assure +24˚C in buildings.

Table 1. Average gulf of Finland depth profile.

Distance from coast m	Depth (sea) m
500	20
1500	25
3200	30
4000	35
5500	40

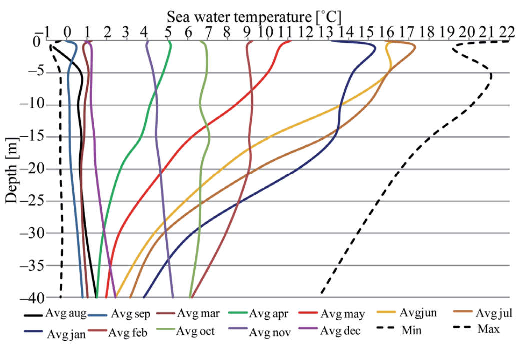

Figure 1. Monitoring station F3 measurement results.

3. Results and Discussion

3.1. Case Study

Based on the local area development plan 21 buildings (see **Table 2**) are included to the research from Port of Tallinn area. There are existing buildings, but a majority is considered to be erected. The heating and cooling consumption total network is planned <1 km radius from the coast.

In preliminary stage 80 W/m^2 public area for heating load calculations and 100 W/m^2 public area for cooling calculations was calculated. These values include transportation losses 5% for cooling and 10% for thermal energy. 60 W/m^2 public area is calculated for Building no 17 cooling demand.

Total 14.3 MW heating and 16.4 MW cooling load is calculated. Simultaneous factor of 0.85 is applied to the calculation results. The plant maximum thermal capacity is 12 MW and cooling capacity 14 MW. Plant shall be located beside Gulf of Finland

The Tallinn costal area depth profile is presented in following **Figure 3**. The depth of 25 m is located 500 m from the area. Flow pipe shall be directed there. Return pipe can be located near to the coast.

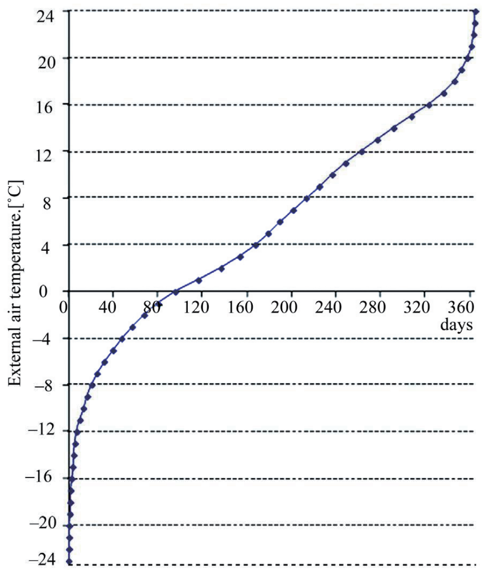

Figure 2. Tallinn external air duration diagram.

Table 2. Heating and cooling load calculation.

Building no	Building height m	Storeys above ground	Public area m^2	Cooling demand kW	Heating demand kW
1	24	6	8764	876	701
2	24	6	18870	1887	1510
3	24	6	1458	146	117
4	24	6	3564	356	285
5	24	6	5780	578	462
6	18	5	5198	520	416
7	11	2	2340	234	187
8	18	5	8775	878	702
9	24	6	2268	227	181
10	24	6	2430	243	194
11	24	6	10260	1026	821
12	24	6	5049	505	404
13	24	6	4860	486	389
14	20	5	24500	2450	1960
15	16	4	4250	425	340
16	19	5	11200	1120	896
17	-	4	37221	2233	2978
18	19	5	10500	1050	840
19	19	5	2200	220	176
20	19	5	5250	525	420
21	22	5	3700	370	296

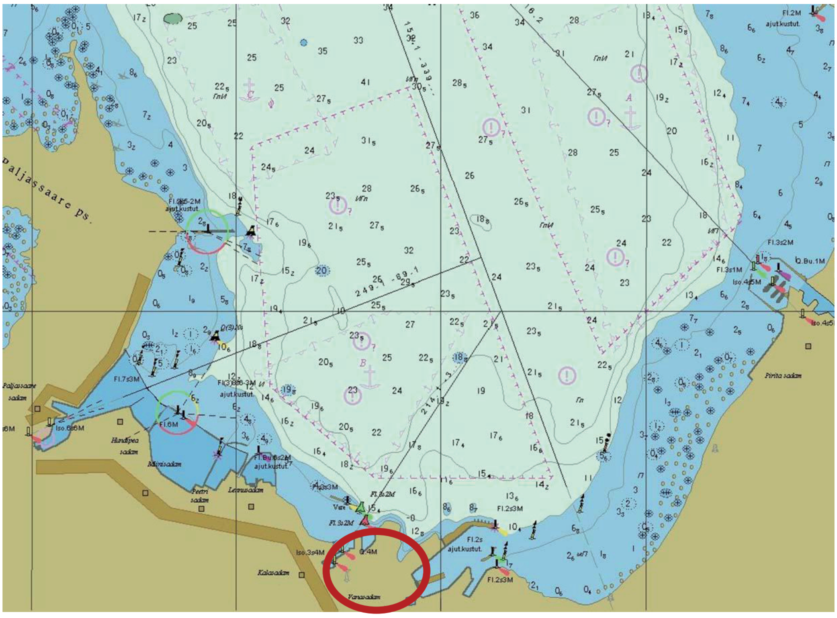

Figure 3. Tallinn coastal area sea water profile.

