EXPERIENCES OF USING MODELS AND INFORMATION OF BUILDING AUTOMATION SYSTEM IN COMMISSIONING

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1. Summary

Simulation programs are widely used in the design of heating and cooling devices. However, modeling of the whole building with simulation programs is exceptional at least in Finland. We have built and utilized whole building models in a commissioning project to estimate the energy consumption and the indoor climate in an educational building. We have also used component models in the commissioning of a ventilation system.

One of our pilots was modeled very accurately using IDA-ICE /1/. Finnish engineering office Granlund LTD has modeled the same building with a simulation program called RIUSKA /2/, which is based on DOE-2. We present an analysis based on verification results of simulation to measured energy consumption, and the results of component models to the actual properties of HVAC system.

Keywords: whole building simulation, component models, air handling unit, measurements, energy, electricity

2. INTRODUCTION

2.1 The pilot

The building is situated in Jyväskylä, 350 km from the Finnish capital Helsinki. The building gives accommodation for the Department of Information Technology of Jyväskylä Polytechnic. The construction works was finished in May 2003 and the building was taken into actual use in August 2003. The educational building was build by the Educational Facilities of Jyväskylä and was partly funded by EU.

2.1.1. Use and size of building

The building consists mainly of classrooms. The building has also an assembly hall, a library, an auditorium, a lunchroom, a kitchen and two bomb shelters, which are situated in the first floor. The working rooms of teachers are situated in the fifth floor.

The floor area of Pilot is approximately 9500 m^2 and its exterior volume is 38600 m^3. Over 1000 students are studying and more than 40 teachers and other personnel are working in the building.

2.1.2. Principle of the HVAC-system

The classrooms and the working rooms have heating and cooling panels detached from the roof. Most of the panels are intended for cooling. Floor heating is used all over the first floor. The conventional radiators are not used for the heating.

The building is heated by district heating and cooled by electricity using two refrigeration compressors and one storage tanks. The ventilation system has heating and cooling coils and a rotating heat recovery system. AHU has also a system, which used the exterior air for free cooling.

The building is conditioned using a HVAC system with integrated heating, ventilation and cooling system. The heating and cooling liquid is transferred through a 3-pipe system. Two of the pipes are for liquid flowing to the zones and one pipe for the return water of the heating and the cooling. The cooling is needed all around the year because of heat gains given by personal computers. The Finnish climate is quite cold except the summer time. That is why it is reasonable to use the cold outdoor air when possible for cooling.

The cooling liquid returning from the cooling panels flows through a heat exchanger of air handling unit. There heat is transferred into liquid flowing through the AHU, which flows further through a water-to-air heat exchanger. As a result the temperature of the return liquid is decreased to 12-15 °C and the temperature of the supply air is increased by 0.5 °C in average. The return liquid as well as the heating and cooling liquid has to be controlled using several valves. They are opened or closed according to the heating or cooling need of the zones. The system visualized by Niagara of Vykon /3/ is presented in figure 1.

