RIGA TECHNICAL UNIVERSITY
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IMPACT OF INDOOR CLIMATE ON ENERGY EFFICIENCY AND PRODUCTIVITY IN OFFICE BUILDINGS

Summary of the doctoral thesis

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RTU Press
Riga 2014

UDK 697.1(043.2)
St 117 i

Stankeviča G. Impact of indoor climate on energy efficiency and productivity in office buildings. Summary of the doctoral thesis.- R.:RTU Press, 2014.-21 pages.

Printed according to resolution of the HGWT institute, 29th May, 2014. Protocol No.5

ISBN 978-9934-10-575-3

DOCTORAL THESIS
NOMINATED FOR AWARD OF DOCTORAL DEGREE IN ENGINEERING SCIENCE AT RIGA TECHNICAL UNIVERSITY

For awarding of doctoral degree in engineering science, doctoral thesis will be publicly defended on 20th June, 2014, at 15:00, at the faculty of Civil Engineering at Riga Technical University, Azenes street 16/20, lecture room No. 250.

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CONFIRMATION

I hereby confirm that I have myself developed this doctoral thesis, which has been submitted for consideration to Riga Technical University for obtaining the doctoral degree in engineering science. The doctoral thesis has not been submitted to any other university for the purpose of obtaining a scientific degree.

Gaļina Stankeviča ……………………………. (Signature)

Date: ………………………

The doctoral thesis is written in English and contains introduction, 5 chapters, conclusions, references, 38 figures and illustrations for a total of 91 pages. Bibliography lists 83 references.

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INTRODUCTION

The working population normally spends about 25% of its time at work, from which many have their workplaces in office environments. Therefore, it is important to establish a healthy, comfortable and productive work environment that majority of building occupants will find pleasant and stimulating to stay and work in. Selection of heating and cooling capacities of an air handling unit (AHU) has a direct effect on maintained indoor air parameters. During the design process creation of productive indoor climate is usually neglected, leading to economically unjustified capacity selection.

The aim of doctoral thesis is to develop methodology for complex, economically justified evaluation of indoor climate and energy use, with respect to maximized profit.

The main **tasks** include:

1) Proposal of method for outdoor climate data procession;
2) Development of mathematical model for energy calculations based on outdoor air parameters (temperature and relative humidity), wind speed, cloud cover and solar radiation;
3) Development of productivity metrics with respect to indoor air parameters (temperature and relative humidity);
4) Optimization of selection of heating and cooling capacities for an air handling unit, as well as selection of building envelope design elements based on maximized profit.

Scientific novelty: selection of heating and cooling capacities for an air handling unit based on maximized profit.

Practical applications:

1) Recommendations for designers, when selecting heating and cooling capacities for an air handling unit, building envelope design elements, e.g. window area, as well as when evaluating effects of solar radiation on room heat balance, taking into account building orientation;
2) Developed Excel tool for investigation of impact of indoor climate on energy efficiency and productivity in office buildings.

Research in this field was also carried out by the following researchers: Anatolijs Borodiņecs, Joe Huang, Uldis Iljins, Gaļina Kaškarova, Andris Krēsliņš, Anna Ramata, Olli Seppänen, Pēteris Šipkovs, Pawel Wargocki, David Peter Wyon, Qingyuan Zhang, etc.

1.REVIEW ON PRODUCTIVITY AND ENERGY STUDIES

There are several factors affecting productivity, including social environment, organizational structure, indoor environment and personal characteristics. Research indicates that indoor environment has the biggest influence on productivity with respect to job dissatisfaction and job stress. Air temperature is one of the most important indoor environmental factors affecting employee productivity. Despite temperature range of 20-24°C as optimal for productivity, it does not always correspond to the values for comfortable environment stipulated by standards. For example, European standard EN 15251 recommends indoor temperature levels of 20°C and 25.5°C for winter and summer seasons respectively.

Installation of humidification or dehumidification equipment in buildings for human occupancy is not very common. Building owners simply avoid installation of such equipment due to insufficiently strong comfort benefits as opposed to high operating and energy costs. However, humidification or dehumidification can be actually needed not only for occupant comfort and health considerations, but also to avoid negative impacts on HVAC systems, integrity of building structure and systems, furnishing and equipment. Indoor air quality, incl. dry air is among most frequent complaints issue from building occupants in office environments (about 45% people dissatisfied). Furthermore, performance decreases at low air humidity, since eyes tend to be more susceptible to low relative humidity (RH) starting to blink more frequently, especially when visual display unit work is carried out. As to the effects of elevated humidity levels sensory irritation of the eyes has also been associated with moisture-damaged buildings. Moreover, elevated RH enhances spreading of certain types of airway vira, which may increase the probability of viral infection.

Several studies are available on quantification of energy expenses with respect to indoor climate conditions, but they are limited to simple calculations, e.g. for estimations of yearly heating and cooling energy consumption the mean temperatures are used. For office buildings more complex methods should be used including frequencies of particular outdoor temperature and humidity conditions since both desired indoor temperature and relative humidity set-points should be maintained.

2.OUTDOOR CLIMATE DATA PROCESSION

Outdoor climate data (temperature, relative humidity, wind speed and cloud cover), measured at a meteorological station in Riga during entire period of 2010 was obtained from Raivis Pauls, who in its turn collected 10 year data (2001-2010) from Latvian Environment, Geology and Meteorology Centre. Initial data was provided as three-hour averages. For further energy and indoor climate calculations hourly data of outdoor air parameters is necessary and therefore it was decided to use the same value of three-hour averages for all given three hours. The Microsoft Office work package Excel was used to process statistical data of outdoor air parameters.

During 2010 outdoor temperature varied between -23.1°C and 31.9°C, and the relative humidity was in a range of 21-99%. Hourly values of outdoor temperature and relative humidity were also plotted on Mollier chart, as shown in Fig. 2.1.

In Fig. 2.1 quadrangular area confined by 20-24°C temperature and 40-60% relative humidity corresponds to the optimal productivity zone. Most of the time (97% or 8643 h) outdoor temperature and relative humidity did not correspond to the optimal productivity zone, indicating necessity for air conditioning nearly all year round.

For calculation of hourly average global solar irradiance, i.e. solar flux striking a horizontal surface, for Latvian capital Riga (latitude 56.967, longitude 24.050), Zhang-Huang model was used.