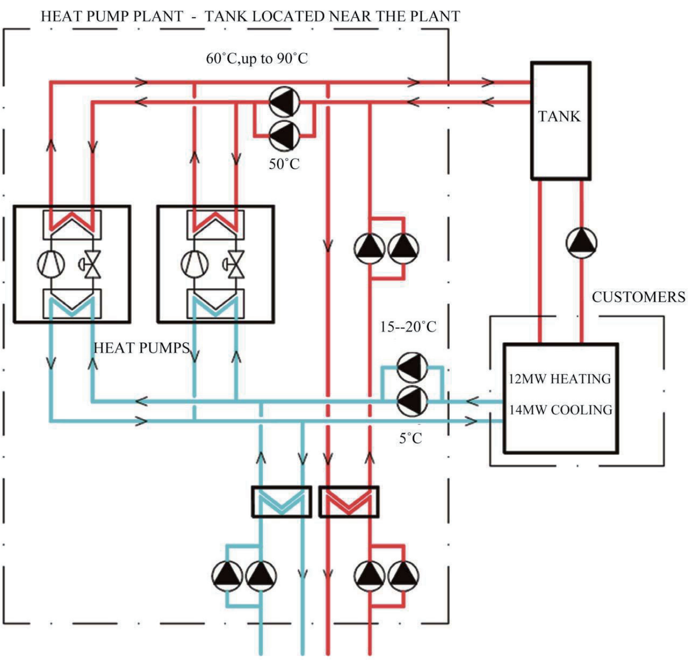

Figure 4. The principle schematic of sea water district heating and cooling plant.

3.2. Technology

Two industrial heat pumps (e.g. Uniturbo 34FY a´8.0 MW) with high condenser water outlet temperatures for heating and with cooling operation are considered to cover the heating and cooling demand of the buildings. The principle schematic is presented in **Figure 4**.

3.2.1. Heating Mode Operation

Supply water temperature to district network 60˚C - 90˚C (70˚C).

Return water temperature from district network 50˚C.

Thermal storage tank is to provide district heating network temperature stability and prevent freezing of the evaporator side of return sea water. 3600 m^3 tank could provide up to 7 days thermal energy (DT = 20 K).

Sea water DT = 2 K (0˚C/2˚C).

The new buildings must be deigned for low temperature heating (55˚C/40˚C) to allow max efficiency of the heat pump plant. For existing buildings (80˚C/60˚C or 70˚C/50˚C) combination of heat pump plant and district heating shall be considered.

District heating network shall be insulated to provide minimum thermal losses of the system.

3.2.2. Cooling Mode Operation

Supply water temperature to district network 5˚C. Return water temperature from district network 15˚C - 20˚C.

Sea water temperature < 4˚C.

Completely free-cooling;

Sea water temperature 4˚C - 10˚C.

Pre-cooling with sea water + compressor cooling;

Sea water temperature > 10˚C.

Only compressor cooling (free cooling heat exchangers are equipped with bypasses).

Due to fact that summer period soil temperature in 1.5 m depth is 10˚C it is not necessary to insulate the return pipe of the district cooling network. Supply pipe is insulated with 10 cm nowadays heat insulation material.

The titanium heat exchangers allow usage of the soft water in distribution network while problematic salty sea water handling will be done in open central circuit.

3.2. Comparable Research and Risk Definition

Based on the reference projects studied and referred in introduction part of current study the sea water for district heating and cooling is a favourable renewable energy source. Still there are several matters to be considered before the real investment decision could be made.

Environmental impact study is required before any of the projects will be executed. In addition to evaluation of the deep zone cold water pumping, the analysis of recycling the sea water back to lower sea water zone with higher and lower temperatures should be carried out.

Possibilities to use old underground tunnels, etc must be studied to find economically reasonable solutions for district network construction.

The thermal storage tank size optimization is necessary to do as it affects both the stability of the district heating network and economical possibilities to continue with the combined plant design.

There is a risk to have too low temperatures in evaporation side during cold winter period which will cause shut-off the heat pumps. A storage tank helps to overcome this, but can not fully prevent it, if the cold period will last longer than designed. The design parameters must be carefully considered.

Also minimum altitudes between heat exchangers and water resource level should be designed.

Centralized district heating and cooling plant, heat exchangers, pumping station is normally less expensive than decentralised systems altogether.

Centralized system has less maintenance problems.

Usually conventional cooling systems utilize electrical energy, which in Estonia is produced from oil-shale. Sea water is a huge cold water resource, so free cooling can be used.

4. Conclusions

In the current study possibilities of sea water utilization as thermal and cooling energy resource are studied in continental climate area. The Gulf of Finland as well as Tallinn outdoor climate parameters were taken to inputs for the study.

There are 21 office buildings selected from real development project with 14 MW cooling and 12 MW heating energy demand.

Possible connection diagram is presented for the buildings. The most important concern is to provide thermal energy also in low sea water temperature conditions, where the return glycol-water mixture from heat pump can cause sea water to freeze inside the heat exchanger. The selection of sea water pipes routing shall be studied in future to provide more the most effective conditions. Also closed-loop pipe system shall be studied to prevent the freezing problem (glycol-water mixture inside the piping).

Low temperature (55˚C/40˚C) heating shall be designed for new buildings. For existing buildings the new district heating system must be combined with old city district heating network.

The summer period district cooling solution is simpler. Three possible control modes are applied—free cooling is preferred and automation system shall be designed according to this requirement.

The parallel heating and cooling operation mode can be applied with 2 heat pumps. It is important mostly in spring and autumn season, where different buildings and even building sides can have both, cooling and heating demand.

The optimization of systems and economical feasibility study should be carried out before to continue with research and real design. Furthermore, trigeneration versus sea water district heating and cooling evaluation is needed to be researched.

5. Acknowledgements

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REFERENCES

[1] K. J. Chua, S. K. Chou and W. M. Yang, "Advantages in Heat Pump Systems: A Review," *Applied Energy*, Vol. 87, No. 12, 2010, pp. 3611-3624. doi:10.1016/j.apenergy.2010.06.014

[2] J. W. Lund, D. H. Freeston and T. L. Boyd, "Direct Application of Geothermal Energy: 2005 Worldwide Review," *Geothermics*, Vol. 34, No. 6, 2005, pp. 691-727. doi:10.1016/j.geothermics.2005.09.003

[3] J. W. Lund, D. H. Freeston and T. L. Boyd, "Direct Utilization of Geothermal Energy 2010 Worldwide Review," *Geothermics*, Vol. 40, No. 3, 2010, pp. 159-180. doi:10.1016/j.geothermics.2011.07.004

