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DEMAND CONTROL VENTILATION SYSTEMS IN SPORT FACILITIES

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DESCRIPTION

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Demand Control Ventilation Systems in Sport Facilities

Abstract

Aim of this thesis work was to show benefits of demand control ventilation spaces in sport facilities. They are spaces with varying occupancy during the day. This fact indicates a need for applying demand control ventilation (DCV) to get maximum energy savings. My assumption was that occupancy based and carbon dioxide based DCV systems offer best decision in these spaces.

The first part is a theoretical description of DCV. Then investigations in U-building of Mikkely University of Applied Sciences were made. And in the last part of thesis, I calculated energy requirements of actual ventilation system, determined the locations of carbon dioxide sensors and required airflow for pre-designed DCV according to CO_2 measurements in the studied locations.

As the main result, performance and savings of DCV in sport spaces was calculated. Results of measurements and calculations are given in graphs and tables. According to calculations and measurements I made a decision, that DCV in sport space of U-building is the best approach for saving money and energy.

Subject headings, (keywords)

Ventilation, Demand Control Ventilation, Carbon Dioxide based Demand Control Ventilation, Occupancy Based Demand Control Ventilation.

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CONTENTS

1 INTRODUCTION

The purpose of building services engineering is to make such conditions in the building, which will satisfy occupant's comfort requirements. To achieve the desired indoor climate and low energy consumption at the same time, designers should use modern solutions in HVAC-systems. One modern solution is demand control ventilation (DCV).

This thesis discusses the ventilation systems of sports facilities. They are places with a variable number of occupants at different times of the day. In case of variable occupancy the best solution to reduce over-ventilation and save energy are DCV systems. They are very sensitive to non-steady conditions, such as fluctuations in carbon dioxide concentration, temperature and other variable climate factors, which are the results of occupancy.

The first part of the thesis discusses theoretical background of DCV. I will describe applications and components of DCV, design requirements from standards and solution in case of sport facilities. The second part of the thesis will be about research, which will be made in sport spaces of U-building in Mikkeli University of Applied Sciences (MUAS).

In my thesis I want to prove that DCV clearly outperforms constant airflow ventilation (CAV) in sport facilities. To show performance of DCV system energy consumption will be calculated in the real conditions of U-building. Then I will compare results with existing ventilation. In addition I will compare the energy costs using energy prices of year 2011.

2. THEORETICAL BACKGROUND

2.1 Demand Control Ventilation

DCV is a ventilation system with a response control of the air flow rate according to the measured demand. The demand is determined by a set of indoor air quality parameters. Temperature, occupancy, carbon dioxide level and humidity are the most important. The principles of automatic control of airflow based on actual demand have been known for over 20 years. Only the prices for equipment and limited understanding of DCV have slowed down customers. Investigations in field of ventilation and air conditioning have helped to reduce prices for sensors and control devises. /1, p.1./

Ordinary DCV system in addition to parts of conventional constant air flow ventilation (CAV) has also dampers with activators, variable air flow diffusors, sensors in different parts of the system, communication units and fans with frequency control systems. DCV works generally on the sensor readings. Sensors can provide infrormation about variations in humidity, carbon dioxide, temperature and occupancy as well. Besides, combined sensors or so called «air quality sensors» can measure more than one indoor air parameter at the same time, and therefore provides more flexibility to DCV. /2, p.8./

Two common schemes of operating DCV are shown on Figure 1. In figure “A” airflow is controlled by help of a variable supply air (VAV) flow diffuser. This is a device, which changes the position of diffuser according to the sensor readings. The device has stable pressure range, approximately 20-50 Pa, which is maintained in the inlet side by keeping constants pressure in each branch with help of control dampers. In figure “B” there are VAV boxes. They are independent of the pressure changes in the system, because each device is equipped with damper for airflow measurement and a sound absorber, which is used to decrease noise occuring from the damper. /2, p. 11-12./

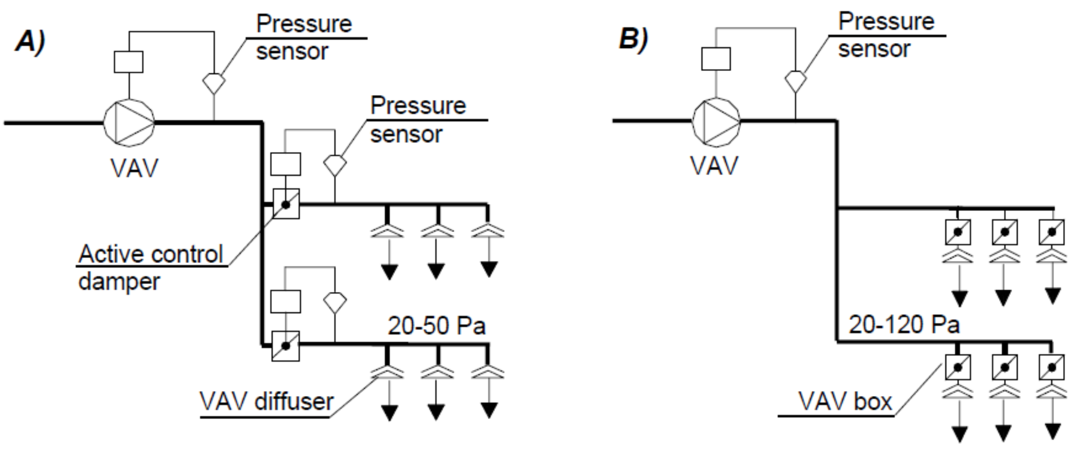

Figure 1. Commonly used DCV solutions /2, p. 11/

DCV offers significant advantages in such kind of spaces like lecture halls, exhibition halls and sport facilities. These spaces are designed for large numbers of people with high outside air flow requirements according to standards. Decreasing of average airflow rate according to real demand allows to reduce energy consumption of fan and heating or cooling units as well.

Despite the obvious functional advantages of DCV this systems is more complicated than conventional CAV systems. Wrong selection of airflow control devises causes too much noise in supply air divices. Moreover unexpected occupancy near a sensor causes overflow and wastes of energy. Summing it up, careful installation, maintenance and commissioning are required to get expected parameters from DCV.

2.2 Recommendations for Demand Control Ventilation systems from standards and authorities

Finland's National Building Code D2 and Finland's Classification of Indoor Air 2008 give us inadequate information about demand controlled systems. "On demand control of ventilation systems shall normally be implemented in the rooms where human occupancy or emissions of impurities vary significantly" /3, p.30/.

As for ASHRAE standard 62.1-2007 there is some kind of design guide for DCV.

"6.2.7

The system may be designed to reset the design outdoor air intake flow (V_{ot}) and/or space or zone airflow as operating conditions change" /4, p.15/.

Conditions mentioned before include following changes: "Variations in occupancy or ventilation airflow in one or more individual zones for which ventilation airflow requirements will be rest" /4, p. 15/. These variations are based on occuppancy shcedules, direct count of occupants and more often on occupancy or CO_2 sensors. There are also other variations:

- "Variations in the efficiency with which outdoor air is distributed to the occupants under different ventilation system airflows and temperatures"
- "A higher fraction of outdoor air in the supply due to intake of additional outdoor air for free cooling or exhaust air makeup." /4, p. 15./

2.3 Occupancy based Demand Control Ventilation system

Occupancy based DCV is a system, where outdoor airflow changes according to real occupancy in a space. When the space is without occupancy then ventilation provides minimum required amount of outdoor air. For example, it can be according to minimum air change rate. Otherwise, at the highest allowed occupancy, DCV works like a common CAV system with maximum designed air flow. Between these two set points DCV maintains air flow in a proportional way with help of occupancy sensors.

As I mentioned in chapter 2.2, ASHRAE standard 62.1 2007 allows variable outdoor airflow rate. Following equation helps to determine set points in single zone system:

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \tag{1}$$

where V_{bz} is the breathing zone outdoor air flow, l/s, P_z is the zone population, R_p is the outdoor airflow rate required per person, l/s/person, A_z is the zone area and R_a is the outdoor airflow rate required per unit area, l/s/m^2. /4, p.11./

Zone population at the minimum set point equals zero. Maximum occupation should be predicted. If it can not be predicted then ASHRAE 62.1-2007 gives Table 6-1 with occupance density. Between these set points required outdoor air flow rate in presence based DCV can be determined in two ways: by use of occupancy schedules and by use of occupancy sensors. First solution needs accurate people counting during the day and building-automation system (BAS) as well. BAS predicts population based on time. Second solution uses sensor readings. They are transmitted to automation center. It tranfers sensor readings to air flow values. According to these values VAV box regulates needed air flow rate. /5, p.1./

Occupancy based DCV offers best solution in case of spaces, where air flow rate per person is the highest. Lecture halls, office spaces with varyable occupancy predict very good efficiency of occupancy based DCV system.