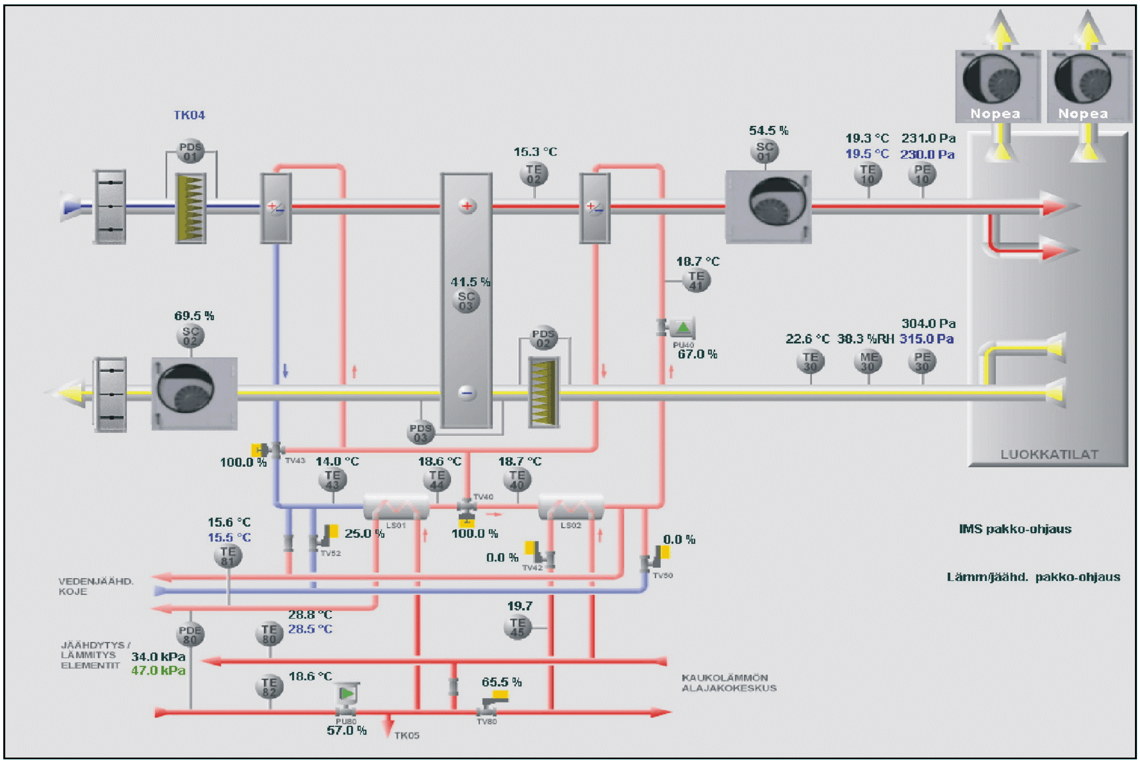


Figure 1. The principle of HVAC-system

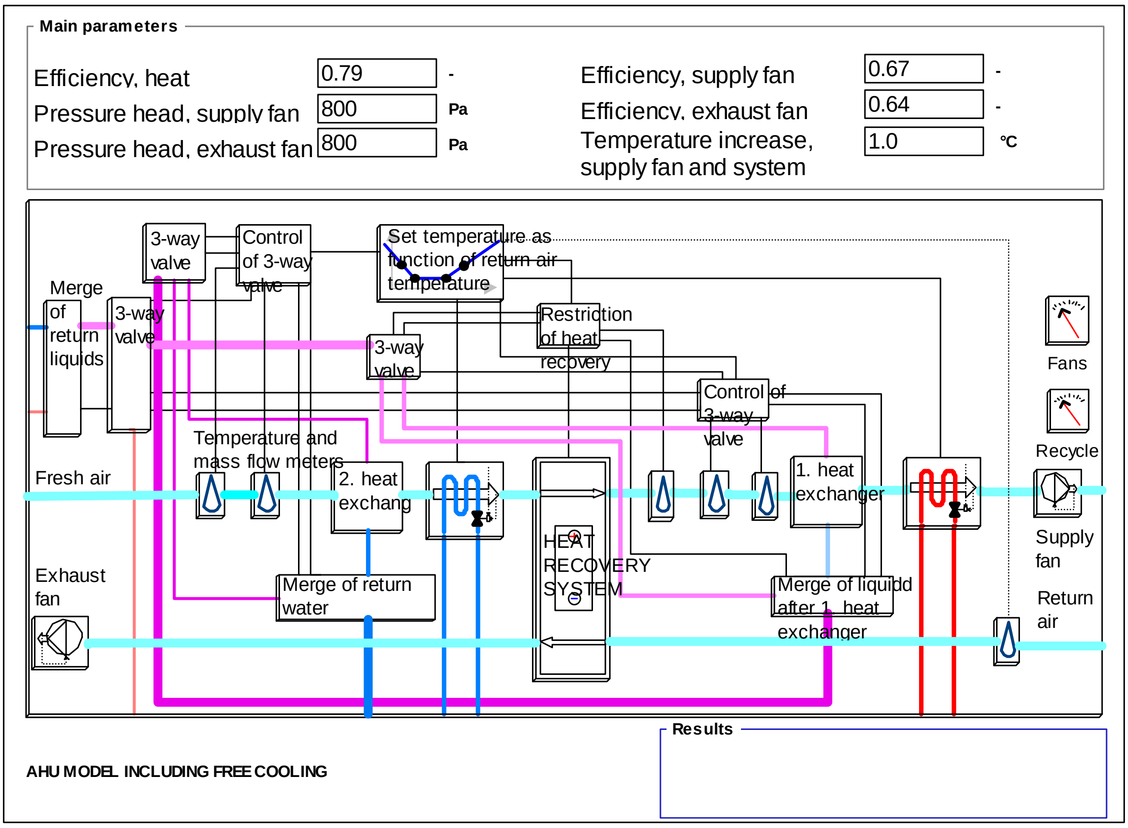


Figure 2. HVAC-system as it is modelled in IDA-ICE

The air valves control the supply and the exhaust airflow rates through the air terminals in the classrooms and in the working rooms. The airflow is controlled according to the carbon dioxide concentration and the temperature of the indoor air. The lower and upper limits of carbon dioxide concentration are 800 ppm and 1000 ppm respectively. Between these values the airflow rates change from the minimum to the maximum. Airflow changes also from its minimum to its maximum, when the indoor temperature increases from 23 to 24 °C. The temperature of the exhaust air usually determines the airflow rates of the supply air, when the lower limit of indoor temperature 23 °C is reached.

3. METHODS

3.1 Modeling the building and HVAC-system with simulation programs

The Finnish HVAC-engineering company Granlund LTD has simulated the energy consumption of the building. They have calculated the heat use and the electricity use for cooling, for pumps and for blowers concerning the second year of the building in use. They have used a simulation program called RIUSKA based on DOE-2. The special properties causing energy saving (11 %) in IT-Dynamo's HVAC system compared to the conventional HVAC system has not been taken into account in the RIUSKA-simulation. The results of both simulations calculated with IDA-ICE and RIUSKA are presented in chapter 4.1. A company called Enerkey LTD /4/ measures the heat and the electricity consumption as whole, and the measurements results are used in our analysis. In addition to the measurements some additional measurements were made for energy flows.

Figure 2 presents how the HVAC system is modeled in the simulation program IDA-ICE. It can be seen comparing figures 1 and 2 that one water-to-water heat exchanger is missing in the model. The cooling water returning from the panels is going directly through water-to-air heat exchanger in the model. In practice, the heat is first transferred to liquid circulating loop inside the AHU and then transferred to supply air, which is presented in Figure 1.

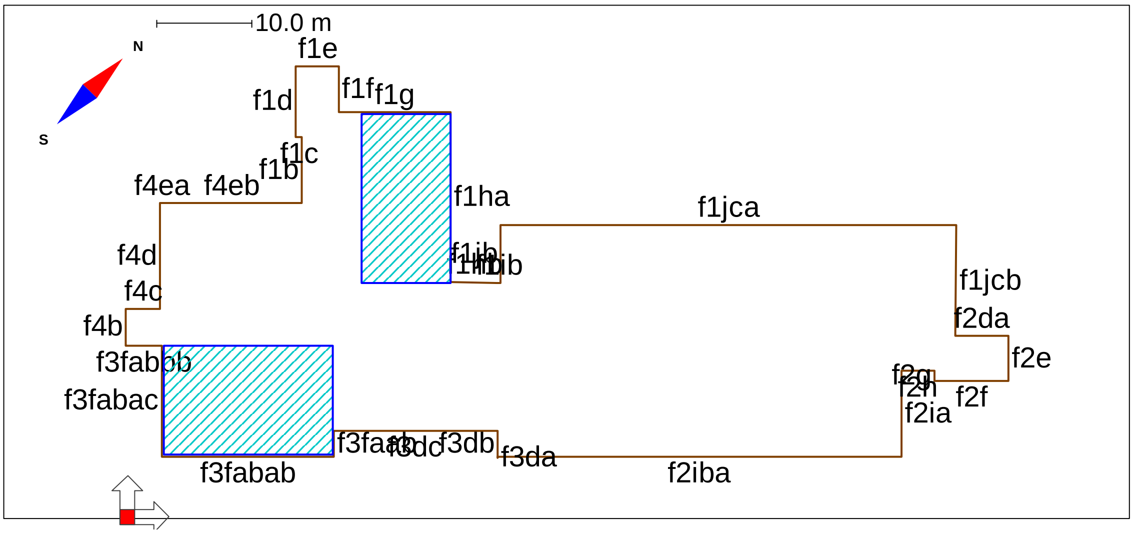


Figure 3. An example of the second floor connected to the AHU 2 of IDA-ICE model

Figure 3 presents a plan as an example of IDA-ICE model. Rooms are grouped to the zones. The zones are again grouped so, that the zones connected to certain air handling unit are in the same model. Six sub-models and about 30 zones are needed to model the whole building.

3.2 Component models

The ductworks system and a part of HVAC system and have been modeled using component models. The ventilation system has been modeled with a program called MagiCAD /11/. The heat flows of the HVAC system were modeled using heat balance model and Matlab 13. We have also made an EES-model of the HVAC system and it is explained in reference /11/.

3.2.1. MagiCAD-design tool

MagiCAD /5/ is an AutoCAD-based application that is created for designing and drawing of building systems. It is the most used application in the design of HVAC systems in Nordic countries. Beside flexible drawing abilities MagiCAD includes modules for calculation of the airflow rates and the pressure drops in the ductworks. The main advantage of MagiCAD is that it handles every piece and device of ductworks as an own “block” (an example in figure 4). These blocks include all features that a real device has, e.g. curves for pressure drop and sound generation. Wide ranges of different products; supply and exhaust air devices, flow dampers, silencers, are modeled and available as product databases at manufacturers web page. Also it is easy to build own component models. Self-made modeling is often needed for some sub-components of air handling units: filters, rotating regenerators, heating and cooling coils etc.

3.2.2. The use of MagiCAD design tool in the commissioning of duct systems

In the commissioning of duct systems it is essential to figure out what is the optimum performance of the ductworks and the air-handling units in actual use. Several types of problems may be found when duct systems are commissioned. Fans can be oversized in order to ensure the performance is sufficient in extreme conditions. The same kind of problem can occur if the variable rotation speed regulators are improperly used to adjust the operation. On the other hand ductworks can be even undersized in order to lower the construction costs. That kind of failures in the design and the adjustment of the duct systems are not unusual and can cause the pressure level of the ductworks to be unnecessarily high. It would be fruitful to examine whether there is potential to lower pressure level of the ductworks and energy consumption as well. It is also a need to examine the interaction between the fan and the ductworks.