[4] H. W. Shu, D. M. Lin, X. L. Li and Y. X. Zhu, "Energy-Saving Judgment of Electric-Driven Seawater Source Heat Pump District Heating System over Boiler House District Heating System," *Energy and Buildings*, Vol. 42, No. 6, 2010, pp. 889-895. doi:10.1016/j.enbuild.2010.01.001

[5] H. W. Shu, D. M. Lin, C. H. Zhang and Y. X. Zhu, "Study on the Decision-Making of District Cooling and Heating Systems by Means of Value Engineering," *Renewable Energy*, Vol. 35, No. 9, 2010, pp. 1929-1939. doi:10.1016/j.renene.2010.01.021

[6] Y.-H. Song, Y. Akashi and J.-J. Yee, "Effects of Utilizing Seawater as a Cooling Source System in a Commercial Complex," *Energy and Buildings*, Vol. 39, No. 10, 2007, pp. 1080-1087. doi:10.1016/j.enbuild.2006.11.011

[7] H. W. Shu, D. M. Lin, X. L. Li and Y. X. Zhu, "Quasi-Dynamic Energy-Saving Judgment of Electric-Driven Seawater Source Heat Pump District Heating System over Boiler House District Heating System," *Energy and Buildings*, Vol. 42, No. 12, 2010, pp. 2424-2430. doi:10.1016/j.enbuild.2010.08.012

[8] T. Nagota, Y. Shimoda and M. Mizuno, "Verification of the Energy-Saving Effect of the District Heating and Cooling System-Simulation of an Electric-Driven Heat Pump System," *Energy and Buildings*, Vol. 40, No. 5, 2008, pp. 732-741. doi:10.1016/j.enbuild.2007.05.007

[9] M. Eriksson and L. Vamling, "Future Use of Heat Pumps in Swedish District Heating Systems: Short-and Long-Term Impact of Policy Instruments and Planned Investments," *Applied Energy*, Vol. 84, No. 12, 2007, pp. 1240-1257. doi:10.1016/j.apenergy.2007.02.009

[10] C.-J. Winter, "After Nuclear Has Gone: Energy in Germany," *International Journal of Hydrogen Energy*, Vol. 37, No. 1, 2012, pp.1-5. doi:10.1016/j.ijhydene.2011.08.001

[11] Z. Sagia, C. Rakopoulos and E. Kakaras, "Cooling Dominated Hybrid Ground Source Heat Pump System application," *Applied Energy*, Vol. 94, 2012, pp. 41-47. doi:10.1016/j.apenergy.2012.01.031

[12] S. L. Russo, G. Taddia, G. Baccino and V. Verda, "Different Design Scenarios Related to an Open Loop Groundwater Heat Pump in a Large Building: Impact on Subsurface and Primary Energy Consumption," *Energy and Buildings*, Vol. 43, No. 2-3, 2011, pp. 347-357. doi:10.1016/j.enbuild.2010.09.026

[13] C. M. Chen, Y. F. Zhang and L. J. Ma, "Assessment for Central Heating Systems with Different Heat Sources: A Case Study," *Energy and Buildings*, Vol. 48, 2012, pp. 168-174. doi:10.1016/j.enbuild.2012.01.025

[14] V. Verda, G. Baccino, A. Sciacovelli and S. L. Russo, "Impact of District Heating and Groundwater Heat Pump Systems on the Primary Energy Needs in Urban Areas," *Applied Thermal Engineering*, Vol. 40, 2012, pp. 18-26. doi:10.1016/j.applthermaleng.2012.01.047

[15] Y. Wang and Y. F. Zhang, "Analysis of the Dilatancy Technology of District Heating System with High-Temperature Heat Pump," *Energy and Buildings*, Vol. 47, 2012, pp. 230-236. doi:10.1016/j.enbuild.2011.11.038

[16] B. David, J. Ramousse and L. G. Luo, "Optimization of Thermoelectric Heat Pumps by Operating Condition Management and Heat Exchanger Design," *Energy Conversion and Management*, Vol. 60, 2012, pp. 125-133. doi:10.1016/j.enconman.2012.02.007

[17] S. Okamoto, "A Heat Pump System with a Latent Heat Storage Utilizing Seawater Installed in an Aquarium," *Energy and Buildings*, Vol. 38, No. 2, 2006, pp. 121-128. doi:10.1016/j.enbuild.2005.04.004

[18] K. Bakirci and B. Yuksel, "Experimental Thermal Performance of a Solar Source Heat-Pump System for Residential Heating in Cold Climate Region," *Applied Thermal Engineering*, Vol. 31, No. 8-9, 2011, pp. 1508-1518. doi:10.1016/j.applthermaleng.2011.01.039

[19] K. Hirata and H. Kakiuchi, "Energy Saving for Ethylene Process by Adsorption Heat Pump," *Applied Thermal Engineering*, Vol. 31, No. 13, 2011, pp. 2115-2122. doi:10.1016/j.applthermaleng.2011.03.031

[20] W. E. TeGrotenhuis, P. H. Humble and J. B. Sweeney, "Simulation of a High Efficiency Multi-Bed Adsorption Heat Pump," *Applied Thermal Engineering*, Vol. 37, 2012, pp. 176-182. doi:10.1016/j.applthermaleng.2011.11.012

[21] B. T. Austin and K. Sumathy, "Transcritical Carbon Dioxide Heat Pump Systems: A Review," *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 8, 2011, pp. 4013-4029. doi:10.1016/j.rser.2011.07.021

[22] K. Yasukawa and S. Takasugi, "Present Status of Under-

ground Thermal Utilization in Japan," *Geothermics*, Vol. 32, No. 4-6, 2003, pp. 609-618. doi:10.1016/j.geothermics.2003.07.011

[23] A. Hall, J. A. Scott and H. Shang, "Geothermal Energy Recovery from Underground Mines," *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 2, 2011, pp. 916-924. doi:10.1016/j.rser.2010.11.007

[24] B. Jonsson, K. Doos, J. Nycander and P. Lundberg, "Standing Waves in the Gulf of Finland and Their Relationship to the Basin-Wide Baltic Seiches," *Journal of Geophysical Research*, Vol. 113, 2008, Article ID: C03004. doi:10.1029/2006JC003862

[25] T. Liblik and U. Lips, "Characteristics and Variability of the Vertical Thermohaline Structure in the Gulf of Finland in Summer," *Boreal Environment Research*, Vol. 16, 2011, pp. 73-83.