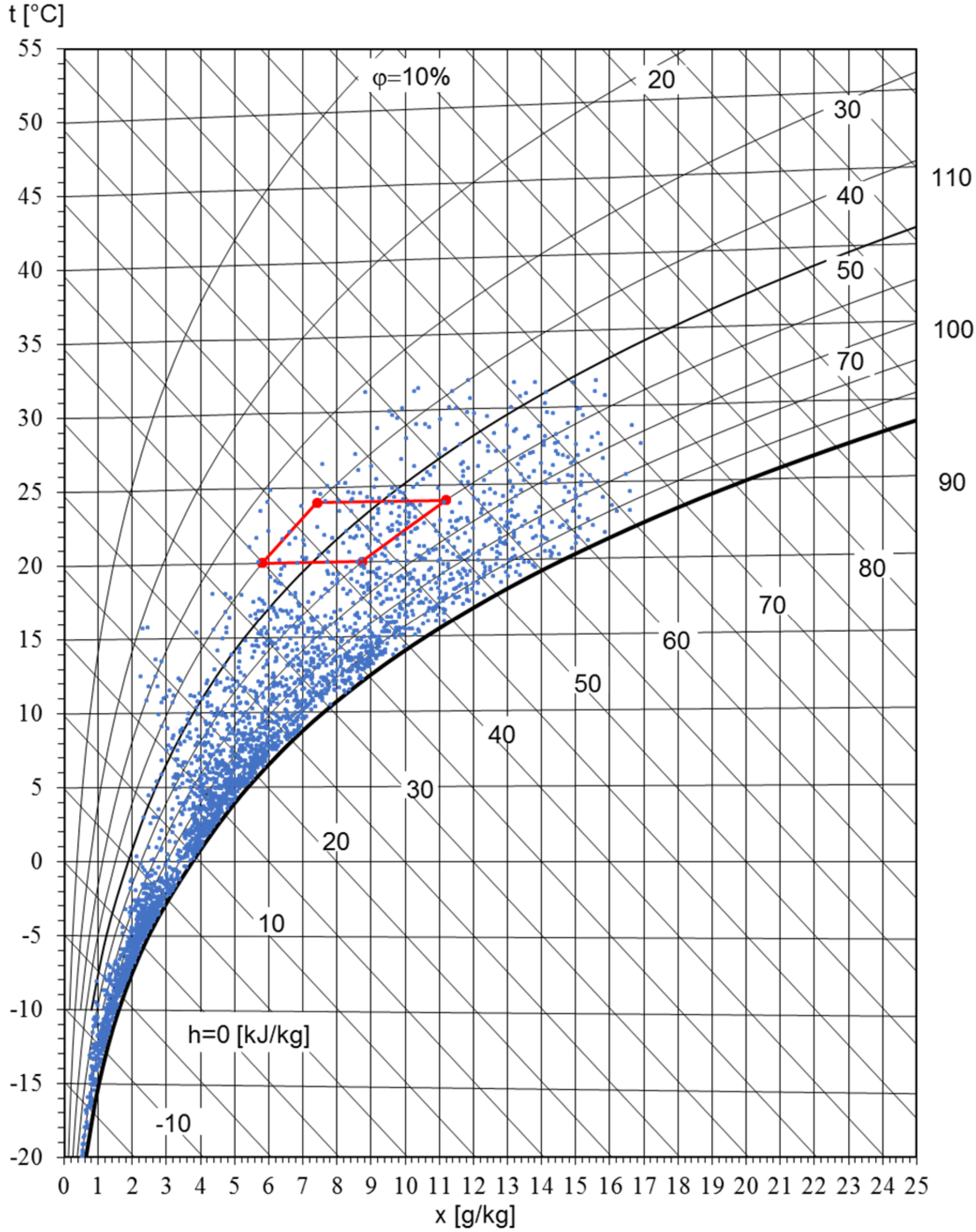

Fig. 2.1 Outdoor temperature and relative humidity on Mollier chart

Hourly global solar irradiance was calculated by equation (2.1).

$$I = I_0 \cdot 3600 \cdot sin\alpha \cdot \; c_0 + c_1 \; CC \; + c_2 \; CC \; ^2 + c_3 \; t_n - t_{n-3} \; + c_4\varphi + c_5 \upsilon + d \; /k \quad when\ I > 0$$

$$I = 0\ when\ I < 0, \tag{2.1}$$

where: I – global solar irradiance, W/m^2;
I_0 – solar constant, 1355 W/m^2;
$\sin\alpha$ – sine of solar altitude angle;
CC – cloud cover, tenths;
φ – relative humidity, %;
t_n and t_{n-3} – temperature in at hours n and n-3 respectively, °C;
ν – wind speed, m/s;
c_0, c_1, c_2, c_3, c_4, c_5, d, k – regression coefficients.

The calculated global solar irradiance on the horizontal for entire 2010 year is given in Fig. 2.2.

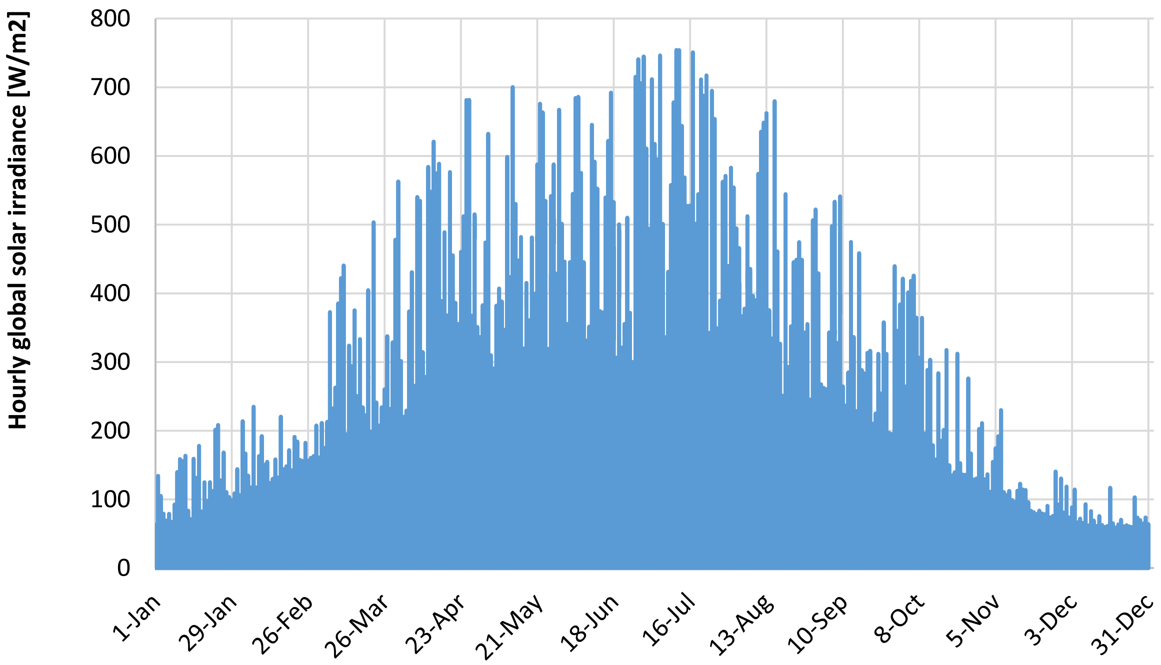

Fig. 2.2 Hourly global solar irradiance on horizontal

The greatest solar irradiance was obtained from June to August, with a maximum of about 750 W/m^2 in July. During the winter months hourly solar irradiance rarely exceeded 200 W/m^2.