2.4 CO_2-based Demand Control Ventilation

DCV using carbon dioxide is the combination of two complex solutions. First is CO_2 sensors, which monitors carbon dioxide levels indoors and outdoors and transfers data to communication units. Second is the AHU regulation system, which recieves processed data from communication units and delivers air to spaces according to actual air flow requirements. It means that dampers change their position and fan regulates speed according to changes in carbon dioxide concentration. /6, p.3./

Carbon dioxide is one of the most common gases in atmosphere. Minimum amount of outdoor CO_2 concentration was found in the center of the Pacific Ocean atop Mauna Loa Hawaii with value of 366 ppm. In urban areas outdoor concentration of carbon dioxide varies from 375 to 450 ppm. Often this concentration depends on the combustion processes near the current location, where CO_2 level measured. Outdoor concentration of CO_2 has also influence on indoor concentration of carbon dioxide as well as human activity indoors. /7, p.1./

All human breathe out carbon dioxide with a certain concentation. It mostly depends on human health, diets or duration and intencity of physical activity. Figure 2 shows dependance between activity level and carbon dioxide production. When the activity level and breathing rate of person is very high, like at heavy work, then concentration of CO_2 is the highest as well. /5, p.1./

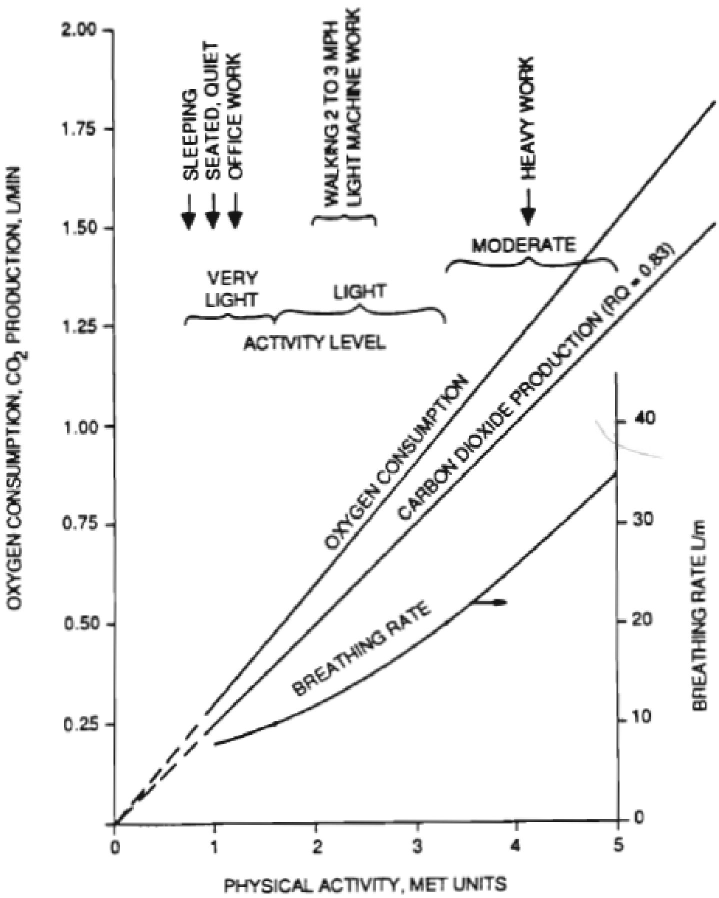

Figure 2. Dependence between CO_2 production and physical activity of person /4, p.32/

There are different ways to design CO_2 based DCV and calcucate its performance. Equation 2 explains general approach to find required ventilation airflow rate, pollutant generation rate and carbon dioxide concentrations, which vary in time (non-steady state conditions).

$$\dot{V} \cdot C_s + \dot{M} = \dot{V} \cdot C_s + V \cdot \frac{dC_r}{dt} \quad (2)$$

where *V'* is the airflow rate, *M'* is the strength of indoor sources, C_s is the concentration in supply air, C_r is the concentration in indoor air and *V* is the volume of the room. /8, p.128./

But the easiest way to evaluate CO_2 based DCV is with the assumption of steady-state conditions indoors. It means that pollutant generation rate and indoor carbon dioxide concentration may be assumed to be constant in each time periods between sensor readings. Equation 3 helps to determine set points between minimum and maximum allowed CO_2 concentration in a certain space.

$$C_r = C_s + \frac{M}{q_v} \tag{3}$$

where C_r and C_s are the indoor(space) and outdoor concentrations respectively, mg/m^3, M is the pollutant source strength indoors, mg/h, q_v is the ventilation airflow rate, m^3/h. /8, p.126./

So, to define outdoor airflow rate q_v designer should measure concentrations of carbon dioxide and estimate CO_2 generation rate of the occupants M , equation 3.

$$q_v = \frac{M}{C_r - C_s} \tag{4}$$

With the same way BAS functions in real time with help of CO_2 sensors indoors. It is necessary to have one sensor to each ventilation zone. In addition, if outdoor concentration of carbon dioxide varies more than 100 ppm, then outdoor sensor should be installed. /5, p.2./

There are four main sensor types avaible on the markets: infrared, electrochemical, photoacoustic and mixed gas sensor. Non-dispersive infrared (NDIR) carbon dioxide is most used. This sensor provides long-term calibration stability and low price as well. Its price depends on supplier, but the average is 250-300 dollars per sensor in prices of year 2011.

Table 1 below shows the average enegry-cost savings from CO_2 based DCV. This table presents, that the more occupancy varies in time the more energy savings can be predicted.

Table 1. Estimated energy-cost savings from CO_2 based DCV /9, p.25/

Application	**Energy-cost savings range**
Schools	20 % to 40 %
Day nurseries	20 % to 30 %
Restaurants, canteens	20 % to 50 %
Lecture halls	20 % to 50 %

Open-plan offices (40 % average occupancy)	20 % to 30 %
Open-plan offices (90 % average occupancy)	3 % to 5 %
Entrance halls, booking halls, airport check-in areas	20 % to 60 %
Exhibition halls, sports halls	40 % to 70 %
Assembly halls, theatres, cinemas	20 % to 60 %

Besides advantages, this DCV has limitation of using. It offers best performance in spaces, where the main contaminant is carbon dioxide. Other contaminants must be at the level of zero, otherwise CO_2 based DCV can't provide adequate indoor climate.

2.5 Utilizing of DCV in sport areas

Sport areas are the places with high physical activity of people and required ventilation rates as well. Table 2 shows requirements to airflow rates in these spaces from different standards. For example, I take a gym hall with 100 m^2 of area and calculated required outdoor airflow rate.

Table 2: Required airflow rate in sport facities from different standards and authorities

Standard	Finnish national building code D2	Classification of indoor climate 2008, S1 category	ASHRAE standard 62.1-2007	Russian building code SniP 41-01-2003
Required flow rate	From 2 l/s to 6 l/s	6 l/s per m^2	1,5 l/s per m^2	80 m^3/hour per person
Airflow rate for 100 m^2 of gym ($q_{v.cav}$)	From 200 l/s to 600 l/s	600 l/s	150 l/s	667 l/s (according to 30 persons/100 m^2)

As I mentioned before, occupancy in sport facilities varies in time. According to my own observation maximum occupancy is before and after working hours of most people and also differs during the day. This kind of variation indicates a need for applying DCV to get maximum energy savings. Occupancy based and CO_2 based DCV offers best decision in this space. Following paragraphs show effeciency of use CO_2 based DCV in 100m^2 gym hall.

Supposedly, that average occupancy during the day is 60% (18 persons) with low level of physical exercise (3 met) we can calculate required ventilation airflow rate with help of equation 3. People's carbon dioxide production is 50 l/h per person /8, p.144/, outdoor concentration is 400ppm and indoor concentration equals 1200ppm, which is maximum allowed according to Finnish National Building code D2. Last thing that we need is to satisfy requirements in dimensions of equation 3:

$$C_r = 1200ppm = 2190\ \frac{mg}{m^3},$$

$$C_s = 400ppm = 730\ \frac{mg}{m^3};$$

$$M = n \cdot M_p \cdot \rho_{cd} \cdot 1000 \qquad (5)$$

where n is the amount of people, M_p is the generation of carbon dioxide per person, l/s, ρ_{cd} is the density of carbon dioxide, g/l and *1000* is the factor for converting the denomination to mg/l.

Then total generation of carbon dioxide, required flow rate, and energy savings of CO_2 based DCV are:

$$M = 18\ \cdot 50 \cdot 1{,}977 \cdot 1000 = 1779300\ \frac{mg}{h},$$

$$q_{v.req} = \frac{1779300\ mg/h}{2190-730\ mg/m^3} = 1218{,}7\ \frac{m^3}{h} = 338{,}5\ \frac{l}{s},$$

$$s = \frac{600-338{,}5}{600} \cdot 100\ \% = 43{,}5\ \%$$

To sum it up, performance of CO_2 based DCV in this case is 43,5 %. It means that required airflow rate 43,5 % less than actual airflow in CAV. Here were got average performance, because I assumed occupancy and physical activity on the average levels. To achieve more accurate values designer must know real occupancy and activity intensities. Following chapters 3 and 4 show investigations in performance of CO_2 based DCV in real conditions of gym hall. In these chapters I described methods and discussed research results.

3. INVESTIGATION OF SPORT HALL IN U-BUILDING

3.1 Overview of sport area

U-building of the main campus of the Mikkeli University of Applied Sciences was renovated in year of 2010. The first floor is used for recreational purposes. Second floor accomodates sport facilities. Sport hall working schedule are shown in Table 3.

Table 3. Sport hall working schedule

Day of week	Monday, Tuesday Wednesday, Thursday	Friday	Saturday Sunday
Working time	07 - 19.30	07 - 18.00	9 - 18.00
Hours per day	12,5	11	9

Sport hall consists of 3 spaces. One of them is the fitness room (MUAS code is 232A). Average area of this room is 108,2 m^2 (A_1). Figure 3 shows the picture of the room.

Figure 3. Picture of investigated room (232A)

Second and third spaces are for gym purposes. Here are exersice bikes, leg machines, treadmills, exercise benches and other special equipments. Codes of room are 232B and 232C. The area of 232B is 76 m^2 (A_2) and 232C is 82,5 m^2 (A_3). These spaces are shown in Figure 4 and Figure 5 below.

Figure 4. Picture of investigated room (232B)

Figure 5. Picture of investigated room (232C)

Ventilation in sport facilities of U-building is provided by use of mechanical exhaust and supply systems. Supply air handling unit (AHU) is situate in 232A. Exhaust fan is near the roof. Separate location of supply and exhaust systems don't give any possibility to use heat recovery system and get energy savings. These spaces were chosen for investigations because I want to show that DCV systems can reduce energy consumption (with comparison of existing ventilation).