PAPER IV

Hani, A.; Koiv, T-A.; Mikola, A. (2011). Ventilating with Room Units in Educational Institutions . International Journal of Energy and Environment, 5, 629 – 636.

The Fig.15 in paper IV shall be not considered.

Ventilating with room units in educational institutions

Allan Hani, Teet-Andrus Kõiv and Alo Mikola

Department of Environmental Engineering
Tallinn University of Technology
Ehitajate tee 5, 19086
ESTONIA
allan.hani@rkas.ee, teet.koiv@ttu.ee http://www.ttu.ee

Abstract— In current article the results of the research about indoor climate in educational institutions are presented. The study is mostly concentrated on the research of different ventilation systems and carbon dioxide (CO_2) levels. CO_2 is one of the most important indicators about air quality in buildings. The correlation between air change rate and CO_2 levels in certain rooms is already well proven fact. European Standard EN-15251 about indoor climate conditions requirements gives the basis for new and renovated buildings. The renovation process in reality can either improve or deteriorate the indoor climate. The success lays in the renovation measures used. Demand based ventilation gives better energy conservation possibilities. Therefore, room based ventilation solutions are studied. The research results show carbon dioxide levels in educational institutions with different ventilation systems.

Keywords— Carbon dioxide concentration, room unit based ventilation, CO_2 concentration analysis, air change rates, CO_2 in educational buildings, naturally ventilated buildings, mechanically ventilated buildings.

I. Introduction

The most cited literature on indoor climate available in the whole world does not indicate only the air change rates, but also describes the maximally permitted CO_2 concentrations in buildings. Currently the air change rates are mostly fixed values which do not take into consideration the parameters of the external air pollution. The European indoor climate normative EN15251:2007 [1] takes into account different allowed CO_2 levels depending on the external air CO_2 concentration. but the air change rates are still constant. Table 1 presents the CO_2 values according to the EN15251.

Table 1. CO_2 levels according to the EN15251

Category	Respective CO_2 level exceeding external air concentration in ppm for energy calculations
I	350
II	500
III	800
IV	> 800

According to regulations in Estonia enforced by the Ministry of Social Affairs the maximum allowed CO_2 concentration in schools is 1000 ppm [2]. In most cases this figure is not achievable without bigger investments and heavier life cycle costs made to ventilation systems. Medical investigations have discovered diseases, headache and lethargy in patients in case the CO_2 concentrations exceed 10 000 ppm. A visually summarizing graph [3] is presented as follows:

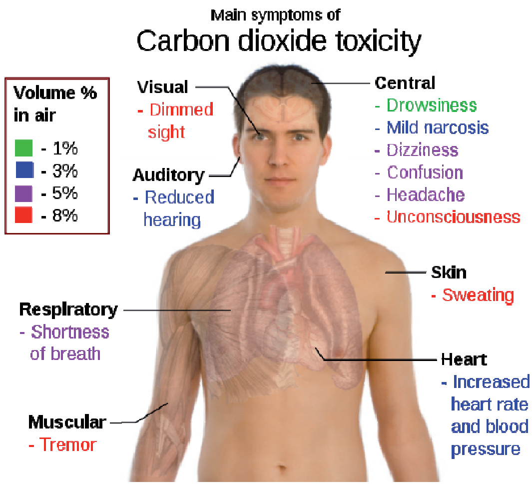

Fig.1. Symptoms of carbon dioxide.

Studies in Europe refer also to the huge problems related to CO_2 concentrations in schools. The studies carried out In Dutch schools show that in some cases the CO_2 level is more than 5000 PPM at the end of a class. 7 schools had CO_2 levels between 1500 – 3700 PPM [4]. A comprehensive study of 141 schools [5] gives the following results:

Table 2. Dutch studies: CO_2 levels.

Study	No. schools	CO_2 levels ppm	
		Average	Range
1984	11	1000	500-1500
1990	6	1290	950-1950
1995	6	1320	700-2700
1997	96	990	425-2800
2004	5	1220	480-2400
2004	11	1580	450-4700
2005	6	1355	550-3000

A study in the United Kingdom (UK) in 2 different classrooms shows the average CO_2 concentration 1638 ppm and 2086 ppm by the outdoor concentration of 593-709 ppm [6]. Table 3 presents the weekly average results of the study in the UK primary school in 2001.

Table 3. UK studies: CO_2 levels.

School	CO_2 levels PPM
	Range
1	200-1300
2	300-2000
3	300-3500
4	310-2830

In the UK studies in most cases the CO_2 range during occupation of the classrooms was above 1000 ppm.

The overall air quality in educational buildings is usually worse than the normative allow. A similar situation can also be found in Estonian schools.

In Estonia the internal climate in educational buildings has been studied and analyzed in different investigations [7, 8, 9, 10, 11, 12, 13, 14, 15].

A comprehensive theoretical analysis of the air change rate and CO_2 levels generated by occupants and level prediction possibilities with simulation calculations is given in the Building and Environment Journal [16].

An interesting study of natural ventilation possibilities in schools has been carried out in the UK [17]. The results are presented in Table 4.

Table 4. Natural ventilation: CO_2 levels during 8:40-15:00.

Weekday	CO_2 levels PPM	
	Average	Range
Monday	1504	601-2804
Tuesday	1303	489-2718
Wednesday	735	296-1770
Thursday	691	341-1940
Friday	1208	345-2608

The figures are promising but in reality they are achieved by opening the windows. There are also several other parameters of indoor climate that affect the indoor air quality and thermal comfort negatively. Therefore this solution should not be recommended for educational buildings. It is also necessary to carry out a study throughout a year. Furthermore, the Sick Building Syndrome (SBS) caused by insufficient air change is very dangerous in children's institutions [18, 19, 20].

It is commonly known that the indoor climate and the CO_2 levels depend on the type of ventilation and its functioning [21], Table 5.