3. ENERGY CALCULATIONS

The indoor climate depends mainly on the interaction of building envelope, activities inside and outdoor climate. All these factors consequently determine the energy need for a building. The combined effect of these factors result in a load, i.e. heat deficit or surplus. Since indoor climate often deviates from the desired level, it is necessary to compensate it by the HVAC system.

The schematic of an air handling unit that was chosen for realization of air conditioning processes within scope of this doctoral thesis is presented in Fig. 3.1.

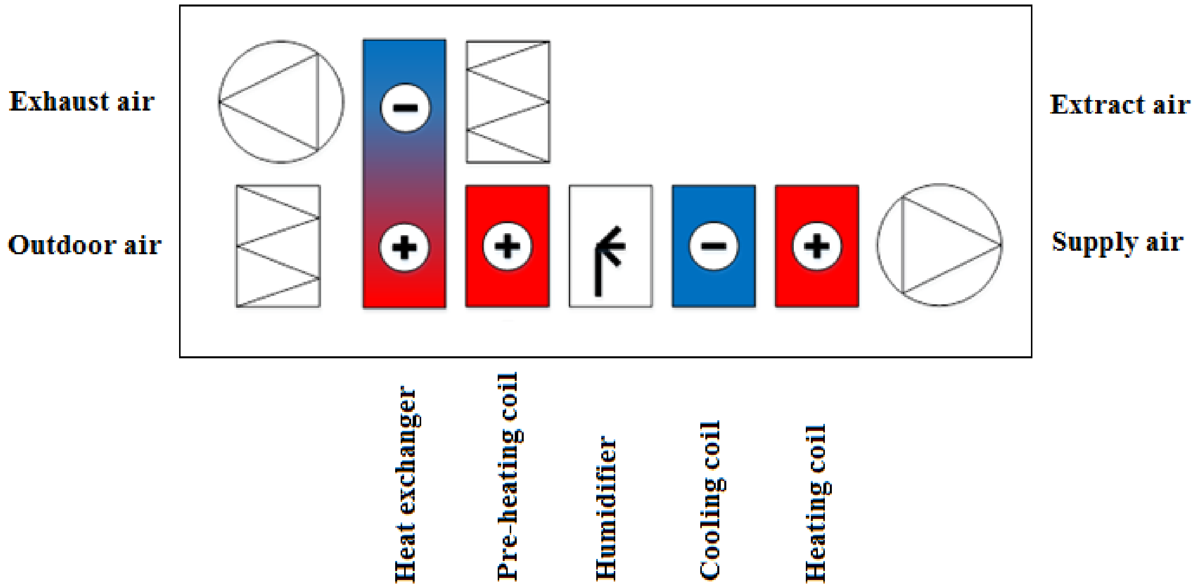

Fig. 3.1 Schematic of a basic air handling unit

AHU presented in Fig. 3.1 has a heat exchanger, a pre-heating coil, a humidifier, a cooling coil and a secondary heating coil. The following AHU configuration allows maintenance of a given supply air temperature and humidity during the entire year.

4. PRODUCTIVITY METRICS

Majority of research studies on employee productivity investigated effects of individual parameters on performance, e.g. effect of temperature only, while in normal working conditions the combined effect of, e.g. temperature and humidity should be considered. The effects of indoor temperature on employee productivity are well established in literature, while very few studies investigated the relative humidity effects on productivity in office buildings. Since the data of combined effect of temperature and relative humidity on employee productivity is very limited, it was decided to use Koehn-Brown model, which was initially developed for construction branch. Since the differences between indoor and outdoor environments exist, as well as differences between types of work carried out, i.e. construction versus office work, data in Koehn-Brown model was statistically compared to available data published in literature for office buildings. Loss in relative performance as a function of indoor temperature and relative humidity, calculated using Koehn-Brown model and adjusted for the maximized productivity based on findings from literature is presented in Fig. 4.1.

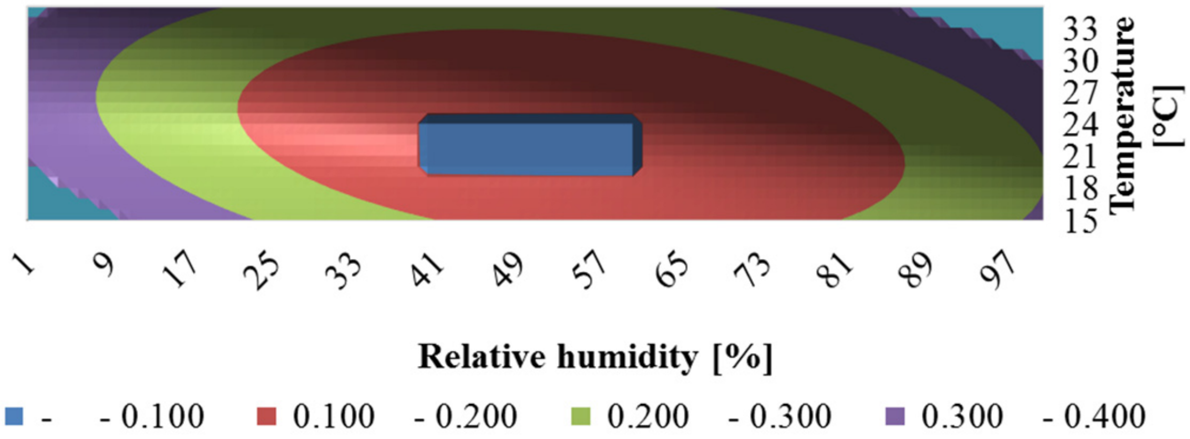

Fig. 4.1 Relative performance loss as a function of indoor temperature and relative humidity

Top of the relative performance surface confined by temperature of 20-24.0°C and RH of 40-60% comprises area with minimum performance loss. Performance loss increases when indoor conditions are outside this confined area.

5. ECONOMIC EVALUATION

The working regimes of an air conditioning system studied in this paper are presented in Fig. 5.1.