The following paragraphs will discuss supply AHU. I will describe the main parts and characteristics of each part. It is necessary to clarify opportunity to use DCV instead of existing system.

AHU consists of filter, damper, heating coil, and fan. It operates 14 hours per day, from Monday till Friday, and 10 hours per day on Saturday and Sunday. Totally it works 90 hours per week. Figure 6 shows placement of supply AHU in 232A.

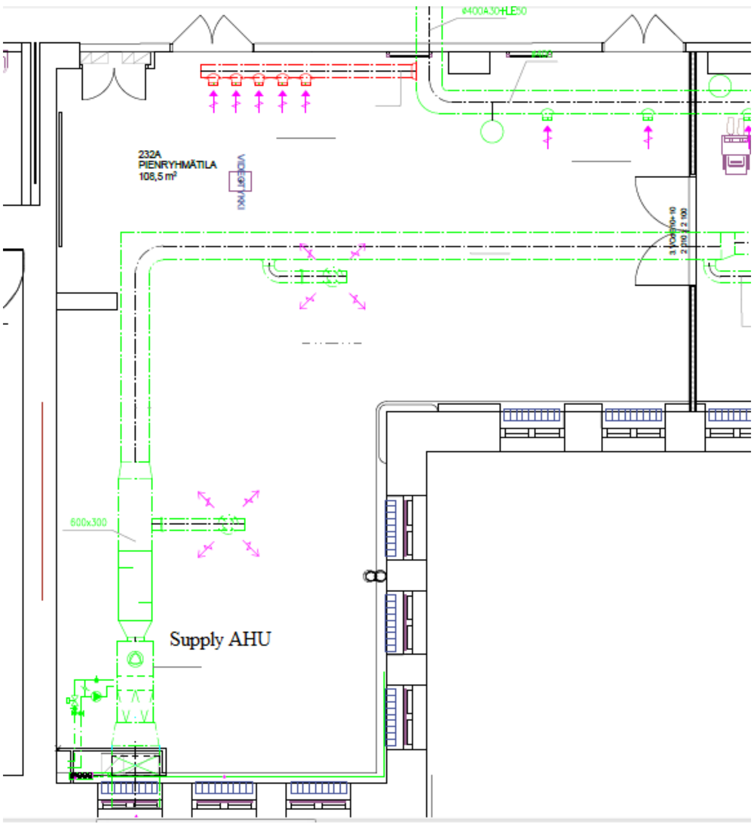

Figure 6. Plan of ventilation system in 232A

Source of heat in heating coil is a hot water. Water is delivered by ESE district heating company. This system is equipped by thermostat, which regulates temperature of supply and exhaust water flow according to requirements in heating power.

The fan is manufactured by FlaktWoods Company. Cross-section of VEKA-2 fan is shown in Figure 7.

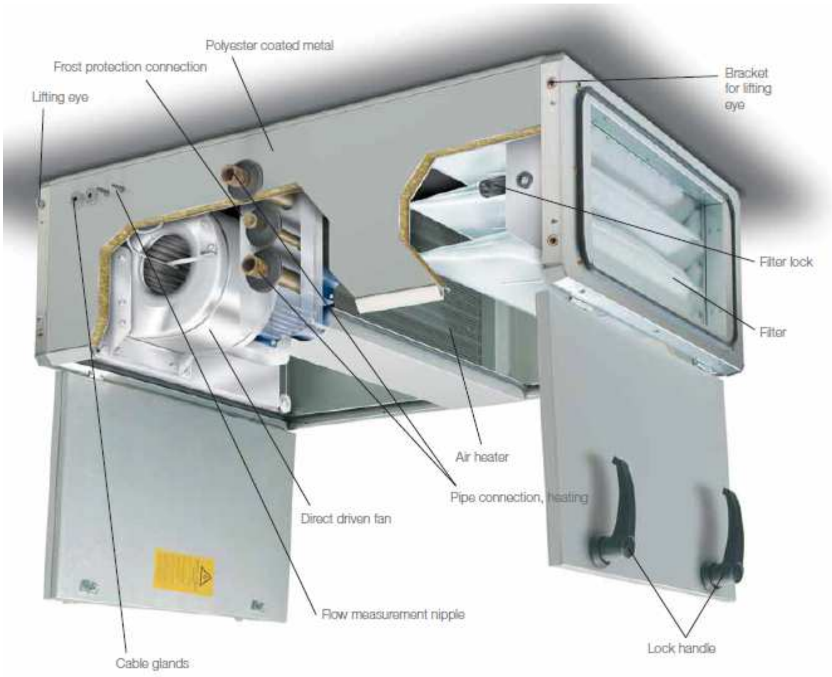

Figure 7. Cross-section of VEKA-2 fan /10/

The fan produces constant outdoor air flow rate of 620 liters per second with electricity power of 1,1 kW to sport spaces. Exhaust fan takes 630 liters per second from the same spaces with power consumption of 0,2 kW. To vary fan speed and air flow rate as well frequency inverter can be used. It would help to change fan speed in a wide range. Concerning DCV using frequency inverter reduces energy consuption of fan.

The fan delivers different air flow to each room with help of air ducts and therminal units. Supply and exhaust air flow rates are shown in Table 4.

Table 4. Supply and Exhaust air flow rate in each room /showed on drawings from maint.person

Room's code / Type of flow	232A	232B	232C
Supply, l/s	220	220	170
Supply, m^3/h	792	792	612
Exhaust, l/s	230	220	170
Exhaust, m^3/h	828	792	612

3.2 Methods

3.2.1 General Overwiew

To find performance of DCV in sport spaces the following procedure was prepared. I started with annual energy consumption calculations of existing ventilation system. Then I made measurements of carbon dioxide concentration and temperature in 2 main steps:

1. Determination of the best location in the room for measuring devices

2. Measurements in each determined location for one week

Summing it up, operation cost calculations for pre-designed DCV system and comparison with existing ventilation were made.

I made measurements with help of two TSI IAQ Calc and EBRO EBI 20. TSI IAQ Calc determines carbon dioxide concentration in real time. I programmed it so, that device took a sample every 2 minutes. The picture of installation is shown on Figure 8.

Figure 8. Picture of instalation

3.2.2 Calculations of energy consumption of existing ventilation

Energy consumption of existing ventilation can be calculated like a sum of energy which uses for fan operating and energy for heat of supply air until acceptable indoor temperature.

The heating energy need for ventilation can be calculated by using the Equation 6:

$$Q_{iv} = \rho_i \cdot C_{pi} \cdot t_d \cdot t_v \cdot q_{v,supply} \cdot (T_{sp} - T_{recov}) \cdot \Delta t \qquad (6)$$

where Q_{iv} is net heating energy need for ventilation, kWh, ρ_i is the air densitiy, 1.2 kg/m^3, c_{pi} is the specific heat capacity of air, 1000 Ws/(KgK), t_d ventilation system's mean daily running time ratio, h/24h, t_v ventilation system's weekly running time ratio, days/7 days, q_v is the supply air flow, m3/s, T_{sp} is the supply air temperature, °C, T_{recov} is the temperature after heat recovery device, °C, Δt is the time period length, h. /11, p. 19/

In our case we don't have heat recovery, so temperature after heat recovery (T_{recov}) equals outdoor air temperature and inblown air temperature equals the indoor air temperature. To sum it up were got following equation:

$$Q_{iv} = \rho_i \cdot C_{pi} \cdot t_d \cdot t_v \cdot q_{v,supply} \cdot (T_{in} - T_{out}) \cdot \Delta t \quad (7)$$

Equation 7 can be used to calculate heating energy need in certain time period. In order to calculate annual heating consumption of ventilation, we have to sum each of these periods during the year. Values of $q_{v,supply}$, ρ_i, c_{pi}, t_d and t_v assumed to be constant during the year. According to Finnish National Building code D2 indoor air temperature in sport facilities must be at least 18°C. In assumation of constant indoor temperature during occupancy T_{in} equals 18°C in each case. The trouble is outdoor air temperature, because it varies during all year. Duration of each outdoor temperature was taken from «Ympäristöminiteriön moniste 122, Ilmanvaihdon lämmöntalteenotto lämpöhäviöiden tasauslaskennassa» with use of following equation:

$$\Delta t_i = \frac{l_i - l_{i-1}}{100} \cdot 24 \cdot 365 \quad (8)$$

where l_i and l_{i-1} are the time percentages of the year for i and i-1 temperatures, 365 are days per year, 24 are hours per day.

Summing it up, total energy consumption for heat of supply air can be calculated with following equation:

$$Q_{tot.v} = \rho_i \cdot c_{pi} \cdot t_d \cdot t_v \cdot q_{v,supply} \cdot \sum_{i=1}^{64} (T_{in} - T_{out}) \cdot \Delta t_i \quad (9)$$

To calculate energy consumption of fan, we can use following equation:

$$W_{fan} = (P_{eh} + P_{sp}) \cdot t_d \cdot t_v \cdot \Delta t \quad (10)$$

where P_{eh} and P_{sp} are the actual powers of exhaust and supply fans respectively , t_d is the ventilation system's mean daily running time ratio, h/24h, t_v is the ventilation system's weekly running time ratio, days/7 days (day=24 h) and Δt is the time period length, h.

3.2.3 Determing the best location of the measuring device

Right position of carbon dioxide sensors helps accurate DCV working. To achieve this designer should find location with maximum activity and carbon dioxide concentration during occupancy in the area. I made measuremetns in each room to find the best location of CO_2 measuring device and sensor as well.

Fitness room 232A has very low occupancy. Often it is 1-2 persons at the same time. In spite of it I put sensors in two locations and measured carbon dioxide concentration and temperature there. Then I did the same procedure in 232B and 232C. The placements of carbon dioxide and temperature mearuring devices are shown on Figure 9.