This paper introduces how a CAD-based design tool with calculation modules is used in commissioning of duct systems. The main purpose is to clarify the possibility and potential to use this kind of tool in the commissioning. The case study comes from IT-Dynamo Building where one duct system has been taken under examination.

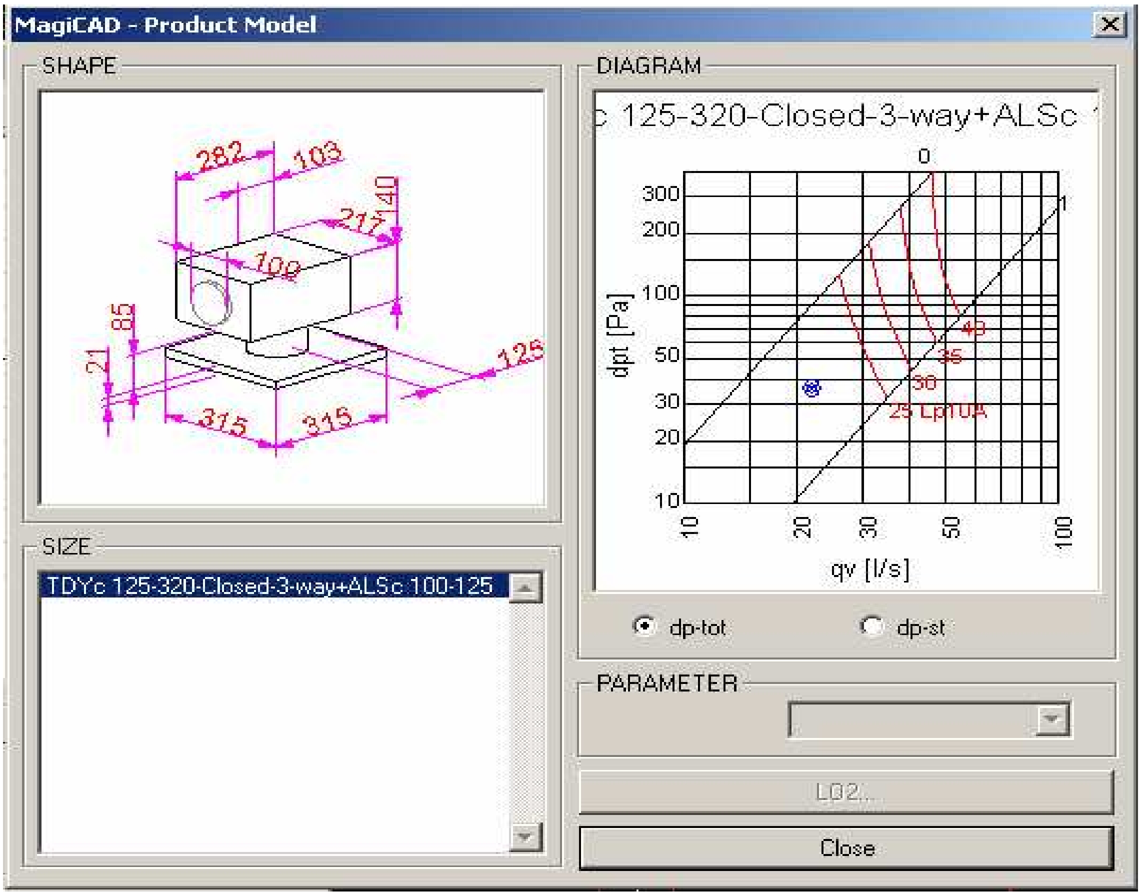


Figure 4. MagiCAD includes every unit of ductworks as an own block

The basic design procedure begins with choosing a terminal device and defining the air flow rate for it. When the ductworks or the branch is ready, the whole air flow rate can be calculated with the specified module. MagiCAD includes also modules for sizing and balancing of the ductworks. The sizing module chooses an optimum duct size by using some criteria, usually a sufficiently low air velocity and pressure drop. The balancing module calculates pressure drops in the ductworks and balances all branches to have the same pressure drop. This balancing procedure can be done to the different pressure levels, either to a minimum level or to a chosen fan pressure level

3.2.3. Model of HVAC-system

A part of HVAC system is modeled with Matlab 13 /6/. The heat balance model of the HVAC system is presented in figure 5. The system consists of ventilation ducts, liquid pipes, two water-to-air heat exchangers, two water-to-water heat exchangers, two 3-way valves, and a pump. The system is connected to the district heating and to the cooling system based on two compressors and the free cooling.

The main philosophy of the system is that the cold outdoor air is used for cooling of classrooms during late autumn, wintertime, and early spring, when it is possible. As side effect of that, supply air is warmed up and less heating energy is needed to heat up the incoming air.

The purpose of our model was to find out, what is the temperature difference over the heat recovery system of the supply air, how much the system uses district heat and how much it produces free cooling energy.

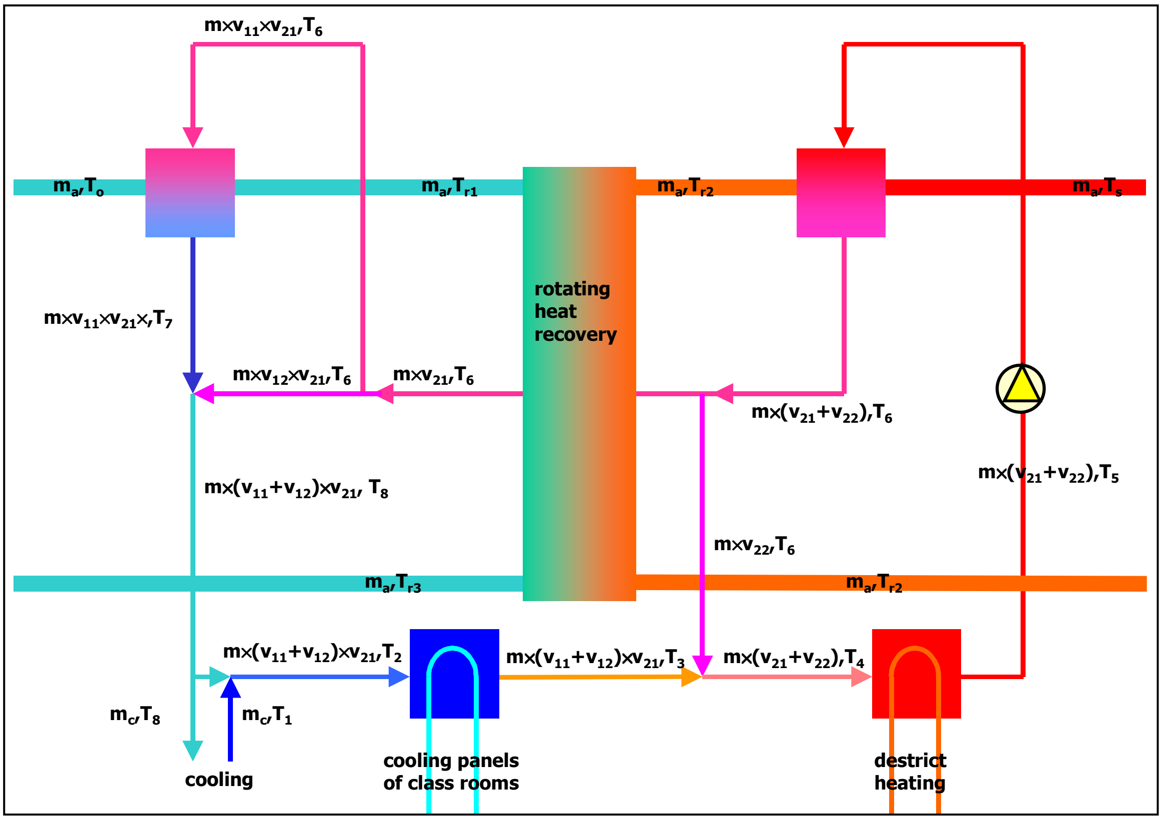


Figure 5. Heat balance model of HVAC system

Four temperatures and four relative mass flow rates through valves are known, but six temperatures are unknown, which can be calculated using the energy balance model. The most complicated problem has been to determine a correlation between the return signals of a valve and relative mass flow rates through two routes of the three-way valves (v_{11}, v_{12}, v_{21}, v_{22}).