Fig. 5.1 shows snapshot with supply air temperature zone at particular outdoor conditions. For AHU configuration studied in this paper, one can generally distinguish between five main regimes of operation of the air conditioning system. In Zone I the desired set-points of temperature and RH can be achieved by single heating of air. In Zone II it is possible to achieve the required temperature set-point first by air heating, followed by humidification process. In Zone III only humidification is required to reach the set-point. If the outdoor air condition corresponds to Zone IV, it is better to start with air humidification, followed by cooling process, since it is less expensive to cool air from lower temperature. Finally, reaching supply temperature set-point from an outdoor air condition in Zone V is accomplished first by cooling the air until 100% RH curve and consequent heating after the condensation process.

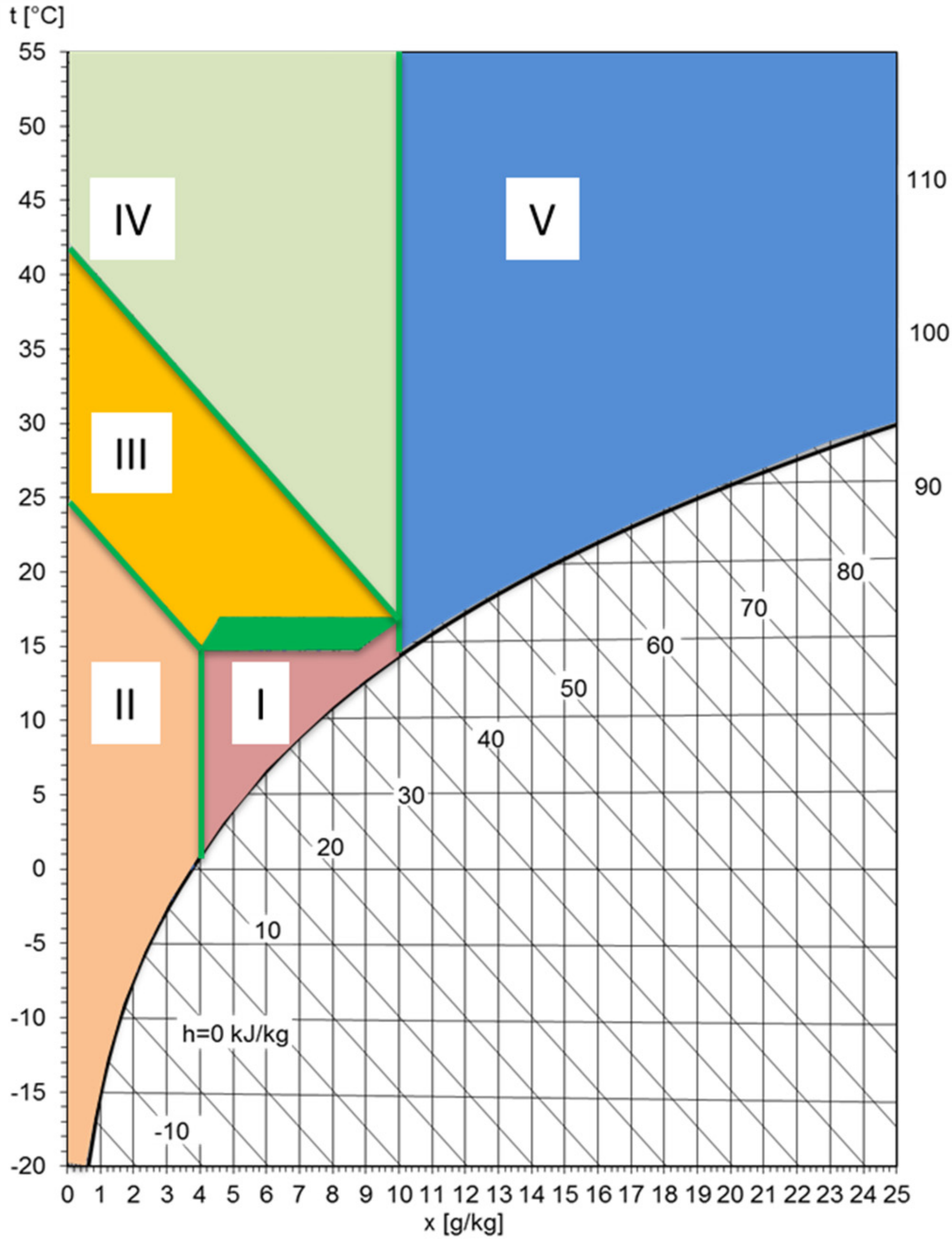

Fig. 5.1 Ventilation system operation regimes in the Mollier chart

Fig. 5.2 presents duration lengths of different AHU operation regimes, summarized as hours and expressed in percent.

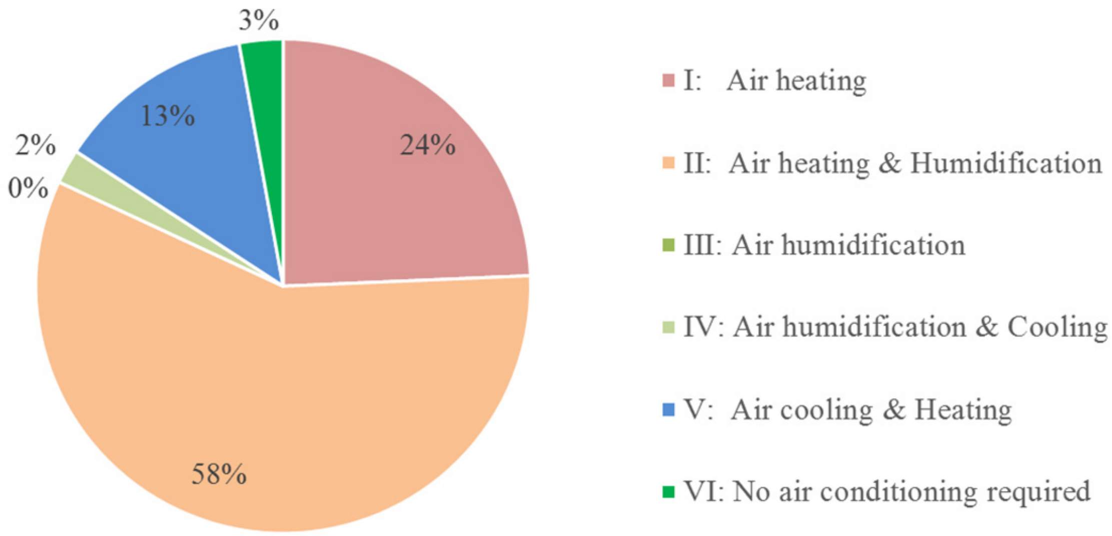

Fig. 5.2 Duration lengths of different AHU operation regimes in 2010

In addition to the five previously mentioned AHU operation regimes, additional zone VI was introduced, which corresponds to the case when air conditioning of outdoor air is not required. According to the calculation results outdoor air condition (T and RH) were in Zone II for most of the time (58%), followed by Zone I (24%). It can thus be concluded that there was need to heat outdoor air for most of the time in 2010. From Fig. 5.2 it can also be seen that in Latvian climatic conditions, rather long periods of time (more than half) are present when air should be humidified.