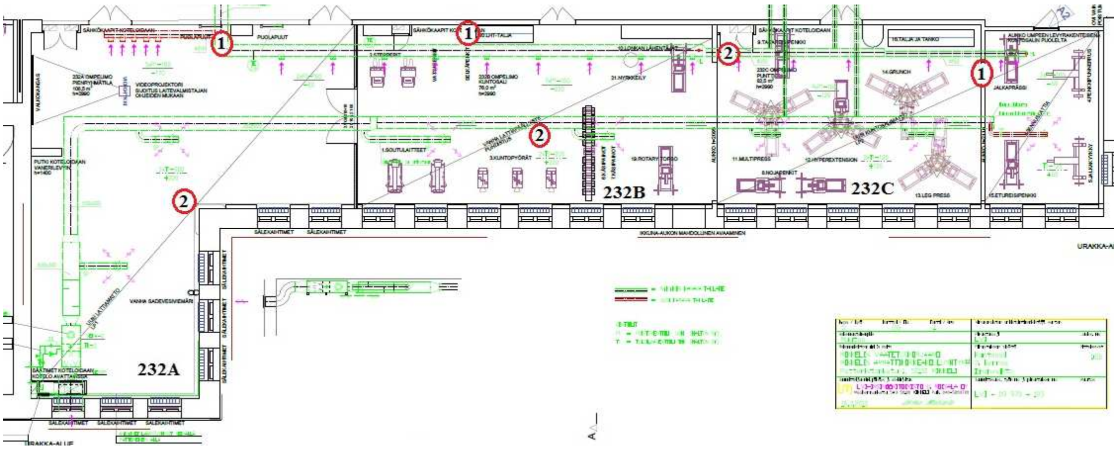

Figure 9. Location of CO_2 measuring devices

3.2.4 Measurements of carbon dioxide levels and temperature

Measuments of CO_2 level were made during one week in sport hall operating time. Due to different ventilation zones I made these measurements in each room. I have put TSI IAQ Calc in each room in the place with highest occupant activity. This place I found from 1st step measurements, which I described before. Also these placements satisfied ASHRAE requirements:

"Criteria for placement of wall-mount sensors are similar to those for temperature sensors. Avoid installing in areas near doors, air intakes or exhausts or open windows. Because people breathing on the sensor can affect the reading, find a location where it is unlikely that people will be standing in close proximity (2 ft [0.6 m]) to the sensor. One sensor should be placed in each zone where occupancy is expected to vary. Sensors can be designed to operate with VAV based zones or to control larger areas up to 5,000 ft2 (465 m^2) (if an open space)" /8, p.4/.

Measurements of temperature were also made. Their purposes were to show that temperature did not exceed maximum allowed values, when the carbon dioxide level at the maximum point. Actually, maximum value can't exceed 1200ppm, but during measurements were got very different results.

3.2.5 Calculations of energy consumption of pre-designed demand control ventilation

From 2nd step measurements were got indoor carbon dioxide concentrations in certain time in each ventilation zone. Table 4 in chapter 3.1 shows airflow rates, which are delivered in each room by existing CAV. With help of these values and equation 3 is possible to calculate carbon dioxide generation rate:

$$M = (C_r - C_s) \cdot q_{v.cav} \tag{11}$$

where C_r is the indoor concentration (readings from measuring device TSI IAQ Calc in every 2 minutes), C_s is the outdoor concentration, which is assumed to be constant during daily measurements and $q_{v.cav}$ is the constant airflow rate.

Then I made the same calculations, like in the chapter 2.5 and deterimined required airflow rate ($q_{v.req}$) in each zone in a certain time period and average daily airflow rate ($q_{v.aver}$). Minimum required airflow rate ($q_{v.min}$) was calculated according to minimum air exchange rate n and volume of each room V_{room}:

$$q_{v.min} = n \cdot V_{room} \tag{12}$$

When calculated $q_{v.req}$ less than $q_{v.min}$, I choose $q_{v.min}$ in calcucations of $q_{v.aver}$, otherwise, if $q_{v.req}$ more than $q_{v.min}$ I take $q_{v.req}$ in calculations of $q_{v.aver}$. Then I summed $q_{v.aver}$ from each room to get $q_{v.dcv}$. Last step was to calculate heat energy consumption and electricity consumption of pre-designed DCV with help of equations 9 and 10 and with the same way like I did in chapter 3.2.2.

4. RESULTS

4.1 Annual energy consumption of existing ventilation

Annual energy needed for fan operation, according to Equation 10:

$$W_{fan} = (1{,}1 + 0{,}2)\ kW \cdot \frac{90}{7 \cdot 24} \cdot 8760h = 6100{,}7\ kWh$$

This energy is taken from electric network. The distributor of energy is ESE Company. According to prices of year 2011 1kWh energy costs 10,49 eurocents (C_{en}). So, to sum it up, annual energy for fan operation costs:

$$M_{fan} = W_{fan} \cdot C_{en} = 6100{,}7\ kWh \cdot \frac{0{,}1049\ euro}{kWh} = 640\ euro$$

Annual heat energy needed for achievement desired temperature condition in gym hall is calculated with help of Equation 9. Appendix 1 shows that sum of heat energy is $Q_{tot,v} = 52727\ kWh$. According to prices of year 2011 1kWh heating energy costs 4,638 eurocents (C_{he}). Summing it up, annual heat energy costs:

$$M_{he} = Q_{tot,v} \cdot C_{he} = 52727\ kWh \cdot \frac{0{,}04638\ euro}{kWh} = 2445{,}48\ euro$$

Total energy costs in case of CAV:

$$M_{CAV} = M_{fan} + M_{he} = (640 + 2445{,}48)\ euro = 3085{,}48\ euro$$

4.2 Estimation locations of measuring devices

Measuremnt results in room 232A are shown in table 5. From this table we can see that there is no difference in two measuring points, because carbon dioxide and tempereature levels are close to each other. Figure 10 corresponds that carbon dioxide concentration in this room during the day is near with measured outdoor carbon dioxide level of 385ppm. It means that 232A was almost without any activity and ventilation delivered overflow. Measurements of temperature show that temperatures in these points are in allowed values.

Table 5. Measurement results in 232A

Position of device	Carbon dioxide concentration, ppm			Temperature, °C		
	Max	Min	Average	Max	Min	Average
1	444	385	405	19,8	19,2	19,6
2	429	388	404	19,6	19,2	19,6

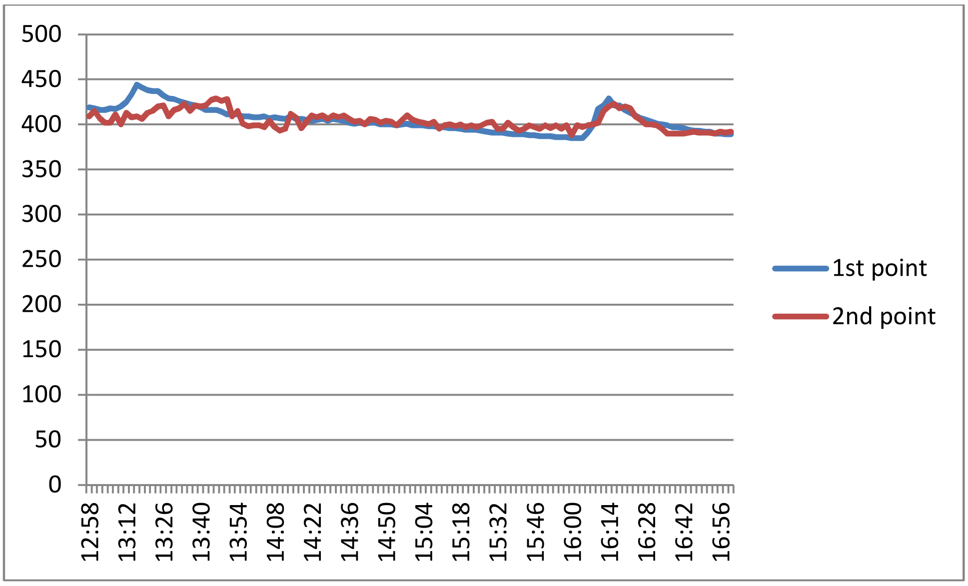

Figure 10. Measured values of carbon dioxide concentration in 232A in 1st and 2nd measuring points

Measurement results in room 232B are shown in table 6. Values in 1st point quite near to 2nd point, but average value is bigger. It happened due to placement of supply air device. Perhaps it made an influence on 2nd carbon dioxide sensor.

Temperature values at maximum CO_2 concentration are acceptable. Figure 11 shows that activity in room 232B higher than in 232A, because fluctiations in carbon dioxide occur more often.

Table 6. Measurement results in 232B

Position of device	Carbon dioxide concentration, ppm			Temperature, °C		
	Max	Min	Average	Max	Min	Average
1	548	404	440	20,4	19	19,8
2	527	382	416	20,2	19	19,6

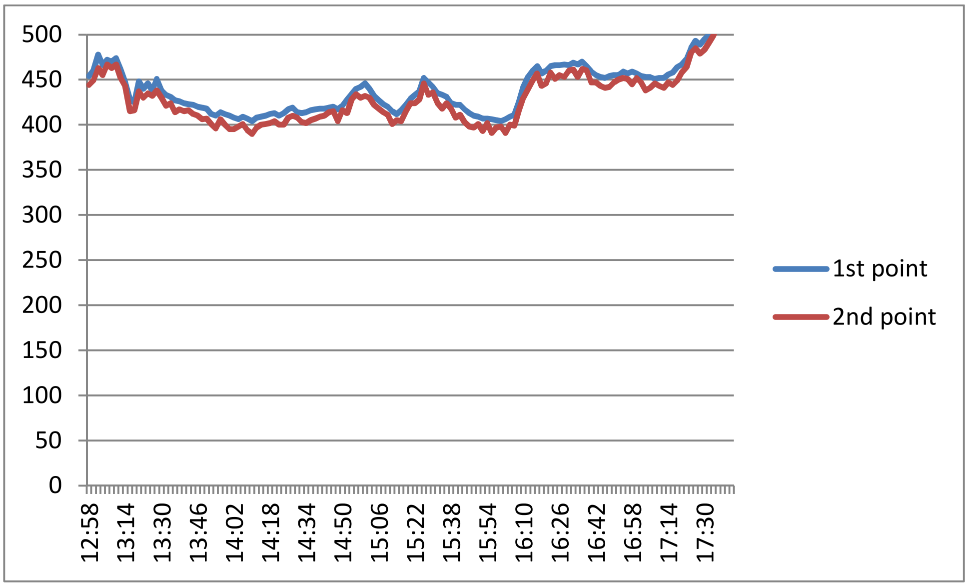

Figure 11. Measured values of carbon dioxide concentration in 232A in 1st and 2nd measuring points

In 232C was found the highest carbon dioxide concentration during the day. Here are the devices for heavy exercises and level of carbon dioxide exhales is high as well. Table 7 shows that 1st point is charecterized by maximum value of 1464 ppm, which is not acceptable according to Finnish National Building Code D2. It might be possible, that someone breathed toward the sensor, or ventilation in this zone delivered lower outdoor airflow, than necessary.