Table 5. CO_2 levels for different types of ventilation

Room	CO_2 levels ppm		
No	Average	Max	Vent. type
1.1	960	1857	Natural
1.2	1054	1725	Natural
2.1	789	1047	Mechanical
2.2	733	880	Mechanical
3.1	853	1472	Hybrid
3.2	1100	1615	Mechanical
4.1	1801	4016	Natural
4.2	1255	2676	Natural
5.1	1536	3181	Natural
5.2	2636	5567	Natural
6.1	1185	2570	Natural
6.2	1391	2585	Natural
7.1	1972	2530	Natural
7.2	1778	3109	Natural
8.1	932	2578	Natural
8.2	1031	2488	Natural
9.1	1695	3359	Natural
9.2	1199	2590	Natural

II. METHODOLOGY

In theory there is a well proven formula for estimating the CO_2 concentration in indoor conditions [7, 15] with natural ventilation. Suppose that the initial carbon dioxide concentration in the air of a classroom before the beginning of the class is C_o. As the class starts, carbon dioxide begins to generate intensively. The air change in the classroom is relatively low. The distribution of temperature in classrooms is uniform (conditions are isothermal), supply and exhaust airflows are equal. The carbon dioxide concentration in the inflow air is C_v and in the outflow air C (distribution of carbon dioxide in classrooms is uniform). We can write the balance equation

$$m \cdot d\tau + L \cdot C_v \cdot d\tau - L \cdot C \cdot d\tau - V \cdot dC = 0 \qquad (1)$$

From equation (1)

$$dC = -d\left(\frac{m}{L} + C_v - C\right) \qquad (2)$$

By integration of equation (1)

$$\frac{L}{V}\cdot\tau = -\ln\frac{\frac{m}{L}+C_v-C}{\frac{m}{L}+C_v-C_o} \quad (3)$$

where
m - carbon dioxide generation in classroom,

L - air change in classroom,
V - volume of room,

C_v - carbon dioxide concentration in external air (in supply air),
C - carbon dioxide concentration in classroom air (in exhaust air),
C_o - carbon dioxide concentration in the air of the classroom at the beginning of the class,
τ - time.

From equation (3) we can express the basic equation for carbon dioxide concentration C at the time moment τ

$$C = C_v + \frac{m}{L} - \left(C_v + \frac{m}{L} - C_o\right)\cdot\left(e^{-\frac{L}{V}\cdot\tau}\right) \quad (4)$$

By carbon dioxide concentration (in external air, in classroom air at the beginning of a class and in classroom air at the time moment of τ), carbon dioxide generation rate in classroom and parameters of room, by formula (3 or 4) it is possible to determine the air change in a room.

Fig.2 presents a theoretical rise in carbon dioxide during a 45 minute class (outside air 400 ppm) in a normal Estonian school with classroom volume about 240 m^3) and 25 students.

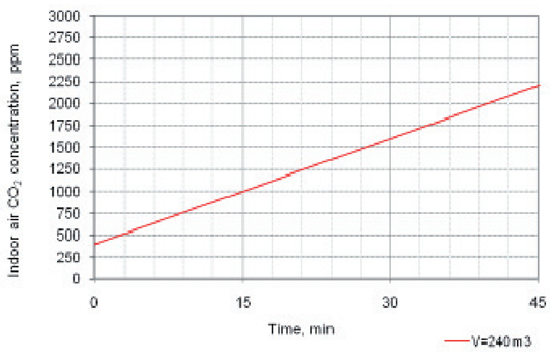

Fig.2. Calculated change in CO_2 concentration in typical Estonian classroom (natural ventilation).

The normative [2] defines 1000 ppm as a maximum level for CO_2 concentration in classrooms. Not acceptable conditions will be reached during first 15 minutes of the class.

Nevertheless, full ventilation renovation programs are not affordable for all Estonian schools. Furthermore, there are technical difficulties to build balanced centralized ventilation systems due to lack of space for air handling unit (AHU) rooms and especially for ventilation ducts. There is also a problem with energy consumption of the centralized units as not all the classrooms are used simultaneously. Therefore the current research studies the possibilities of local ventilation room units with heat recovery.

III. Experimental Measurements

The case study was made in three different classrooms in a school located near Tallinn.
All classrooms had a physical volume of 240m^3.

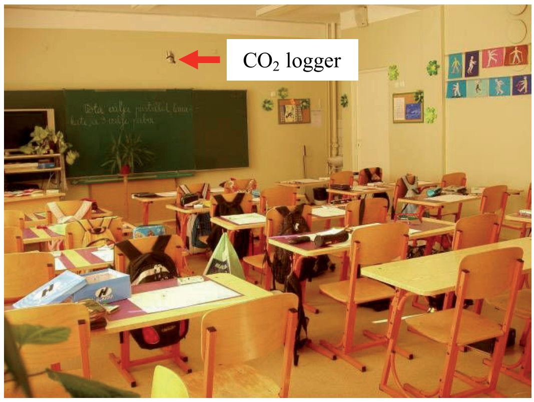

Fig.3. Logger position in classroom.

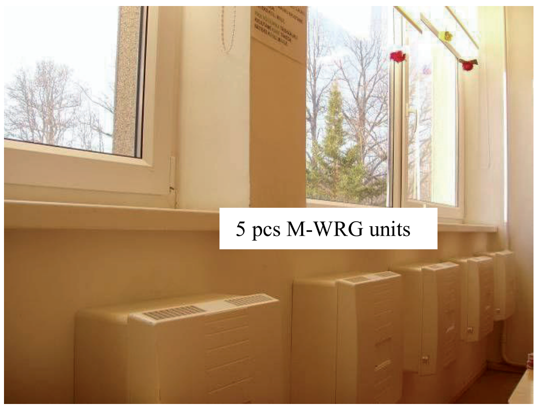

Fig.4. Room units locations.

Parameters of the natural ventilation, room units and regular ventilation are presented in Table 6.

Table 6. Air change and rise of CO_2 concentration

No	Ventilation system	CO_2 rise, ppm	Air change l/s person
1	Natural ventilation	1091	1.1
2	Room unit (M-WRG) 2nd speed	339	3.6
3	Room unit (M-WRG) 3rd speed	377	4.3
4	Room unit (M-WRG) 4th speed	500	5.7
5	Room unit (M-WRG) 5th speed	43	6.0
7	Regular supply and exhaust vent. 1st speed *	161	8.8

* 2nd and 3rd speed exceeded allowed sound levels.