Within framework of the current study an Excel tool was developed for calculation of energy use for air conditioning of a single office. Additionally, tool enables indoor climate simulations and performance of economic calculations, taking into account productivity. The plan of a single office is shown in Fig. 5.3.

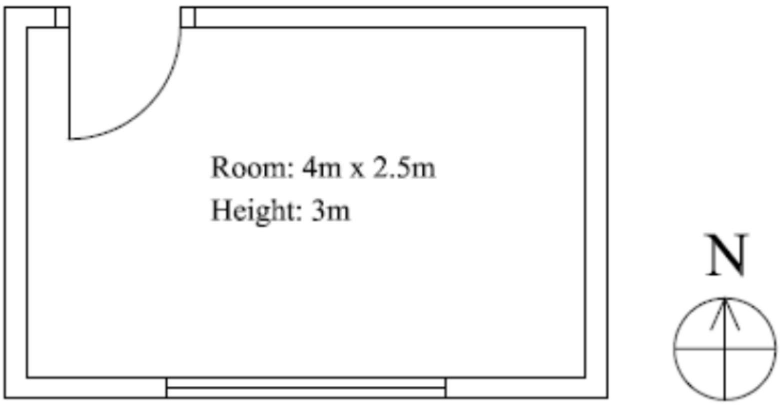

Fig. 5.3 Plan of a single office used for simulation

It was assumed that the South façade is the only exterior surface in direct contact with the ambient air. The temperature and humidity levels around other surfaces correspond to the conditions in the given space.

Initial simulation parameters for the base case, i.e. when desired indoor air parameters for maximized productivity are maintained, are summarized in Table 5.1.

Table 5.1

Simulation parameters

Windows	South façade: 2 m^2 (20% of floor area), double glazed Shading coefficient, glass: 0.88 Shading coefficient, interior shading: 0.5 (light coloured draperies) Overall U-value: 2.2 W/m^2K
South wall	Overall U-value: 0.35 W/m^2K Building wall surface material: aluminium panels
HVAC	Air handling unit for heating and cooling Balanced supply and exhaust Min required ventilation rate: 1.4 $l/s \cdot m^2$ Min supply air temperature for cooling: 16°C Rotary heat exchanger efficiency: 0.75
Occupancy schedule	Weekdays: from 08:00-16:00
Occupancy	10 m^2 per person Constant level of activity: 80 W
Lighting	8 W/m^2
Equipment	11 W/m^2
Moisture generation	55 g/h per person

Calculations started with the outdoor climate data collection and procession, and further estimation of solar radiation. Then information about building was included, e.g. building envelope data, desired indoor climate and consequently heating and cooling loads of the zone were estimated. This enabled further calculation of supply air temperature necessary to cover heating and cooling loads. Since heating and cooling is achieved with air, the ventilation rate was also adjusted so that there was enough airflow to reach the desired supply air temperature set-point. Constant air volume system was considered, i.e. constant air flow supply and variable supply air temperature. Consequently energy use associated with air handling was calculated, incl. energy needed for air transportation. By use of productivity metrics that expresses relationship between indoor temperature, relative humidity and productivity, the optimal heating and cooling coil capacities were found, as well as economic consequences of reduced capacities were estimated.

The example of some input data ("Outdoor climate" section) in Excel tool is given in Fig. 5.4 and it includes results from calculations only for the first hour of the year. The developed tool includes result dataset for entire 2010 (8760 hours).

For the base case confined isolines of energy consumption around the optimal productivity zone were drawn on Mollier chart, as shown in Fig 5.5.

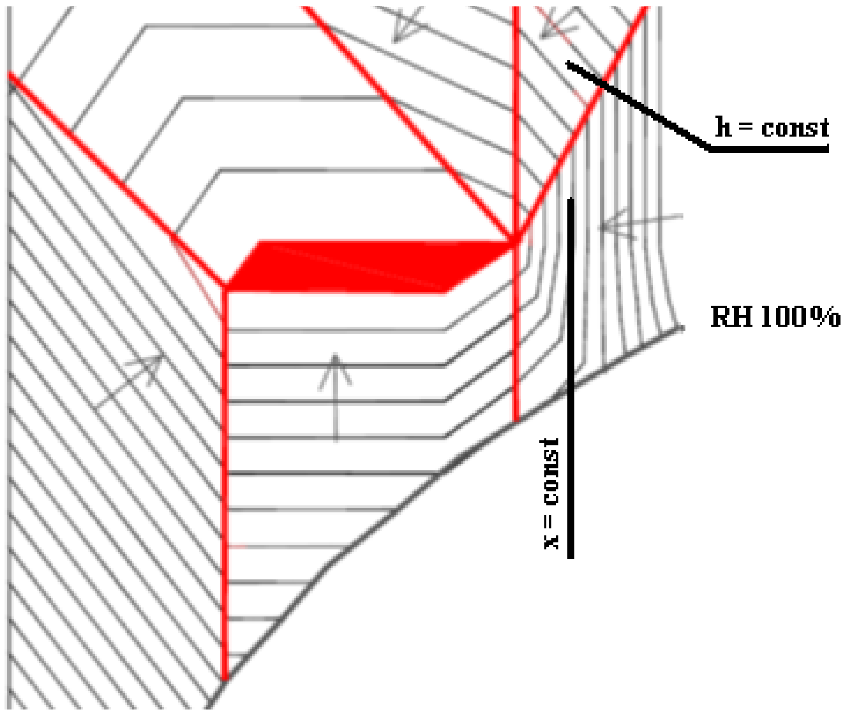

Fig. 5.5 Isolines of energy consumption on Mollier chart for different AHU operation regimes

In Fig 5.5 direction of arrows indicates decrease in energy consumption. Fig 5.5 presents the theoretical model and in a real case processes would have boundaries, since air conditioning equipment has its limits, i.e. capacities are restricted. The limited capacities then directly affect indoor climate and consequently employee productivity and total profit for employer.