Table 7. Measurement results in 232C

Position of device	Carbon dioxide concentration, ppm			Temperature, °C		
	Max	Min	Average	Max	Min	Average
1	1464	697	1020	20,4	19	19,8
2	1015	490	785	20,2	19	19,6

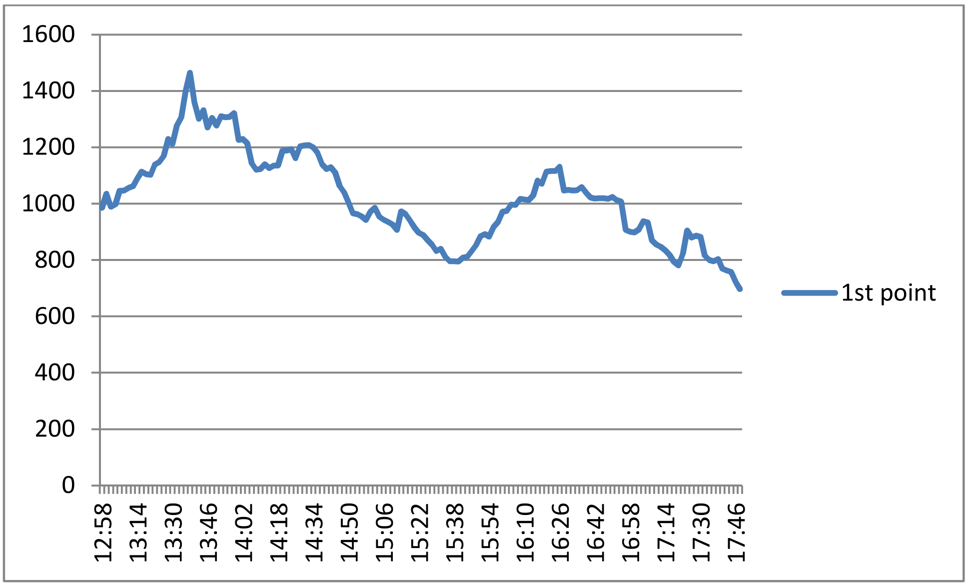

Figure 12. Measured values of carbon dioxide concentration in 232A in 1st measuring point

According to Tables 5, 6, 7 and Figures 10, 11 and 12, I made a conclusion that in 232A and 232B occupancy is very low and in weekly measurements there is no need. On the other hand there was very important to evaluate 232C more precisely and get accurate results, due to fluctuations in occupancy. Summing it up, I take 1st point in each room, like basic positions of carbon dioxide sensors in 2nd step measurements.

4.3 Results of 2st step measurements and calculations of average airflow rate in pre-designed DCV

Measured indoor carbon dioxide concentrations in 232A, 232B, 232C are shown in Appendix 2, 3 and 4 respectively in column 3. In the same appendixes there is outdoor carbon dioxide concentration in column 5, which equals minimum of indoor concentrations.

Supply constant airflow rates ($q_{v.cav}$) were got from table 4 (chapter 3.1). In the 212A $q_{v.cav1}$ = 792 m^3/h, in 232B $q_{v.cav2}$ =792 m^3/h, and in 232C $q_{v.cav3}$ = 612 m^3/h. With help of equation 11 I calculated carbon dioxide generation rate (M) in each room in certain time period (column 8). Then I determined $q_{v.req}$ (column 10), set points for minimum (column 11) and maximum air flow rates and applied airflow rate $q_{v.app}$ (column 12) for calculations of average air flow rate $q_{v.aver}$

$$q_{v.req} = \frac{M}{C_{max} - C_s} \tag{13}$$

C_{max} is the maximum allowed carbon dioxide concentration according to standards. In this case I take it from Finnish National Building Code D2 and it was equal to 1200ppm.

$$q_{v.max} = q_{v.cav} \tag{14}$$

Maximum outdoor airflow rate in pre-designed DCV assumed to equal outdoor airflow delivered by existing ventilation in sport facility of U-building.

$q_{v.max232A} = 792 m^3/h \ (220 l/s)$,
$q_{v.max232B} = 792 m^3/h \ (220 l/s)$,
$q_{v.max232C} = 612 m^3/h \ (170 l/s)$;

$$q_{v.min} = n \cdot A_{room} \cdot h_{room} \tag{15}$$

Minimum outdoor airflow rate in pre-designed DCV is required to achieve adequate indoor climate conditions in sport hall. I calculated it according to allowed minimum air change rate n=0,5 1/h.

$q_{v.min232A} = 0{,}5 \cdot 108{,}2 \cdot 3{,}5 = 189{,}4 m^3/h$,
$q_{v.min232B} = 0{,}5 \cdot 76 \cdot 3{,}5 = 133 m^3/h$,
$q_{v.min232C} = 0{,}5 \cdot 82{,}5 \cdot 3{,}5 = 144{,}4 m^3/h$;

$$q_{v.app} = \begin{cases} q_{v.min}, & q_{v.req} < q_{v.min} \\ q_{v.max}, & q_{v.req} > q_{v.cav} \end{cases} \tag{16}$$

To explain more precisely equation 16, three routes from appendix 4 were shown in Table 8 and explained in following paragraphs.

Table 8: Measurement results at 7:04, 10:22 and 13:36 am in 232A on 10 of October. /Appendix 4/

2	4	6	7	8	9	10	11	12
Time	C_r	C_s	$q_{v.cav}$	M	C_{max}	$q_{v.req}$	$q_{v.min}$	$q_{v.app}$
hh:mm	mg/m^3	mg/m^3	m^3/h	mg/h	mg/m^3	m^3/h	m^3/h	m^3/h
7:04	790,2	711,8	612	48026,7	2190	32,49	144,4	144,4
10:22	1037	711,8	612	260238	2190	176,1	144,4	176,1
13:36	2558	711,8	612	1130303	2190	764,6	144,4	612

C_r and C_s values were measured in 232A and converted in units of mg/m^3, $q_{v.cav}$ was taken from table 4, M was calculated with help of equation 11, C_{max} is the maximum allowed carbon dioxide concentration indoors, $q_{v.req}$ was calculated with help of equation 13 and $q_{v.min}$ according to equation 15. In the first line $q_{v.req}$ less than $q_{v.min}$, therefore $q_{v.app}$ equals $q_{v.min}$. In the third line $q_{v.req}$ bigger than $q_{v.cav}$, therefore $q_{v.max}$ was taken as $q_{v.app}$. In the second line is the most conventional situation, when $q_{v.req}$ located between $q_{v.min}$ and $q_{v.cav}$. In this case $q_{v.app}$ equals $q_{v.req}$.

$$q_{v.aver} = \frac{\sum_{i=1}^{n} q_{v.app}}{n} \quad (17)$$

where $\sum_{i=1}^{n} q_{v.app}$ is the sum of applied outdoor airflow rates in each time period during measurements and n is the quantity of samples on the measuring device.

From appendix 2, 3 and 4 were got following:

$$q_{v.aver232A} = 189{,}4\; m^3/h = 52{,}6\; l/s,$$
$$q_{v.aver232B} = 136{,}14\; m^3/h = 37{,}8\; l/s$$
$$q_{v.aver232C} = 245{,}12\; m^3/h = 68{,}1\; l/s$$

Then airflow rate in pre-designed DCV:

$$q_{v.dcv} = qv.aver232A + qv.aver232B + qv.aver232C \quad (18)$$

$$q_{v.dcv} = 52{,}6 + 37{,}8 + 68{,}1 = 158{,}5\ l/s$$

4.4 Operating costs of DCV in sport spaces

Annual energy needed for fan operation can be according to Equation 10, but power is changed according to found air flow in pre-designed DCV. It is possible, because fan in pre-designed DCV is provided by frequence inverter, which regulates fan speed and power as well. So, annual energy needed for fan operation:

$$W_{fan,dcv} = (P_{eh} + P_{sp}) \cdot \frac{q_{v.dcv}}{q_{v.cav}} \cdot t_d \cdot t_v \cdot \Delta t \tag{19}$$

$$W_{fan,dcv} = (1{,}1 + 0{,}2)\ kW \cdot \frac{158{,}5}{220 + 220 + 170} \cdot \frac{90\ h}{7 \cdot 24\ h} \cdot 8760\ h = 1585{,}2\ kWh$$

Annual energy for fan operation costs:

$$M_{fan,dcv} = W_{fan,dcv} \cdot C_{en} = 1585{,}2\ kWh \cdot \frac{0{,}1049\ euro}{kWh} = 166{,}3\ euro$$

Annual heat energy needed for achievement desired temperature condition in gym hall is calculated with help of equations 7, 8 and 9. Appendix 5 shows that sum of heat energy is $Q_{tot,v,dcv} = 13480 kWh$. Summing it up, annual heat energy costs:

$$M_{he,dcv} = Q_{tot,v} \cdot C_{he} = 13480\ kWh \cdot \frac{0{,}04638\ euro}{kWh} = 625{,}2\ euro$$

Total energy costs in case of pre-designed DCV:

$$M_{DCV} = M_{fan,dcv} + M_{he,dcv} = 166{,}3 + 625{,}2 = 791{,}5\ euro$$

4.5 Comparing results

From chapters 4.1 and 4.4 were got total energy costs of CAV and pre-designed DCV in sport facility of U-building. With help of these values annual savings of DCV were calculated:

$$s = \frac{M_{CAV} - M_{DCV}}{M_{CAV}} \tag{20}$$

$$s = \frac{3085{,}48 - 791{,}5}{3085{,}48} \cdot 100\% = 74\%$$

In this case was got 74% of savings. It means that annual energy costs are 74% lower with CO_2-based DCV than with CAV.