M-WRG unit installation overview and technical parameters are presented as follows:

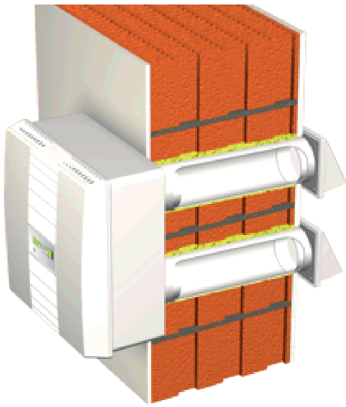

Fig.5. M-WRG installation principle.

- Air volumes 15 – 100 m^3/h per unit;
- Crossflow plate heat exchanger with heat recovery ca 75%;
- Electrical heating 3,8 – 34 W;
- Air filtering G4;
- Sound level 15,5 – 46,5 dB(A)
- EC-DC fans;
- Frost protection;
- Condensate removal to outdoor.

Fig.6. Contence of M-WRG unit.

The results of the measurements in classrooms with natural ventilation are presented in Fig.7 and Fig.8.

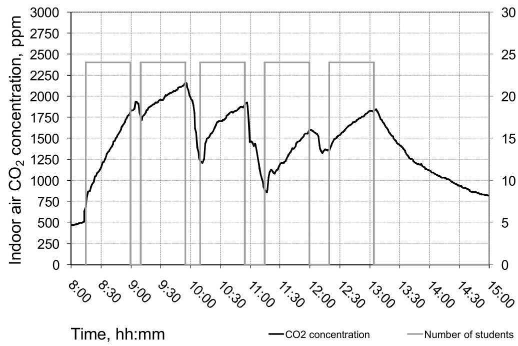

Fig.7. Measured CO_2 concentration change in classroom (natural ventilation).

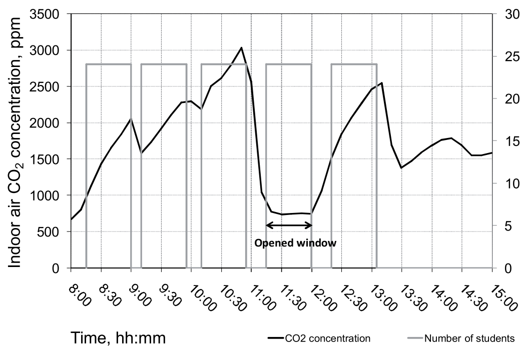

Fig.8. Measured CO_2 concentration change in classroom (natural ventilation).

Overview of Fig.7 and Fig.8 shows rapid CO_2 concentrations rising during the first class and there is a remarkable correlation with Fig.2 that presents the calculation results.

Other measurements were carried out in a classroom with mechanical supply and exhaust ventilation system. These systems usually give good air change results in case they are designed, built and balanced properly. In most cases problems appear with unbalanced systems or not properly completed balancing of ventilation system. The CO_2 measurement results can be found in figures Fig.9 and Fig.10.

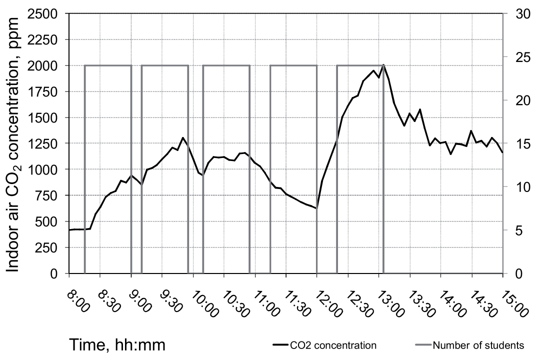

Fig.9. Measured change in CO_2 concentration in a classroom with a mechanical centralized ventilation

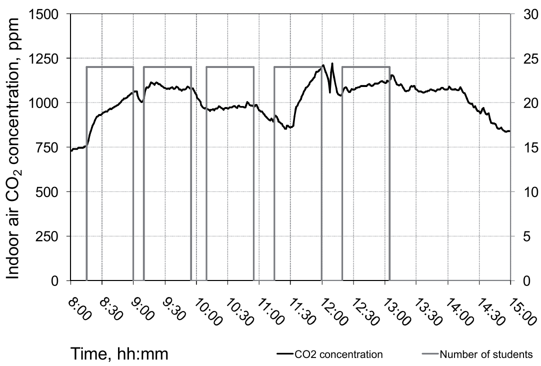

Fig.10. Measured change in CO_2 concentration in a classroom with a mechanical centralized ventilation

Carbon dioxide levels in the previous figures still exceed the normative of 1000 ppm during the school-day several times. EN15251:2007 III category can be averagely achieved.

VENTILATING WITH ROOM UNITS

Five M-WRG room units are installed below the windows in one of the classrooms.

Class start as also in previous cases at 8:00.

Children usually appear 15 minutes earlier.

Three CO_2 data loggers are spread into classroom as follows:

- in front of the board;
- next to the external wall (near the windows);
- next to the internal wall (near to corridor).

Some deviations in measurements can appear due to teachers' activity with tuning the M-WRG units' speeds to lower level during the class.

Figures 11, 12, 13, 14 and 15 present the measurement results in correlation with number of students.

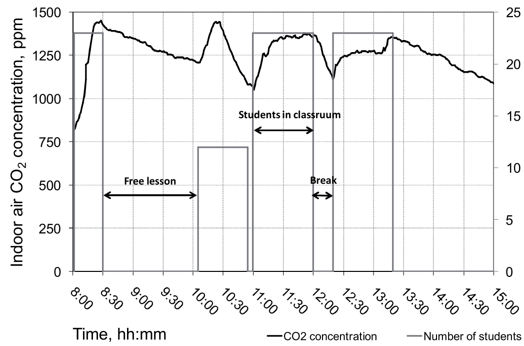

Fig.11. Measured change in CO_2 concentration in a classroom (ventilation with room units)

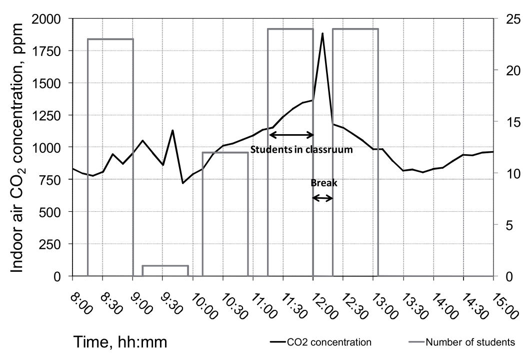

Fig.12. Measured change in CO_2 concentration in a classroom (ventilation with room units).