OUTDOOR CLIMATE

Temperature	t_o	[°C]		-4.3
Relative humidity	φ_o	[%]		90
Wind speed	v_o	[m/s]		1
Saturated vapor pressure	p_s	[kPa]		0.4
Actual water vapour pressure	p_w	[kPa]		0.4
Absolute humidity	x_o	[$kg_{water}/kg_{dry\ air}$]		0.002
Enthalpy	h_o	kJ/kg		1.8

Solar radiation on horizontal

Regression coefficient for Riga, Latvia	c_0	0.69491	[-]	
Regression coefficient for Riga, Latvia	c_1	-0.10822	[-]	
Regression coefficient for Riga, Latvia	c_2	-0.22999	[-]	
Regression coefficient for Riga, Latvia	c_3	0.01232	[-]	
Regression coefficient for Riga, Latvia	c_4	-0.00091	[-]	
Regression coefficient for Riga, Latvia	c_5	0.0039	[-]	
Regression coefficient for Riga, Latvia	d	-3.46883	[-]	
Regression coefficient for Riga, Latvia	k	17	[-]	
Solar constant	I_0	1,355	[W/m^2]	
Latitude of Riga, Latvia	LAT	56.967	[deg]	
Longitude of Riga, Latvia	LON	24.05	[deg]	
Local Standard Time Meridian	LSTM	30	[degh]	
Greenwich Mean Time deviation for Riga	ΔT_{GMT}	2	[h]	
Date		[d-mmm]		1-Jan
Weekday		[ddd]		Fri
Day increment		[-]		1
Equation of time	EoT	[min]		-3.7
Constant B		[-]		-78.9
Time correction factor	TC	[min]		-27.5
Local Time	LT	[h]		1
Local solar time	LST	[h]		0.54
Hour angle	HRA	[deg]		-172
Declination angle	δ	[deg]		-23
Sine of Elevation angle	$\sin\alpha$	[-]		-0.8
Elevation angle	α	[rad]		-1.0

Fig. 5.4 Extract from developed Excel tool with some input data

Simplified cross-section of a visualized 3D surface of productivity gain and energy consumption, presented as a 2D plot is given in Fig. 5.6.

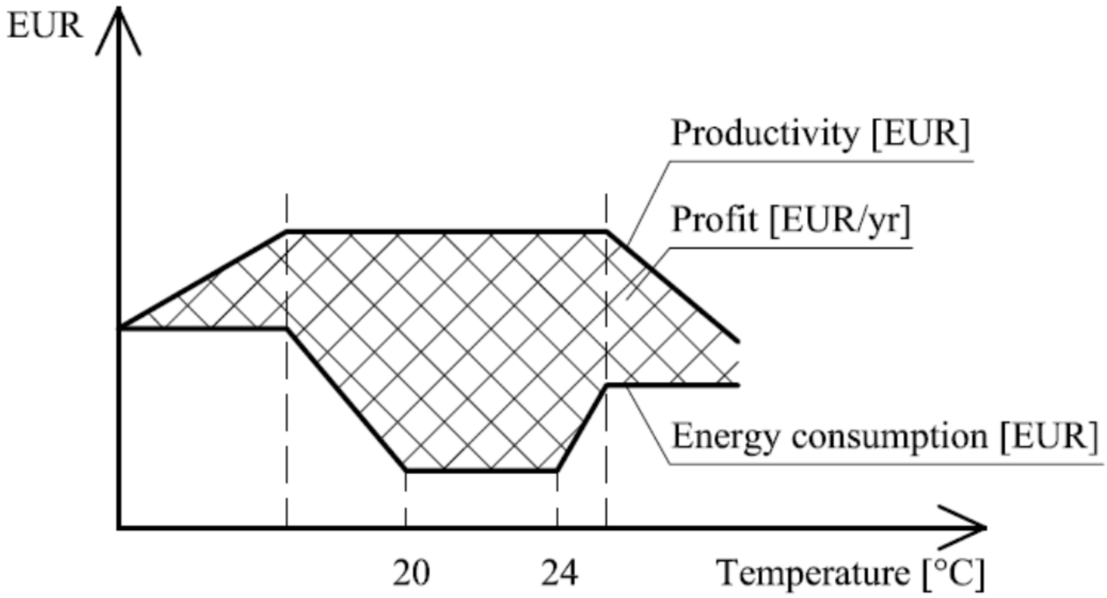

Fig. 5.6 Cross-section of productivity gain and energy consumption; limited capacities

Fig 5.6 presents the principal cross section created with respect to isotherm at certain outdoor conditions. This graph was further used as a principle for economic evaluation. To construct the given graph, it was assumed that supply air conditions correspond to the indoor air conditions. When outdoor air conditions correspond to the desired indoor air conditions for maximized productivity (temperature range of 20-24°C), besides energy for air transportation, no additional energy is used for air conditioning. Employee productivity in its turn is at its maximum. Air heating and cooling equipment have limited capacities, and when outdoor air conditions start to deviate from optimal productivity zone, energy consumption for air conditioning increases. Productivity remains maximum as long as there is enough heating or cooling capacity. Thereafter it starts to drop, since installed equipment cannot maintain optimal indoor conditions. Cross-section between surfaces of productivity and energy consumption lines represents a yearly profit.

Fig. 5.7 also presents cross-section of the visualized 3D surface of productivity gain and energy consumption in case if unlimited heating and cooling capacities are available.

The principle is basically the same as described for Fig. 5.6. The difference is the effect of unlimited heating or cooling capacity. Installed capacities allow maintenance of optimal indoor conditions for maximized productivity at any given conditions all year round. However this maintenance is

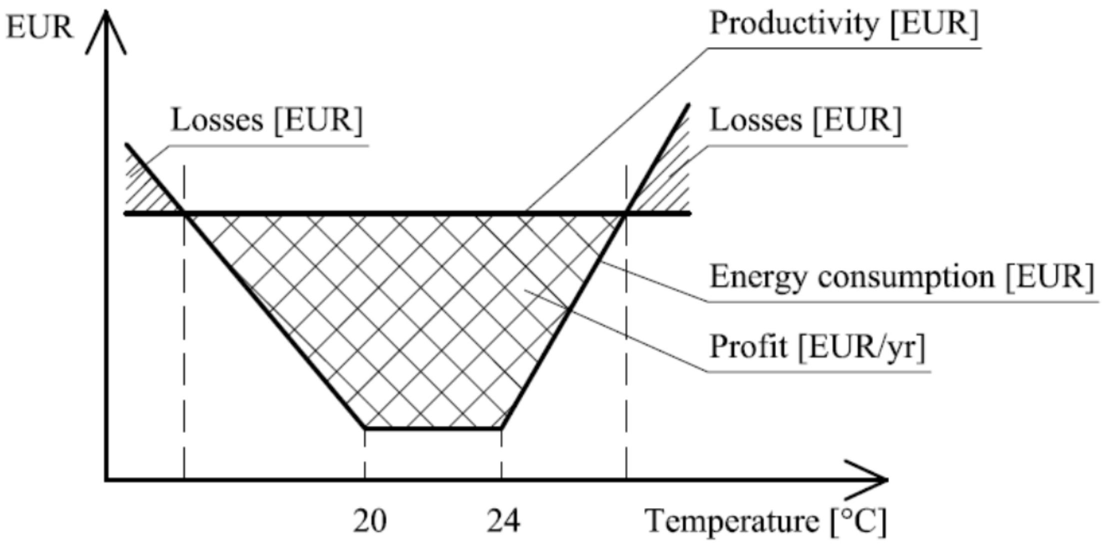

Fig 5.7 Cross-section of productivity and energy consumption, unlimited capacities