Following formulas can be written concerning combined system of AHU and free cooling:

$(T_6 - T_7)\ \dot{m}\ v_1\ v_{21}\ c_{pw} - (T_{r1} - T_o)\ \dot{m}_a\ C_{pa} = 0$ (1)

$(T_5 - T_6)\ \dot{m}\ (v_{21} + v_{22})\ c_{pw} - (T_s - T_{r2})\ \dot{m}_a\ c_{pa} = 0$ (2)

$[T_3\ \dot{m}\ (v_{11} + v_{12})\ v_{21} + T_6\ \dot{m}\ v_{22} - T_4\ \dot{m}\ (v_{21} + v_{22})]\ c_{pw} = 0$ (3)

$[T_6\ \dot{m}\ v_{12}\ v_{21} + T_7\ \dot{m}\ v_{11}\ v_{21} - T_8\ \dot{m}\ (v_{11} + v_{12})\ v_{21}]\ c_{pw} = 0$ (4)

$T_1\ \dot{m}_c + T_8\ (\dot{m}\ (v_{11} + v_{12})\ v_{21} - \dot{m}_c) - T_2\ \dot{m}\ (v_{11} + v_{12})\ v_{21} = 0$ (5)

$(T_6 - T_7)\ \dot{m}\ v_{11}\ v_{21}\ c_{pw} + (T_8 - T_1)\ \dot{m}_c\ c_{pw} - (T_3 - T_2)\ \dot{m}\ (v_{11} + v_{12})\ v_{21}\ c_{pw} = 0$ (6)

where

c_{pw} specific heat capacity of water, J/(kg K);
c_{pa} specific heat capacity of air, J/(kg K);
T_o temperature of outdoor air, °C;
T_s temperature of supply air, °C;
T_{r1} temperature of supply air before heat recovery system, °C;
T_{r2} temperature of supply air after heat recovery system, °C;
T_{r3} temperature of exhaust air after heat recovery system, °C
T_{r3} temperature of exhaust air before heat recovery system, °C;
$T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8$ temperatures of liquids in the circulating loop, °C;
$\dot{m}$ mass flow rate of circulating liquid, kg/s;
$\dot{m}_c$ mass flow rate of cooling liquid, kg/s;
$\dot{m}_a$ mass flow rate of air, kg/s;
v_{11}, v_{12} relative flow rates of free cooling valve
v_{21}, v_{22} relative flow rates of heating and cooling valve

4. RESULTS

4.1 Results of energy consumption measurements vs. simulation results

Figure 6 presents the heat use and the whole electricity use as well as the electricity use of the HVAC system of the building calculated per volume and extrapolated for the whole year. The simulation results are calculated with IDA-ICE. The simulated heat use of RIUSKA (28 kWh/m^3/a) is the official target for the heat use of the second year and after that. The operation of the building will change significantly after first year. The actual heat use in the second year may decrease about 40 % compared to heat use in the first year. That is because the ventilation will be closed during weekends and nights after the first year.

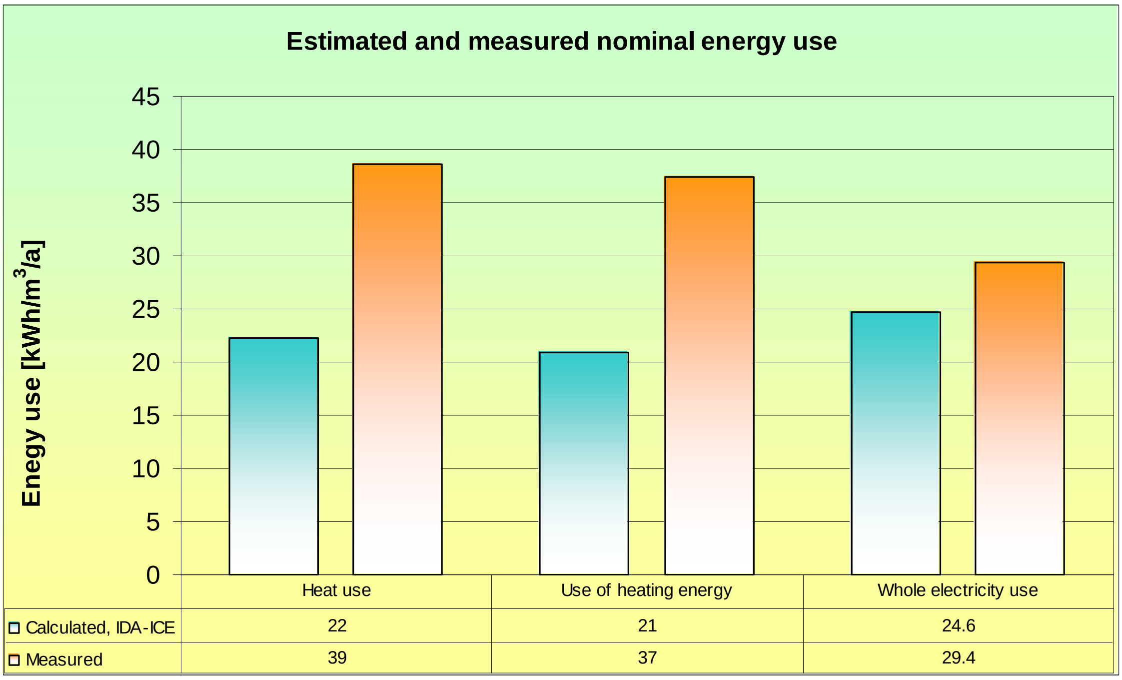


Figure 6. Heat and electricity use of IT-Dynamo building during the first year in operation

4.2 Heat use

The figure 7 presents the heat use (space heating and hot water heating) of the building in each month between 9/2003 – 5/2004. The measured heat use was about 30 % higher than the estimated heat use during the first three months. The difference reduced to 18 % in December, to 3 % in January, and the measured and the estimated heat use were almost equal in February. The difference increased again to 20 % in March and April, and to 40 % in May.