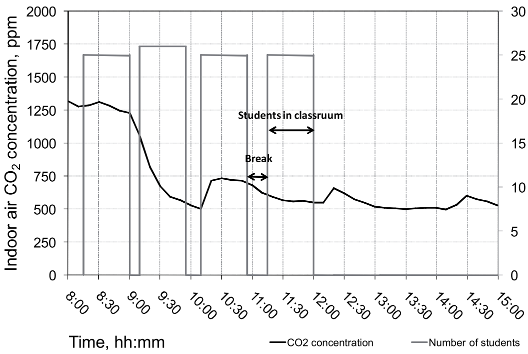

Fig.13. Measured change in CO_2 concentration in a classroom (ventilation with room units).

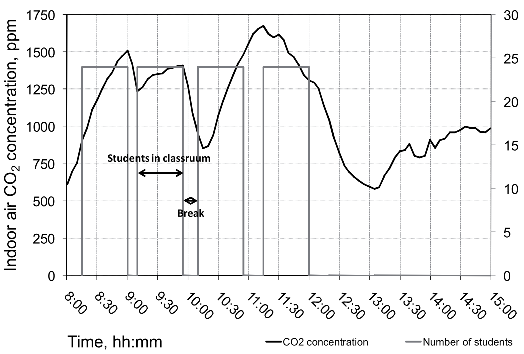

Fig.14. Measured change in CO_2 concentration in a classroom (ventilation with room units).

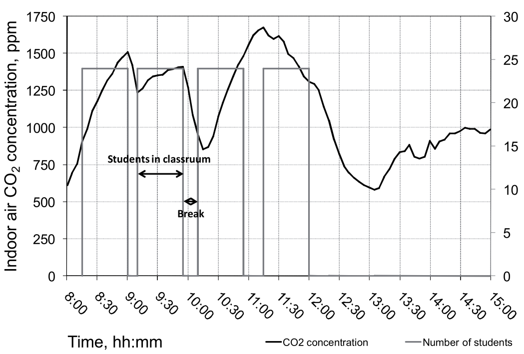

Fig.15. Measured change in the CO_2 concentration in a classroom (ventilation with room units) at the lowest speed

Fig. 16 presents a comparison of the changes in the CO_2 concentration with different ventilation systems based on the research.

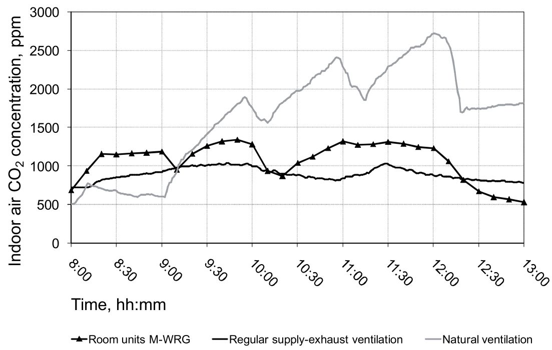

Fig.16. Indoor air CO_2 concentration in observed ventilation systems.

The cumulative duration figures present indoor carbon dioxide levels with room unit based ventilation. Different measurement periods are added.

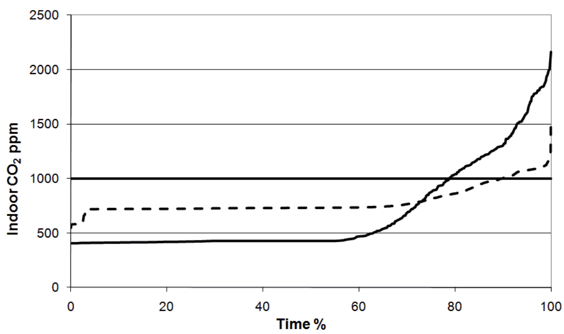

Fig.17. Indoor air CO_2 concentration duration graph in room 1.

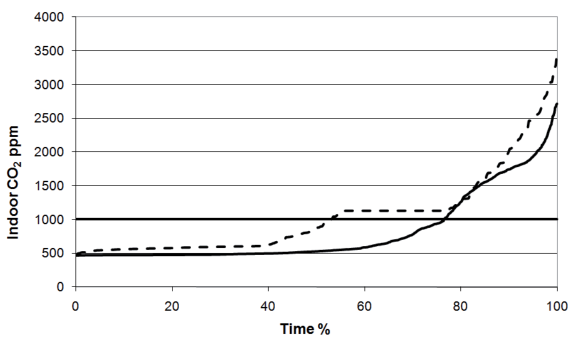

Fig.18. Indoor air CO_2 concentration duration graph in room 2.

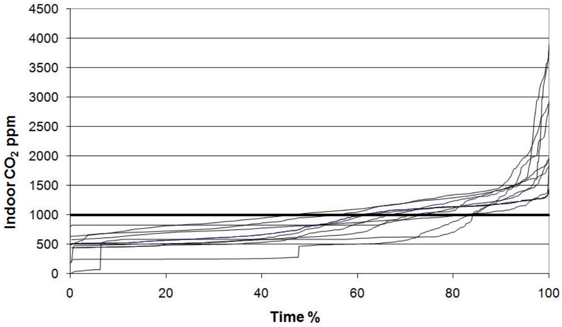

Fig.19. Indoor air CO_2 concentration duration graph in room 3.

Averagely 80% of the measured period satisfies the 1000 ppm normative. It is recommendable to add one more room based unit to one classroom to lower the carbon dioxide concentration and units sound level.