accomplished with increased energy use for air conditioning and at a certain point, it is further not profitable to keep on conditioning the air, since energy consumption becomes larger than the achieved profit. This leads to economically unjustified losses as shown in Fig 5.7 within the areas confined by sloped lines.

Investment costs should be taken into account when selecting optimal heating and cooling capacities. Within scope of this thesis it has been decided that cooling source is a compressor chiller, and price for energy production, including chiller installation, is 400 EUR/ kW installed capacity. Annual savings, if any, due to reduced cooling capacity are equal to the difference between productivity loss and consequent costs for energy. Decision, whether it is profitable to reduce cooling capacity therefore was made using NPV economic model, so that investment costs and annual savings were considered. Investment is generally profitable if net present value of all savings is greater than the total investment.

Fig. 5.8 presents results on whether it is profitable to reduce cooling capacity when window area is 2 m^2 and average employee salary is 750 EUR.

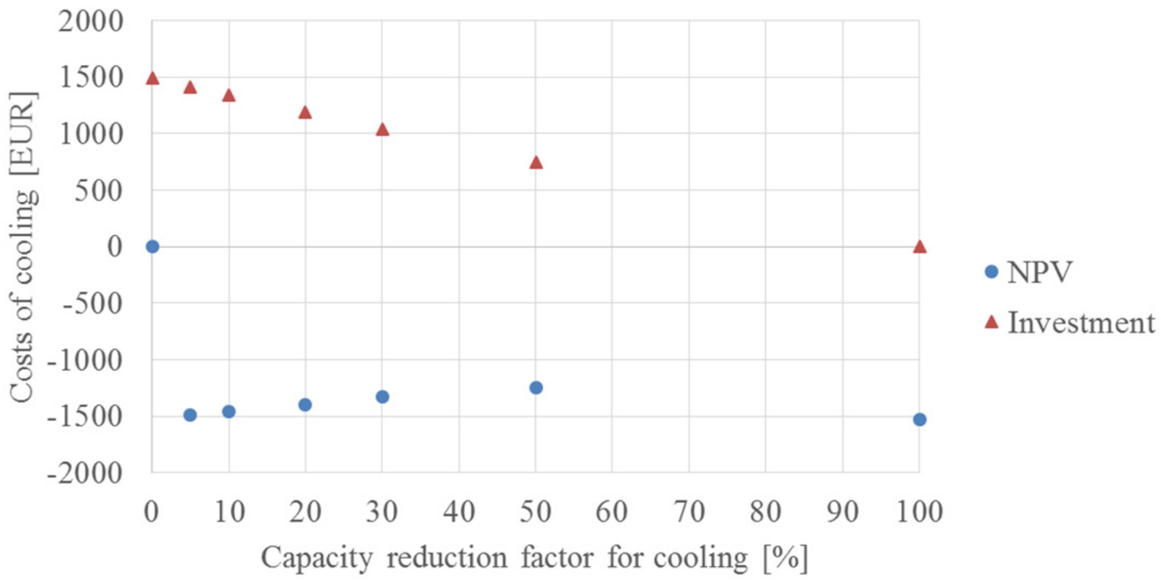

Fig. 5.8 Profitability assessment of reduced cooling capacity; window area 2 m^2; salary 750 EUR

Since net present values are lower than investment, it can be concluded that in long term view (20 years of chiller lifetime), reduction of cooling capacity is not profitable. Therefore the optimum cooling capacity under given conditions is the maximum calculated capacity.

When the window area increased from 2 to 4 m^2, with all other conditions unchanged, the profitability analysis of reduced cooling capacity is shown in Fig. 5.9.

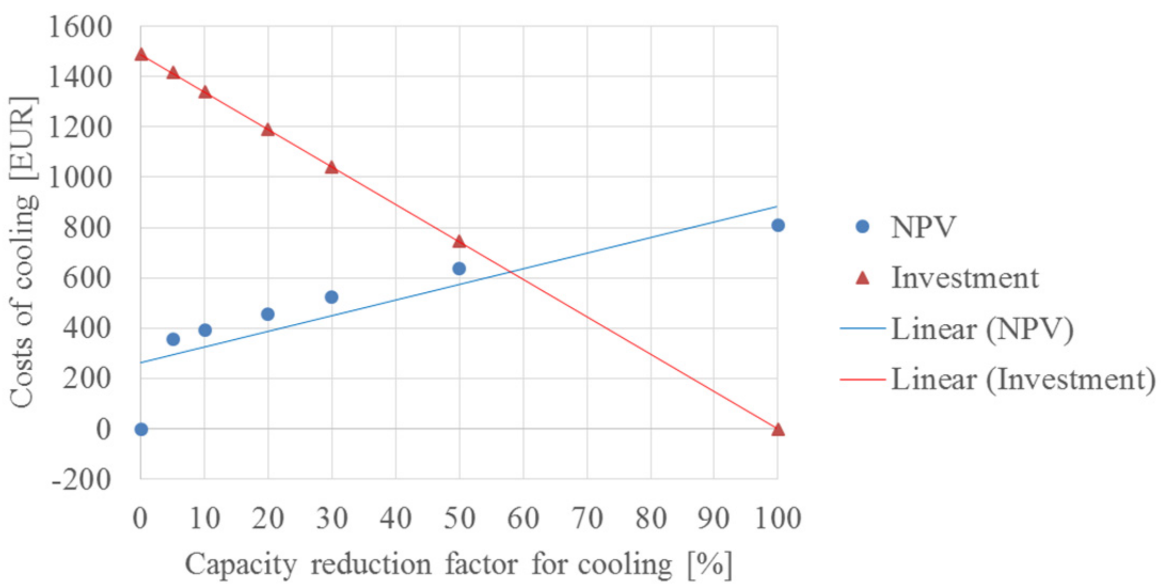

Fig 5.9 Profitability assessment of reduced cooling capacity; window area 4 m^2; salary 750 EUR

The NPV is greater than the investment at the capacity reduction factor of 100%. After completing the graph with linear trendlines, the break point is at about 57% reduction factor. It means that reducing cooling capacity over 57% is profitable. The greatest difference occurs at reduction factor 100%, meaning that most profitable in long term view would be not installing cooling system at all, if outdoor air conditions for the duration of 20 years would be the same as in 2010 as well as the indoor conditions unchanged.