5. DISCUSSION

In this thesis I have shown that demand control ventilation offers better way to reduce energy consumption in comparison with common constant airflow systems in sport facilities. I described theoretical background of DCV, made measurements and determined efficiency of CO_2-based DCV in sport hall of U-building of Mikkeli University of Applied Sciences.

In my thesis I assumed steady-state conditions of carbon dioxide concentration in each period between taking samples. It helped me to define required airflow in pre-designed DCV. In addition, I described factors influenced on right position of carbon dioxide sensor, measuring methods and analyzed results.

I have calculated only operational performance of DCV and got 74% of savings. It means that when pre-designed DCV will be installed it will save 74% more money and energy as well. Annual energy need of DCV for heating is 13480 kWh. It is 4 times less than required for CAV (52727 kWh). The same situation is with energy need of DCV and CAV for fan operation: 1585,2 kWh against 6100,7 kWh. In case of money DCV will save 2294 euro each year.

It is a very high result and of course with high economy in energy we don’t reduce indoor climate: carbon dioxide, temperature level in acceptable values and required minimum air flow rate is provided.

Summing it up, I have to say, that implementing and using DCV in each place required very carefully made approach. Sensors must be installed in right positions.

BIBLIOGRAPHY

1. Stipe Marty. Demand-Controlled Ventilation: A Design Guide. Oregon Office of Energy. PDF document. http://www.oregon.gov/ENERGY/CONS/BUS/DCV/docs/DCVGuide.pdf?ga=t. Updated 06.2003. Referred 16.11.2011.

2. Maripuu Mari-Liis. Demand Controlled Ventilation (DCV) Systems in Commercial Buildings. Technical report D2009:01. Chalmers University of Technology. Department of Energy and Environment.Gothenburg, Sweden. 2009.

3. D2 National Building Code of Finland. Indoor Climate and Ventilation of Buildings Regulation and Guidelines 2003. Decree of the Ministry of the Environment on the Indoor Climate and Ventilation of Buildings.

4. ASHRAE Standard 62.1-2007. Ventilation for Acceptable Indoor Air Quality. American Society of Heating Refrigerating and Air-Conditioning Engineers.

5. Murphy John. CO_2-based Demand-Controlled Ventilation with ASHRAE Standard 62.1-2004. TRANE. Volume 34-5. p. 1-9. 2005.

6. Sand James. Demand-Controlled Ventilation Using CO_2 sensors. U.S. Department of Energy. PDF document. http://www1.eere.energy.gov/femp/pdfs/fta_co2.pdf. Updated 03.2004. Referred 16.11.2011.

7. Mike Schell and Dan Inthout. Demand Control Ventilation Using CO2. ASHRAE Journal. Volume 2-1. p. 1-5. 2001.

8. Nilson Per-Erik. Achieving the Desired Indoor Climate. Denmark. Studentlitteratur, Lund. 2003.

9. Emmerich Steven, Persily Andrew. State-of-the-Art Review of CO_2 Demand Controlled Ventilation. Technology and Application. United States of America. National Institute of Standards and Technology. PDF document. http://www.fire.nist.gov/bfrlpubs/build01/PDF/b01117.pdf. Updated 03.2001. Referred 16.11.2011.

10. FlactWoods Company. Supply Unit Veka Comfort. Technical Data. PDF document. http://www.omega-air.si/user_files/vsebina/doc/veka.pdf . Updated 05.2006. Referred 16.11.2011.

11. D5 National Building Code of Finland. Calculation of power and energy need for heating of buildings. Guidelines 2012. Decree of the Ministry of the Environment on the Calculation of Energy Consumption and Heating Energy Needs for Buildings. Draft 28 September 2010.

APPENDIX 1

i	T_{out}	l_i	Δt_i	T_{in}	Q_{iv}
	°C	%	h	°C	kWh
1	-35	0	0	18	0
2	-34	0,06	5	18	104
3	-33	0,08	2	18	41
4	-32	0,09	1	18	20
5	-31	0,17	7	18	138
6	-30	0,26	8	18	154
7	-29	0,38	10	18	188
8	-28	0,55	15	18	277
9	-27	0,75	18	18	325
10	-26	0,9	13	18	229
11	-25	1,21	27	18	466
12	-24	1,55	30	18	505
13	-23	1,98	37	18	608
14	-22	2,43	40	18	642
15	-21	2,91	42	18	657
16	-20	3,37	40	18	609
17	-19	3,98	54	18	801
18	-18	4,75	67	18	967
19	-17	5,73	86	18	1207
20	-16	6,96	108	18	1472
21	-15	7,74	68	18	900
22	-14	8,4	58	18	744
23	-13	9,06	58	18	721
24	-12	9,68	54	18	650
25	-11	10,45	67	18	779
26	-10	11,95	131	18	1471
27	-9	13,32	120	18	1299
28	-8	14,51	104	18	1084
29	-7	15,96	127	18	1273
30	-6	17,71	153	18	1472
31	-5	19,9	192	18	1771
32	-4	22,91	264	18	2329
33	-3	26,29	296	18	2492
34	-2	29,1	246	18	1973
35	-1	32,93	336	18	2560
36	0	38,18	460	18	3320

37	1	45,47	639	18	4356
38	2	50,21	415	18	2662
39	3	54,03	335	18	2015
40	4	56,95	256	18	1437
41	5	59,39	214	18	1115
42	6	62,07	235	18	1131
43	7	63,95	165	18	728
44	8	65,96	176	18	706
45	9	68,37	211	18	761
46	10	70,88	220	18	706
47	11	73,74	251	18	704
48	12	76,39	232	18	558
49	13	79,26	251	18	503
50	14	82,74	305	18	489
51	15	85,79	267	18	321
52	16	88,69	254	18	204
53	17	91,07	208	18	83
54	18	93,24	190	18	0
55	19	94,9	145	18	0
56	20	96,35	127	18	0
57	21	97,52	102	18	0
58	22	98,39	76	18	0
59	23	99	53	18	0
60	24	99,35	31	18	0
61	25	99,69	30	18	0
62	26	99,86	15	18	0
63	27	99,95	8	18	0
64	28	100	4	18	0
				$Q_{tot,v}$, kWh	52727

APPENDIX 2

1	2	3	4	5	6	7	8	9	10	11	12	13
Date	Time	C_r	C_r	C_s	C_s	$q_{v.cav}$,	M	C_{max}	$q_{v.req}$	$q_{v.min}$	$q_{v.app}$	$q_{v.over}$
	hh:mm	ppm	mg/m3	ppm	mg/m3	m^3/h	mg/h	mg/m3	m^3/h	m^3/h	m^3/h	m^3/h
232A												
09.10.2011	7:00	409	746,4	385	702,6	792	34689,6	2190	23,32	189	189,40	602,60
	7:02	415	757,4				43362		29,15		189,40	602,60
	7:04	407	742,8				31798,8		21,38		189,40	602,60
	7:06	402	733,7				24571,8		16,52		189,40	602,60
	7:08	402	733,7				24571,8		16,52		189,40	602,60
	7:10	411	750,1				37580,4		25,27		189,40	602,60
	7:12	400	730,0				21681		14,58		189,40	602,60
	7:14	413	753,7				40471,2		27,21		189,40	602,60
	7:16	408	744,6				33244,2		22,35		189,40	602,60
	7:18	409	746,4				34689,6		23,32		189,40	602,60
	7:20	406	741,0				30353,4		20,41		189,40	602,60
	7:22	413	753,7				40471,2		27,21		189,40	602,60
	7:24	415	757,4				43362		29,15		189,40	602,60

	7:26	420	766,5				50589		34,01		189,40	602,60
	7:28	421	768,3				52034,4		34,98		189,40	602,60
	7:30	409	746,4				34689,6		23,32		189,40	602,60
	7:32	416	759,2				44807,4		30,13		189,40	602,60
	7:34	418	762,9				47698,2		32,07		189,40	602,60
	7:36	423	772,0				54925,2		36,93		189,40	602,60
	7:38	415	757,4				43362		29,15		189,40	602,60
	7:40	421	768,3				52034,4		34,98		189,40	602,60
	7:42	420	766,5				50589		34,01		189,40	602,60