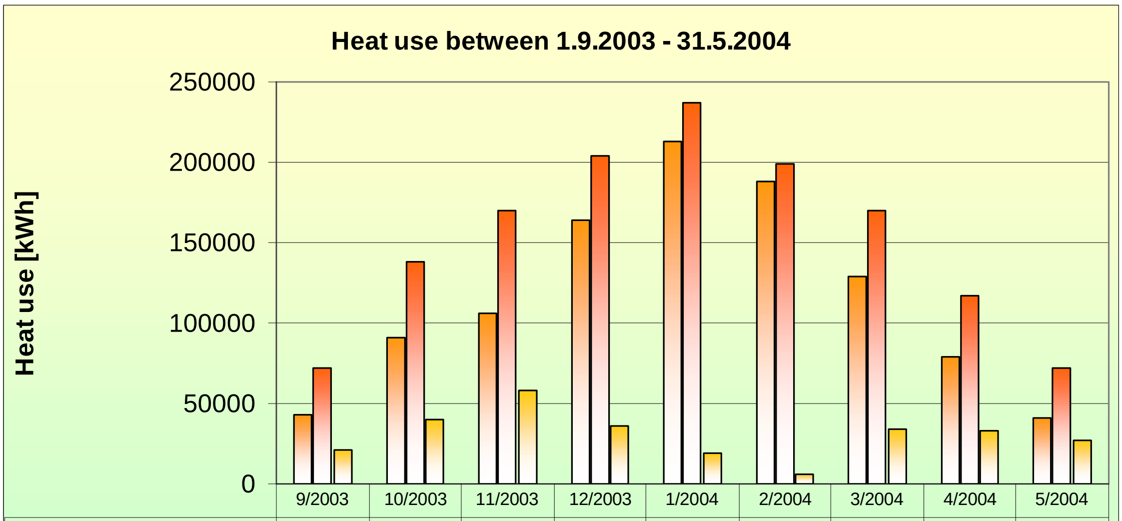
The control of indoor temperature was not working as supposed at the beginning in the working rooms. Either the heating or the cooling was at its maximum in all the working rooms all the time. The minimum and the maximum set point values of the indoor temperature were too near to each other, and the proportional band of the heating and cooling was too narrow. These two reasons led to rapid changes in the need of heating and cooling power. However, the working rooms take only one fifth of the floor area of the building.

The reason for the relatively high energy consumption was found out to be probably in the heat recovery system. The rotating heat recovery system did not perform as well as possible during relatively mild weather. The temperature of supply air was only about 15-16 ºC in average after heat recovery although it could have been about 16 ºC in February, 18 ºC in March and 20 ºC April. The same phenomenon could also be seen in temperature measurements of exhaust air, which were measured using separate measurements apart BAS. The temperature of exhaust air has been even 15 °C at the same time, when the heating of supply air is needed.

4.3 Electricity use

The electricity use has been as well greater than the estimated one during the first year. The difference between the estimated and the measured electricity use has been between 22 and 35 % during the first nine months as can be seen in Figure 8. About a half of the electricity was used by HVAC system. The users of the building have consumed the other half of the electricity using e.g. lighting and PCs. The electricity use of HVAC system was twice compared to the estimated use.

The electricity use is divided in electricity use of equipment and lighting, and electricity use of the heating, ventilation and cooling systems, which is presented in figure 9. This division is based on manually made electricity measurements. The electricity use of the personal computers and lighting of the classrooms and the working rooms as well as the electricity use of the kitchen was measured manually.



	9/2003	10/2003	11/2003	12/2003	1/2004	2/2004	3/2004	4/2004	5/2004
Estimated & corrected heat use	42978	91413	106196	163937	212836	187708	128865	78893	41313
Measured heat use	72000	138000	170000	204000	237000	199000	170000	117100	71800
Difference in heat use [kWh]	21171	40161	57930	35673	18581	6262	34243	32974	26678

Figure 7. Estimated and measured heat use of in each month during the first year

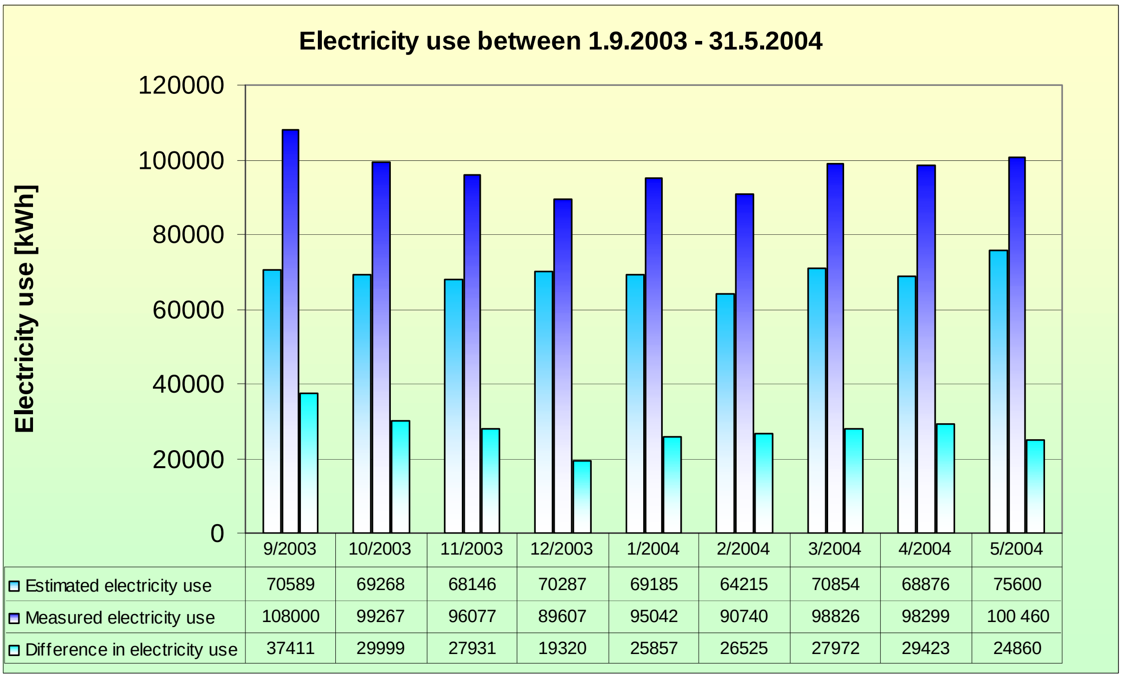


Figure 8. Estimated and measured electricity use of in each month during the first year