The relationship between maximized profit, expressed as maximized productivity and energy savings, and cooling capacity for the case with employee salary of 750 EUR and window area of 4 m^2 is given in Fig 5.10.

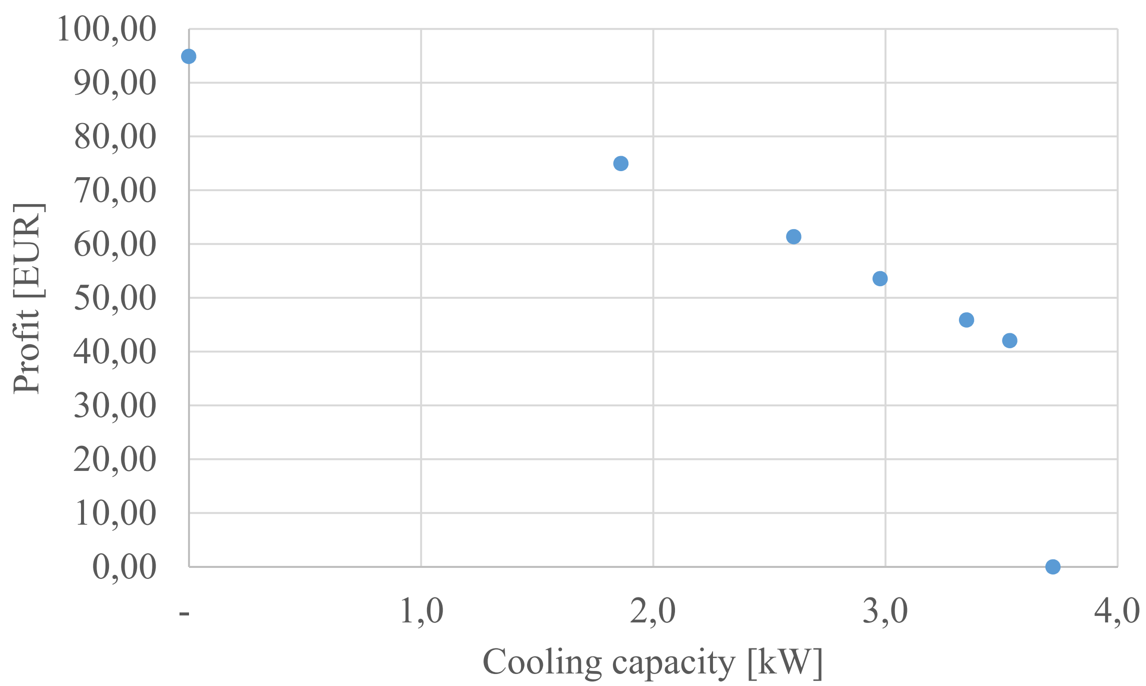

Fig 5.10 Relationship between maximized profit and cooling capacity for the case with window area of 4 m^2 and employee salary of 750 EUR

When window area is equal to 4 m^2 the maximized profit (95 EUR per person annually) can be achieved when no cooling equipment is installed. Energy and investment costs are too high compared to potential productivity benefits. However, it should be mentioned that complete avoidance of installation of cooling system cannot be accomplished since cooling is necessary for comfort and health considerations, as indicated by a number of comfort standards.

Repeating the same calculation procedure by changing the input data, e.g. U-values, window areas, building orientation etc. it is then possible to optimally choose the capacity of heating or cooling equipment with respect to maximized profit.

CONCLUSIONS

1) Despite numerous studies available on quantification of energy expenses with respect to indoor climate conditions, it was found that they are limited to simple calculations, where mean monthly temperatures are used. This doctoral study shows that for office buildings more complex methods should be used, including frequencies of particular outdoor temperature and humidity conditions, data for solar radiation through building envelope, cloud cover and wind speed.

2) The systematized data in literature review on the relationship between productivity and indoor air parameters enables estimation of optimal productivity zone (indoor air temperature and relative humidity) in office buildings. As a result, a mathematical model was developed to estimate productivity based on indoor air parameters.

3) Proposed outdoor climate data procession method enables assessment of indoor climate and energy consumption. Results from the conducted analysis on Latvian outdoor climate shows that most of the time (97% or 8643 h) outdoor temperature and relative humidity did not correspond to the optimal productivity zone, indicating necessity for air conditioning nearly all year round. At present, partial air conditioning is used, i.e. air heating and cooling, while actually air humidification and dehumidification is also necessary when optimal employee productivity is considered.

4) Calculation method was proposed to estimate energy consumption for air conditioning. Method is based on the actual complete set of data on outdoor climate, characteristics of building envelope, buildings orientation, and room occupancy characteristics, provided as hourly values for each month. Developed methodology enables economical estimation for optimization of air conditioning equipment parameters with respect to maximized profit.

5) Developed mathematical model for selection of optimal heating and cooling capacities, at any given outdoor conditions based on the maximized profit criterion and taking into account relationship between productivity and indoor climate.

6) Results of this thesis can be used for design of air conditioning systems, as well as a guidance for operations and maintenance of office buildings.

LIST OF PUBLICATIONS

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2) Stankevica G., Kreslins A. Energy consumption and employee productivity investigation with respect to profit in office buildings// Proceedings of 11th REHVA World Congress & 8th International Conference on IAQVEC, CLIMA 2013. - Prague, Czech Republic, 16-19 June, 2013. - pp. 3238-3246.

3) Stankevica G., Kreslins A. Impact of indoor climate on energy efficiency and productivity in office buildings// Proceedings of the 7th International Cold Climate HVAC Conference. – Calgary, Canada, 12-14 November, 2012. - pp. 169-175.

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5) Stankevica G., Lesinskis A. Indoor air quality and thermal comfort evaluation in Latvian daycare centers with carbon dioxide, temperature and humidity as indicators// Journal of Civil Engineering and Architecture. - 2012. – Vol.6(5). - pp. 633-638.

6) Stankevica G., Kreslins A. Energy efficiency improvement measures and their effect on heating energy consumption and indoor climate: case study in selected Latvian kindergartens// Proceedings of the IFME World Congress on Municipal Engineering. – Helsinki, Finland, 4-10 June, 2012. – pp. 19-27.