APPENDIX 3

1	2	3	4	5	6	7	8	9	10	11	12	13
Date	Time	C_r	C_r	C_s	C_s	$q_{v.cav}$	M	C_{max}	$q_{v.req}$	$q_{v.min}$	$q_{v.app}$	$q_{v.over}$
	hh:mm	ppm	mg/m3	ppm	mg/m^3	m^3/h	mg/h	mg/m3	m^3/h	m^3/h	m^3/h	m^3/h
232A												
3.10	7:00	419	764,7	390	711,8	792	41916,6	2190,0	28,36	133	133,00	659,00
	7:02	425	775,6				50589		34,22		133,00	659,00
	7:04	443	808,5				76606,2		51,82		133,00	659,00
	7:06	431	786,6				59261,4		40,09		133,00	659,00
	7:08	437	797,5				67933,8		45,96		133,00	659,00
	7:10	435	793,9				65043		44,00		133,00	659,00
	7:12	439	801,2				70824,6		47,91		133,00	659,00
	7:14	427	779,3				53479,8		36,18		133,00	659,00
	7:16	413	753,7				33244,2		22,49		133,00	659,00
	7:18	393	717,2				4336,2		2,93		133,00	659,00
	7:20	390	711,8				0		0,00		133,00	659,00
	7:22	413	753,7				33244,2		22,49		133,00	659,00
	7:24	405	739,1				21681		14,67		133,00	659,00
	7:26	411	750,1				30353,4		20,53		133,00	659,00
	7:28	403	735,5				18790,2		12,71		133,00	659,00
	7:30	416	759,2				37580,4		25,42		133,00	659,00

	7:32	403	735,5				18790,2		12,71		133,00	659,00
	7:34	398	726,4				11563,2		7,82		133,00	659,00
	7:36	396	722,7				8672,4		5,87		133,00	659,00
	7:38	392	715,4				2890,8		1,96		133,00	659,00
	7:40	391	713,6				1445,4		0,98		133,00	659,00
	7:42	395	720,9				7227		4,89		133,00	659,00
	7:44	399	728,2				13008,6		8,80		133,00	659,00
	7:46	400	730,0				14454		9,78		133,00	659,00
	7:48	400	730,0				14454		9,78		133,00	659,00
	7:50	399	728,2				13008,6		8,80		133,00	659,00
	7:52	398	726,4				11563,2		7,82		133,00	659,00
	7:54	392	715,4				2890,8		1,96		133,00	659,00
	7:56	390	711,8				0		0,00		133,00	659,00
	7:58	394	719,1				5781,6		3,91		133,00	659,00
	8:00	392	715,4				2890,8		1,96		133,00	659,00
	8:02	390	711,8				0		0,00		133,00	659,00
	8:04	408	744,6				26017,2		17,60		133,00	659,00

APPENDIX 4

1	2	3	4	5	6	7	8	9	10	11	12	13
Date	Time	C_r	C_r	C_s	C_s	$q_{v.cav}$,	M	C_{max}	$q_{v.req}$	$q_{v.min}$	$q_{v.app}$	$q_{v.over}$
	hh:mm	ppm	mg/m3	ppm	mg/m3	m^3/h	mg/h	mg/m3	m^3/h	m^3/h	m^3/h	m^3/h
232A												
10.10.2011	7:00	432	788,4	390	711,8	612	46909,8	2190,0	31,73	144,4	144,40	467,60
	7:02	439	801,2				54728,1		37,02		144,40	467,60
	7:04	433	790,2				48026,7		32,49		144,40	467,60
	7:06	432	788,4				46909,8		31,73		144,40	467,60
	7:08	442	806,7				58078,8		39,29		144,40	467,60
	7:10	446	814,0				62546,4		42,31		144,40	467,60
	7:12	449	819,4				65897,1		44,58		144,40	467,60
	7:14	448	817,6				64780,2		43,82		144,40	467,60
	7:16	447	815,8				63663,3		43,07		144,40	467,60
	7:18	447	815,8				63663,3		43,07		144,40	467,60
	7:20	433	790,2				48026,7		32,49		144,40	467,60
	7:22	427	779,3				41325,3		27,96		144,40	467,60
	7:24	427	779,3				41325,3		27,96		144,40	467,60
	7:26	423	772,0				36857,7		24,93		144,40	467,60
	7:28	421	768,3				34623,9		23,42		144,40	467,60
	7:30	424	773,8				37974,6		25,69		144,40	467,60
	7:32	422	770,2				35740,8		24,18		144,40	467,60
	7:34	432	788,4				46909,8		31,73		144,40	467,60

	7:36	430	784,8				44676		30,22		144,40	467,60
	7:38	424	773,8				37974,6		25,69		144,40	467,60
	7:40	437	797,5				52494,3		35,51		144,40	467,60
	7:42	437	797,5				52494,3		35,51		144,40	467,60
	7:44	429	782,9				43559,1		29,47		144,40	467,60
	7:46	429	782,9				43559,1		29,47		144,40	467,60
	7:48	422	770,2				35740,8		24,18		144,40	467,60
	7:50	421	768,3				34623,9		23,42		144,40	467,60
	7:52	419	764,7				32390,1		21,91		144,40	467,60
	7:54	422	770,2				35740,8		24,18		144,40	467,60
	7:56	430	784,8				44676		30,22		144,40	467,60
	7:58	419	764,7				32390,1		21,91		144,40	467,60
	8:00	416	759,2				29039,4		19,64		144,40	467,60
	8:02	411	750,1				23454,9		15,87		144,40	467,60
	8:04	406	741,0				17870,4		12,09		144,40	467,60
	8:06	401	731,8				12285,9		8,31		144,40	467,60
	8:08	407	742,8				18987,3		12,84		144,40	467,60
	8:10	404	737,3				15636,6		10,58		144,40	467,60
	8:12	405	739,1				16753,5		11,33		144,40	467,60
	8:14	404	737,3				15636,6		10,58		144,40	467,60
	8:16	402	733,7				13402,8		9,07		144,40	467,60
	8:18	410	748,3				22338		15,11		144,40	467,60
	8:20	425	775,6				39091,5		26,44		144,40	467,60
	8:22	417	761,0				30156,3		20,40		144,40	467,60
	8:24	414	755,6				26805,6		18,13		144,40	467,60

	8:26	423	772,0				36857,7		24,93		144,40	467,60
	8:28	497	907,0				119508		80,84		144,40	467,60
	8:30	504	919,8				127327		86,13		144,40	467,60
	8:32	498	908,9				120625		81,60		144,40	467,60
	8:34	497	907,0				119508		80,84		144,40	467,60
	8:36	507	925,3				130677		88,40		144,40	467,60
	8:38	511	932,6				135145		91,42		144,40	467,60
	8:40	514	938,1				138496		93,69		144,40	467,60
	8:42	513	936,2				137379		92,93		144,40	467,60
	8:44	512	934,4				136262		92,18		144,40	467,60
	8:46	512	934,4				136262		92,18		144,40	467,60
	8:48	498	908,9				120625		81,60		144,40	467,60
	8:50	492	897,9				113924		77,07		144,40	467,60
	8:52	492	897,9				113924		77,07		144,40	467,60
	8:54	488	890,6				109456		74,04		144,40	467,60
	8:56	486	887,0				107222		72,53		144,40	467,60
	8:58	489	892,4				110573		74,80		144,40	467,60
	9:00	487	888,8				108339		73,29		144,40	467,60
	9:02	497	907,0				119508		80,84		144,40	467,60
	9:04	495	903,4				117275		79,33		144,40	467,60
	9:06	489	892,4				110573		74,80		144,40	467,60
	9:08	502	916,2				125093		84,62		144,40	467,60
	9:10	502	916,2				125093		84,62		144,40	467,60
	9:12	494	901,6				116158		78,58		144,40	467,60
	9:14	494	901,6				116158		78,58		144,40	467,60

	9:16	487	888,8				108339		73,29		144,40	467,60
	9:18	486	887,0				107222		72,53		144,40	467,60
	9:20	484	883,3				104989		71,02		144,40	467,60
	9:22	487	888,8				108339		73,29		144,40	467,60
	9:24	495	903,4				117275		79,33		144,40	467,60
	9:26	484	883,3				104989		71,02		144,40	467,60
	9:28	481	877,8				101638		68,76		144,40	467,60
	9:30	476	868,7				96053,4		64,98		144,40	467,60
	9:32	471	859,6				90468,9		61,20		144,40	467,60
	9:34	466	850,5				84884,4		57,42		144,40	467,60
	9:36	472	861,4				91585,8		61,96		144,40	467,60
	9:38	469	855,9				88235,1		59,69		144,40	467,60
	9:40	470	857,8				89352		60,44		144,40	467,60
	9:42	469	855,9				88235,1		59,69		144,40	467,60
	9:44	467	852,3				86001,3		58,18		144,40	467,60
	9:46	475	866,9				94936,5		64,22		144,40	467,60
	9:48	490	894,3				111690		75,56		144,40	467,60
	9:50	570	1040,3				201042		136,00		144,40	467,60
	9:52	582	1062,2				214445		145,07		145,07	466,93
	9:54	581	1060,3				213328		144,31		144,40	467,60
	9:56	595	1085,9				228965		154,89		154,89	457,11
	9:58	604	1102,3				239017		161,69		161,69	450,31
	10:00	613	1118,7				249069		168,49		168,49	443,51
	10:02	590	1076,8				223380		151,11		151,11	460,89
	10:04	625	1140,6				262472		177,56		177,56	434,44

	10:06	600	1095,0				234549		158,67		158,67	453,33
	10:08	615	1122,4				251303		170,00		170,00	442,00
	10:10	627	1144,3				264705		179,07		179,07	432,93
	10:12	634	1157,1				272524		184,36		184,36	427,64
	10:14	618	1127,9				254653		172,27		172,27	439,73
	10:16	628	1146,1				265822		179,82		179,82	432,18
	10:18	650	1186,3				290394		196,44		196,44	415,56
	10:20	598	1091,4				232315		157,16		157,16	454,84
	10:22	623	1137,0				260238		176,04		176,04	435,96
	10:24	645	1177,1				284810		192,67		192,67	419,33
	10:26	638	1164,4				276991		187,38		187,38	424,62
	10:28	637	1162,5				275874		186,62		186,62	425,38
	10:30	638	1164,4				276991		187,38		187,38	424,62
	10:32	642	1171,7				281459		190,40		190,40	421,60
	10:34	650	1186,3				290394		196,44		196,44	415,56
	10:36	672	1226,4				314966		213,07		213,07	398,93
	10:38	683	1246,5				327252		221,38		221,38	390,62
	10:40	695	1268,4				340655		230,44		230,44	381,56
	10:42	699	1275,7				345122		233,47		233,47	378,53
	10:44	715	1304,9				362993		245,56		245,56	366,44
	10:46	737	1345,0				387564		262,18		262,18	349,82
	10:48	754	1376,1				406552		275,02		275,02	336,98
	10:50	732	1335,9				381980		258,40		258,40	353,60
	10:52	650	1186,3				290394		196,44		196,44	415,56
	10:54	718	1310,4				366343		247,82		247,82	364,18