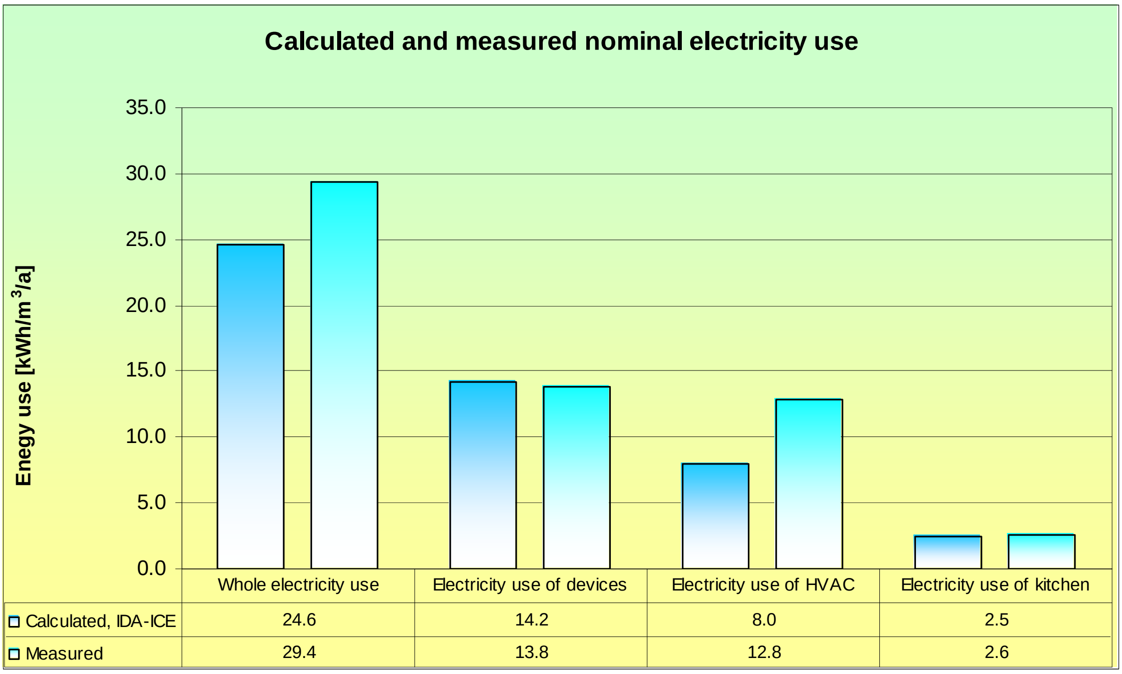


Figure 9. Estimated and measured electricity use by energy consumer

4.3.1. Electricity use of HVAC-system, lighting and devices

Figure 9 presents the estimated and measured whole electricity use, electricity use of lighting, PCs and as well as electricity use of HVAC system and the kitchen based on simulation results and the manual measurements made between 22.9.2003 – 31.5.2004.

As figure 9 shows the reason for high electricity use is probably in HVAC system. HVAC system has consumed electricity twice compared to the simulation results. The electricity consumption of the devices and the lighting has been taken into simulations from the measured consumption.

4.4 The indoor temperature measurements

The indoor temperature should be between 21 and 23 ºC to fulfill design criteria of Finnish indoor air quality classification S2 /12/ in wintertime. At the same time temperature should not differ more than ± 2 ºC from the set value. The duration graph of indoor temperature was calculated for all classrooms where the data was available. The results are presented in figure 10 and 11.

The indoor temperature has been in design limits in all the working rooms all the time (lines with an asterisk in figure 10 and 11). On the other hand the indoor temperature of the classrooms (lines with a circle) has been over 23 ºC in several classrooms. The indoor air temperature has been between 23 and 24 °C in room 321 almost all the time. However, the air temperature has not been over 24 ºC in any room.

The figure 11 presents the temperature difference between indoor temperature and its set value. The difference has been less than the allowed 2 ºC almost all the time.

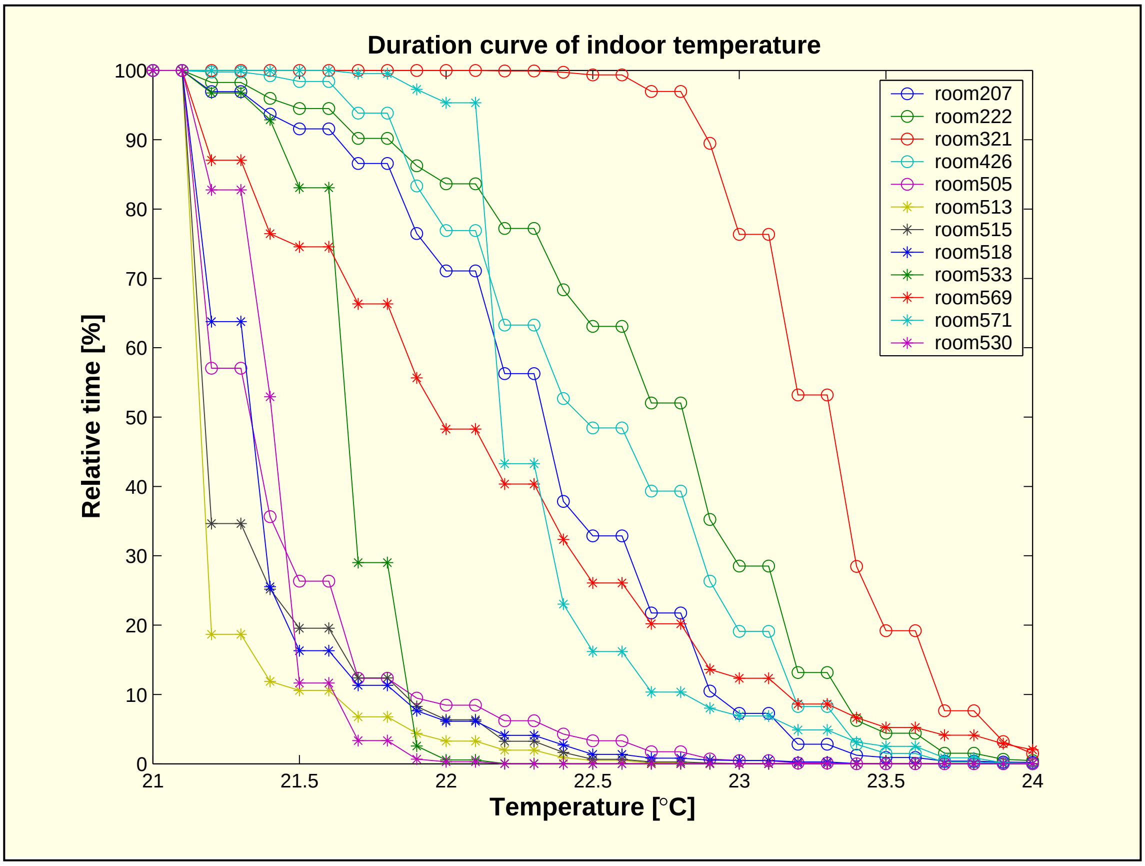


Figure 10. The indoor temperature in the classrooms (o) and in the working rooms (*) between 1.2. – 12.5.2004