IV. CONCLUSION

Problems with indoor climate in educational institutions are well known in all countries. The carbon dioxide concentration is a problem not only in older schools, but also in new or lately renovated schools. Concentrations higher than 1500 ppm are commonly measured. In some cases 4000 – 5000 ppm has been measured.

The normatives about the carbon dioxide concentration in indoor air are quite strict - not more than 1000 ppm is generally allowed. So there is a conflict between the real situation (based on measurements) and health protection regulations. The studies show that the CO_2 concentrations higher than 10 000 ppm in room air cause various health problems. High CO_2 concentrations decrease the students' productivity. As children are more sensitive than adults the strict normatives are well justified.

The present study shows the dynamics of changes in the CO_2 concentration. The investigation includes both theoretical and practical approach. Also different ventilation solutions are compared:

- natural ventilation;
- centralized balanced ventilation;
- ventilation with room heat recovery units

Mostly is focused to the possibility to use room based ventilation units with heat recovery.

A rise in the CO_2 concentration with natural ventilation is in remarkable correlation with calculation results (Fig.1, Fig.2 and Fig.3). After 15 minutes of the normal class usage the indoor climate with natural ventilation is not acceptable. There is a slight decrease in the CO_2 concentration during the break.

The air change rate inside the classrooms can be estimated with the formula presented in methodology. Therefore separately air volumes are not presented.

Centralized mechanical ventilation gives generally good results to ensure the proper indoor climate, but there can also be problems. Energy consumption will be high if the classrooms usage profiles are not taken into consideration. Also the balancing of the centralized systems in many cases have not been done properly. It is also possible to build complicated VAV systems, but in reality these systems are noisy, expensive and hard to maintain.

Ventilation based on room units is flexible and energy efficient. The main shortcomings are higher noise levels at some speeds (must be taken into account in the design process) and human interference into the adjustment of the fan speeds. The best solutions would be control of the units with CO_2 sensors. It is necessary to add one unit to each classroom to satisfy the 1000 ppm requirement. In the city centre more attention has to be paid to outdoor carbon dioxide level, because it is an important aspect for planning the ventilation.

The price level of the small room ventilation units is getting more and more affordable to the different consumers. In addition, the installation does not need room consuming ducting installations. Therefore the solution can be recommended as a ventilation renovation measure. Further research into room-unit-based ventilation systems in educational buildings is be recommended.

REFERENCES

[1] Standard EVS-EN15251:2007.

[2] "Health-protection Ordinance for Educational Institutions", Ministry of Social Affairs in Estonia.

[3] Wikipedia

[4] Hens Hugo S.L.C., De Meulenaer, *Schools: All problem buildings?,* Proceedings of Clima 2007 WellBeing Indoors, 2007.

[5] Wim Zeiler, Gert Boxem, *Ventilation of Dutch schools; an integral approach to improve design.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[6] Zs. Bako-Biro, N. Kochhar, D.J. Clements-Croome, H.B.Awbi and M. Williams, *Ventilation in Schools and Learning Performance.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[7] T. A. Koiv, M. Rebane, P. Parre, *Indoor climate and improvement possibilities in educational premises.*, Proceedings of Clima 2007 WellBeing Indoors, 2007.

[8] T. A. Koiv, *Indoor climate and ventilation in Talllinn school buildings.*, Proceedings of Estonian Academy of Sciences. Engineering, 13(1), 17-25, 2007.

[9] T. A. Koiv, *Indoor climate and energy efficiency of apartment and educational buildings in Estonia.*, Proceeding of 3rd WSEAS International Conference on Engineering Mechanics, Structures, Engineering Geology, Corfu Island, Greece, July 22-24, 2010, 196-199. WSEAS.

[10] T. A. Koiv, H. Voll, M. Rebane, *Indoor climate in educational and residential buildings.*, Journal of Chonqqing University (English edition), December 08, 2009, 35-38.

[11] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, *Indoor Climate and Energy Consumption in residential buildings.*, Proceeding of 3rd International Conference on Energy and Development-Environment-Biomedicine, WSEAS Press 2009, 82-86.

[12] T. A. Koiv, H. Voll, K. Kuusk, A. Mikola, *Indoor Climate and Energy Consumption in residential buildings.*, Proceeding of 3rd

International Conference on Energy and Development-Environment-Biomedicine, WSEAS Press 2009, 82-86.

[13] A. Hani, T. Kalamees, T. A. Koiv, *Determination of energy performance requirements for apartment buildings in Estonia*, Proceeding of Healthy Buildings, Syracuse NY, 2009, Paper 409.

[14] T. A. Koiv, H. Voll, M. Rebane, *Indoor climate in educational and residential buildings.*, International Conference on Sustainable Development in Building and Environment, Chonqquing, 2009, 2.

[15] P. Tint, Ü. Kask, T.A. Koiv, T. Vinnal, K. Reinhold, *Improvement of environmental and health issues in educational institutions.*, Safety and Reliability for Managing Risks, Estoril, Portugal, 18-22 September 2006, 835-840.

[16] T. Lu, A. Knuutila, M. Viljanen, X. Lu, *A novel methodology for estimating space air change rates and occupant CO_2 generation rates from measurements in mechanically ventilated buildings.*, Journal Building and Environment 45, 2010, 1161-1172.

[17] M. Griffits, M. Eftekhari, *Control of CO_2 in naturally ventilated glassroom.*, Journal Energy and Buildings 40, 2008, 556-560

[18] K. Andersson, *Epidemiological approach to indoor air problems.*, Indoor Air , 1998/4, 32-9

[19] H. B. Awbi, AJ. Pay, *A study of the air quality in glassroom.*, Proceeding of 2nd international conference on indoor air quality, ventilation and energy conservation in buildings, Montreal Canada 1995

[20] DJ. Clements-Croome, *Creating the productive workplace.*, Spon-Rouledge, 2000

[21] D. Mumovic, J. Palmer, M. Davies, M. Orme, I. Ridley, T. Oreszczyn, C. Judd, R. Critchlow, H. A. Medina, G. Pilmoor, C. Pearson, P. Way, *Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England* Journal Building and Environment 44, 2009, 1466-1477

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