	10:56	638	1164,4				276991		187,38		187,38	424,62
	10:58	610	1113,3				245718		166,22		166,22	445,78
	11:00	612	1116,9				247952		167,73		167,73	444,27
	11:02	595	1085,9				228965		154,89		154,89	457,11
	11:04	591	1078,6				224497		151,87		151,87	460,13
	11:06	583	1064,0				215562		145,82		145,82	466,18
	11:08	572	1043,9				203276		137,51		144,40	467,60
	11:10	562	1025,7				192107		129,96		144,40	467,60
	11:12	555	1012,9				184289		124,67		144,40	467,60
	11:14	560	1022,0				189873		128,44		144,40	467,60
	11:16	561	1023,8				190990		129,20		144,40	467,60
	11:18	557	1016,5				186522		126,18		144,40	467,60
	11:20	558	1018,4				187639		126,93		144,40	467,60
	11:22	554	1011,1				183172		123,91		144,40	467,60
	11:24	550	1003,8				178704		120,89		144,40	467,60
	11:26	559	1020,2				188756		127,69		144,40	467,60
	11:28	577	1053,0				208860		141,29		144,40	467,60
	11:30	598	1091,4				232315		157,16		157,16	454,84
	11:32	640	1168,0				279225		188,89		188,89	423,11
	11:34	652	1189,9				292628		197,96		197,96	414,04
	11:36	660	1204,5				301563		204,00		204,00	408,00
	11:38	692	1262,9				337304		228,18		228,18	383,82
	11:40	703	1283,0				349590		236,49		236,49	375,51
	11:42	698	1273,9				344005		232,71		232,71	379,29
	11:44	702	1281,2				348473		235,73		235,73	376,27

	11:46	739	1348,7				389798		263,69		263,69	348,31
	11:48	743	1356,0				394266		266,71		266,71	345,29
	11:50	743	1356,0				394266		266,71		266,71	345,29
	11:52	734	1339,6				384214		259,91		259,91	352,09
	11:54	719	1312,2				367460		248,58		248,58	363,42
	11:56	727	1326,8				376395		254,62		254,62	357,38
	11:58	729	1330,4				378629		256,13		256,13	355,87
	12:00	746	1361,5				397616		268,98		268,98	343,02
	12:02	738	1346,9				388681		262,93		262,93	349,07
	12:04	742	1354,2				393149		265,96		265,96	346,04
	12:06	754	1376,1				406552		275,02		275,02	336,98
	12:08	748	1365,1				399850		270,49		270,49	341,51
	12:10	745	1359,6				396500		268,22		268,22	343,78
	12:12	747	1363,3				398733		269,73		269,73	342,27
	12:14	731	1334,1				380863		257,64		257,64	354,36
	12:16	737	1345,0				387564		262,18		262,18	349,82
	12:18	739	1348,7				389798		263,69		263,69	348,31
	12:20	727	1326,8				376395		254,62		254,62	357,38
	12:22	706	1288,5				352940		238,76		238,76	373,24
	12:24	693	1264,7				338421		228,93		228,93	383,07
	12:26	682	1244,7				326135		220,62		220,62	391,38
	12:28	680	1241,0				323901		219,11		219,11	392,89
	12:30	696	1270,2				341771		231,20		231,20	380,80
	12:32	669	1220,9				311615		210,80		210,80	401,20
	12:34	667	1217,3				309381		209,29		209,29	402,71

	12:36	668	1219,1				310498		210,04		210,04	401,96
	12:38	691	1261,1				336187		227,42		227,42	384,58
	12:40	720	1314,0				368577		249,33		249,33	362,67
	12:42	760	1387,0				413253		279,56		279,56	332,44
	12:44	803	1465,5				461280		312,04		312,04	299,96
	12:46	821	1498,3				481384		325,64		325,64	286,36
	12:48	832	1518,4				493670		333,96		333,96	278,04
	12:50	831	1516,6				492553		333,20		333,20	278,80
	12:52	868	1584,1				533878		361,16		361,16	250,84
	12:54	847	1545,8				510423		345,29		345,29	266,71
	12:56	867	1582,3				532761		360,40		360,40	251,60
	12:58	985	1797,6				664556		449,56		449,56	162,44
	13:00	1035	1888,9				720401		487,33		487,33	124,67
	13:02	989	1804,9				669023		452,58		452,58	159,42
	13:04	998	1821,4				679075		459,38		459,38	152,62
	13:06	1045	1907,1				731570		494,89		494,89	117,11
	13:08	1046	1909,0				732686		495,64		495,64	116,36
	13:10	1056	1927,2				743855		503,20		503,20	108,80
	13:12	1061	1936,3				749440		506,98		506,98	105,02
	13:14	1088	1985,6				779596		527,38		527,38	84,62
	13:16	1114	2033,1				808636		547,02		547,02	64,98
	13:18	1104	2014,8				797467		539,47		539,47	72,53
	13:20	1102	2011,2				795233		537,96		537,96	74,04
	13:22	1139	2078,7				836558		565,91		565,91	46,09
	13:24	1148	2095,1				846610		572,71		572,71	39,29

	13:26	1169	2133,4				870065		588,58		588,58	23,42
	13:28	1229	2242,9				937079		633,91		612,00	0,00
	13:30	1211	2210,1				916975		620,31		612,00	0,00
	13:32	1277	2330,5				990690		670,18		612,00	0,00
	13:34	1306	2383,5				1023080		692,09		612,00	0,00
	13:36	1402	2558,7				1130303		764,62		612,00	0,00
	13:38	1464	2671,8				1199551		811,47		811,47	-199,47
	13:40	1359	2480,2				1082276		732,13		732,13	-120,13
	13:42	1301	2374,3				1017496		688,31		688,31	-76,31
	13:44	1332	2430,9				1052120		711,73		711,73	-99,73
	13:46	1270	2317,8				982872		664,89		664,89	-52,89
	13:48	1304	2379,8				1020847		690,58		690,58	-78,58
	13:50	1277	2330,5				990690		670,18		670,18	-58,18
	13:52	1310	2390,8				1027548		695,11		695,11	-83,11
	13:54	1306	2383,5				1023080		692,09		692,09	-80,09
	13:56	1308	2387,1				1025314		693,60		693,60	-81,60
	13:58	1321	2410,8				1039834		703,42		703,42	-91,42
	14:00	1226	2237,5				933728		631,64		631,64	-19,64
	14:02	1229	2242,9				937079		633,91		633,91	-21,91
	14:04	1215	2217,4				921443		623,33		623,33	-11,33
	14:06	1143	2086,0				841026		568,93		568,93	43,07
	14:08	1120	2044,0				815337		551,56		551,56	60,44

APPENDIX 5

i	T_{out} °C	l_i %	Δt_i h	T_{in} °C	Q_{iv} kWh
1	-35	0	0	18	0
2	-34	0,06	5	18	27
3	-33	0,08	2	18	10
4	-32	0,09	1	18	5
5	-31	0,17	7	18	35
6	-30	0,26	8	18	39
7	-29	0,38	10	18	48
8	-28	0,55	15	18	71
9	-27	0,75	18	18	83
10	-26	0,9	13	18	59
11	-25	1,21	27	18	119
12	-24	1,55	30	18	129
13	-23	1,98	37	18	155
14	-22	2,43	40	18	164
15	-21	2,91	42	18	168
16	-20	3,37	40	18	156
17	-19	3,98	54	18	205
18	-18	4,75	67	18	247
19	-17	5,73	86	18	309
20	-16	6,96	108	18	376
21	-15	7,74	68	18	230
22	-14	8,4	58	18	190
23	-13	9,06	58	18	184
24	-12	9,68	54	18	166
25	-11	10,45	67	18	199
26	-10	11,95	131	18	376
27	-9	13,32	120	18	332
28	-8	14,51	104	18	277
29	-7	15,96	127	18	325
30	-6	17,71	153	18	376
31	-5	19,9	192	18	453
32	-4	22,91	264	18	595
33	-3	26,29	296	18	637
34	-2	29,1	246	18	504
35	-1	32,93	336	18	654
36	0	38,18	460	18	849
37	1	45,47	639	18	1114
38	2	50,21	415	18	681
39	3	54,03	335	18	515

40	4	56,95	256	18	367
41	5	59,39	214	18	285
42	6	62,07	235	18	289
43	7	63,95	165	18	186
44	8	65,96	176	18	180
45	9	68,37	211	18	195
46	10	70,88	220	18	180
47	11	73,74	251	18	180
48	12	76,39	232	18	143
49	13	79,26	251	18	129
50	14	82,74	305	18	125
51	15	85,79	267	18	82
52	16	88,69	254	18	52
53	17	91,07	208	18	21
54	18	93,24	190	18	0
55	19	94,9	145	18	0
56	20	96,35	127	18	0
57	21	97,52	102	18	0
58	22	98,39	76	18	0
59	23	99	53	18	0
60	24	99,35	31	18	0
61	25	99,69	30	18	0
62	26	99,86	15	18	0
63	27	99,95	8	18	0
64	28	100	4	18	0
				$Q_{tot,v,dcv}$, kWh	13480