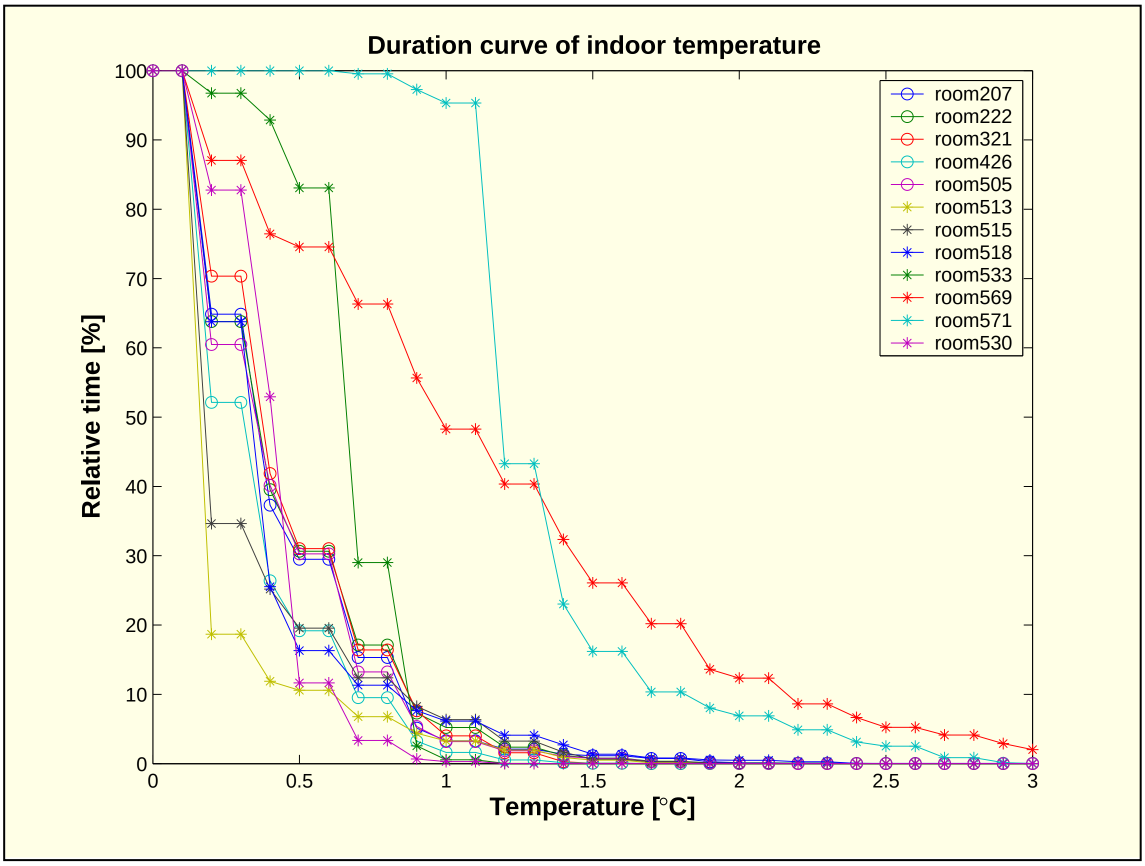


Figure 11. The difference between the indoor and the set temperatures between 1.2.2004- 12.5.2004

4.5 Results of modelling of the ductworks

The model of the ductworks is explained in chapter 3.2.1. The ventilation of IT-Dynamo building is executed with 6 air handling units. Three of these units (units 2, 4 and 5) are connected to ductworks with variable air volume devices. Units include axial fans with variable rotation speed regulation. This MagiCAD aided commissioning procedure was aimed to the air-handling unit 4 because there had been made several measurements for this unit and the necessary information for comparisons was available.

Modeling of the ductworks was accomplished by using as built information, in this case design drawings from the designer. The drawings were made with software, which was incompatible with MagiCAD and therefore the whole ductworks had to be re-drawn. Some of the terminal devices were not available in the product databases and had to be modeled using manufacturers data.

The characteristics of the air handling unit were defined on the basis of information provided by the manufacturer. Filters, the rotating regenerator and the heating and the cooling coils were modeled using this technical data. In MagiCAD it is not possible to directly include a fan in the duct system model as a functional unit. That is why interaction between ductworks and the fan can not (yet) be examined using MagiCAD. Performance data of fans in varying conditions (fan curves) was easily gained using the software provided by the blower manufacturer

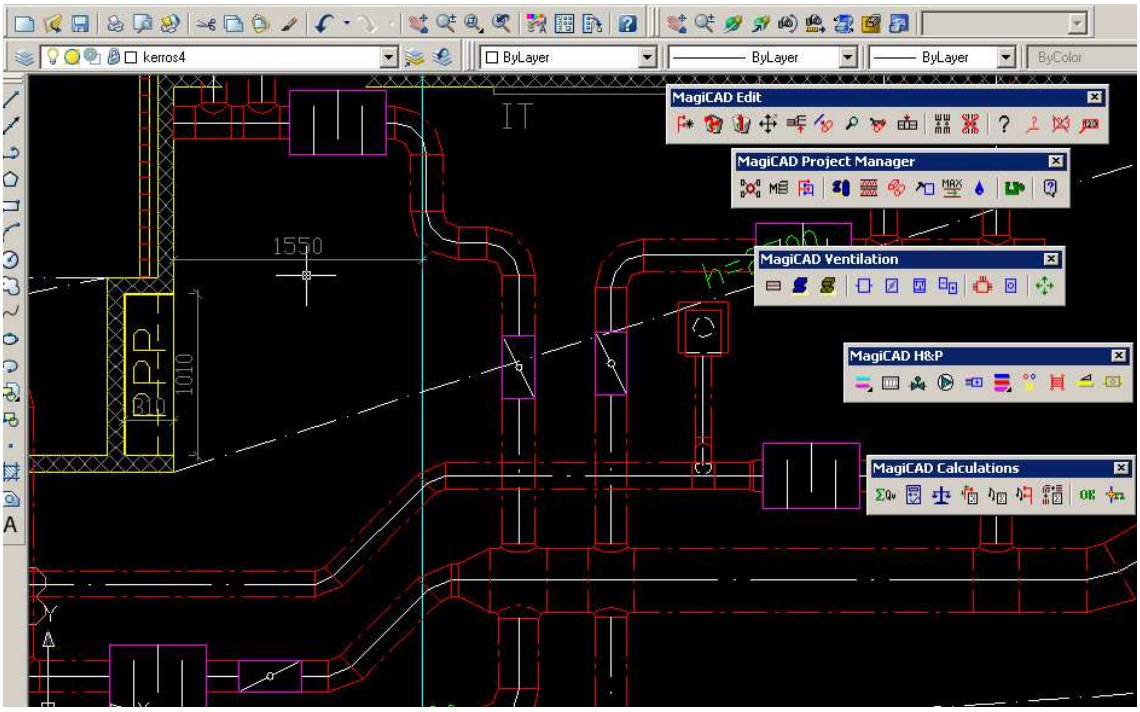


Figure 12. Model of the ductworks

Testing was made examining the performance of the duct system in the design conditions and during a normal usage. In the first case the AHU was regulated to produce its design air flow rates and performance data (rotation speed, flow rates, pressure rise over fan) was collected. In the second case performance data during normal operation was collected from the building automation system. The measurements of BAS were chamber pressure (static pressure after fan), the rotation speed and the air flow rates to the rooms. In both cases the ductworks were modeled as built and the pressure drop of the ductworks was calculated with MagiCAD.

In both cases it was possible to compare the calculated values with measured ones. It turned out that the actual pressure level in the ductworks was only slightly higher than the calculated optimum (minimum) value. So the supply / exhaust devices and flow dampers seem to be adjusted well.

The pressure drop curves for ductworks were defined in first case (design conditions) both by measuring the total pressure rise over the fans and calculating with MagiCAD. Values were so close to each other in the design conditions that the model simulated the real operation very realistically. In the second case there was available only the measured value of the chamber pressure, which was again very close to calculated one. The total pressure drop in the ductworks (pressure rise over fans) was calculated with MagiCAD.

Figures 13 and 14 describe the performance of the exhaust fan and the supply fan respectively. Figures show the operation of the duct system in two different conditions. Dashed upper line shows approximately the border of unstable area. The other increasing lines are the pressure drop curves in both design points. They are different to each other, because the pressures drop of the duct system changes, when terminal units are adjusted. Bold increasing lines describe fan curves with different rotation speeds. As mentioned earlier, the fan curves were defined with the manufacturer’s software (Novenco).

The circles show operation points of the minimum and maximum air flow rates. The maximum airflow rates are on the right and the minimum airflow rates on the left side in the both figures.

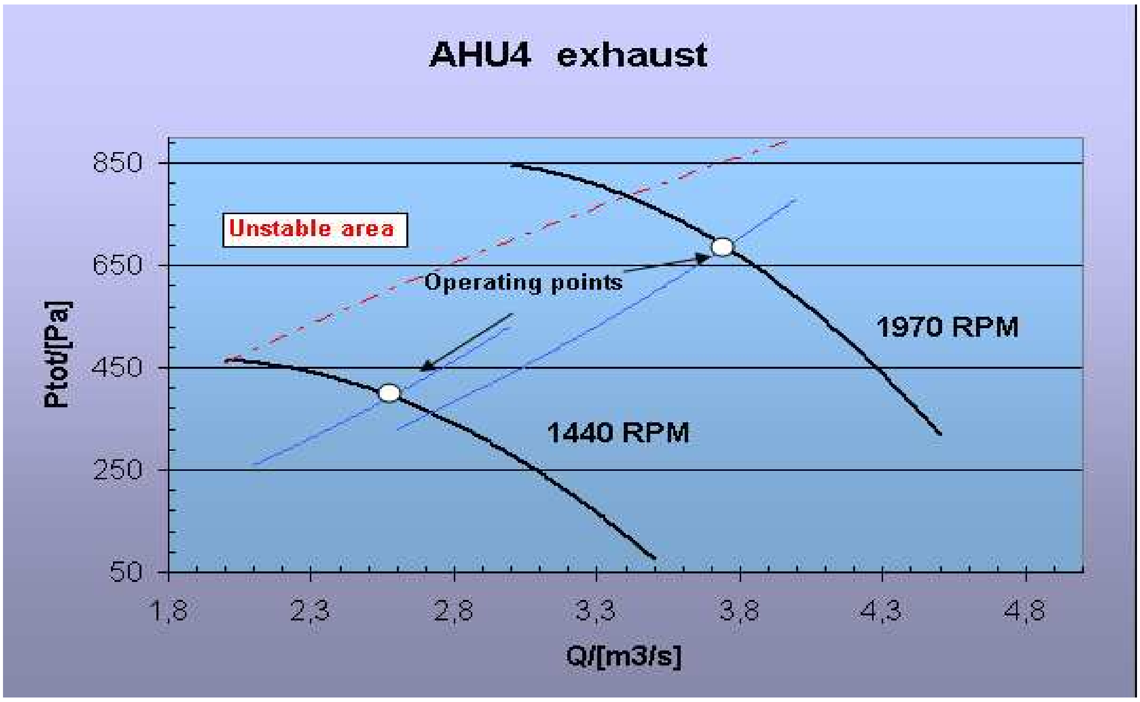


Figure 13. Performance of exhaust fan in design and actual conditions

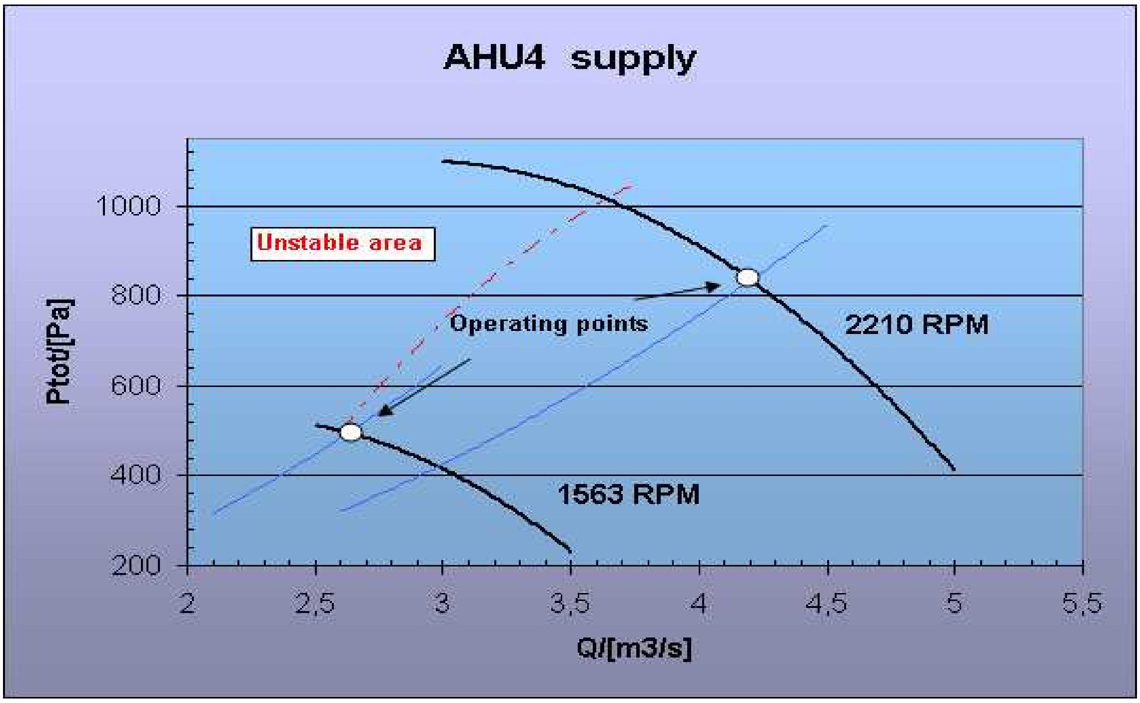


Figure 14. Performance of supply fan in design and actual conditions

It can be seen that the exhaust fan operates well inside its operation area. However, supply fan seems to operate dangerously close to the border of the unstable area. The rotation speed regulator seems to decrease the rotation speed of the fan too much. It is recommended to raise the minimum frequency border in the regulator. Otherwise it is possible that fan crawls to the unstable area.

It was also a great interest to examine whether the duct sizes were large enough and so that the unnecessary pressure drop caused by too small ducts would not take place in the ductworks. The duct system was re-sized using MagiCAD to see if changes were needed. The sizing criteria were for the air a maximum velocity 6 m/s at pressure drop 1 Pa/m. It turned out that the ducts were rather oversized than too small. MagiCAD suggested smaller ducts than designed to several places. However, re-sizing did not have an impact to total pressure drop in ductworks.

The purpose of this paper was to demonstrate the use of design tools in the commissioning. It is clear that with this kind of tool it is possible to create the most detailed model of duct system. If a designer has this kind of efficient tool available, he is able to simulate wide range of different conditions very realistically. The case study is an example of situation in which this simulation procedure had not been performed. One of the main advantages of a well-visualized CAD-based tool is the excellent easiness of usage. The re-drawing of the very detailed duct system took no more than a couple of days. A shortage of MagiCAD is the lack of possibility to examine the interaction between the ductworks and the fan.

However, several manufacturers (e.g. Novenco) provide illustrative software to examine operation of their fans. All the information, which these manufacturer's programs need, is the airflow rates and the system pressures. These values can be gained e.g. with MagiCAD tool. Still it can be mentioned that MagiCAD has environment and basis to be able to build e.g. fans and other features. It is in principle no need to use another calculation programs to figure out the interaction between the ductworks and the fan.

The results of this demonstrative commissioning of AHU 4 in the Pilot Building were following:

- The pressure level in the duct system is very close to optimum
- The devices and dampers operate in competent way
- Sizing of the duct system is also appropriate
- The exhaust fan and its settings are well adjusted
- Rotation speed regulator of the supply fan reduces rotation speed too low when the air flow rate decreases and the operation points are too close to unstable area at the minimum air flow rates
- It is possible that the operation of the supply fan changes to unstable area if the airflow rate decreases more
- Also e.g. disturbance in the meters or in the control system may cause same effect

4.6 Results of modeling ventilation and free cooling system

The heat balance model of the AHU 4 is explained in chapter 3.2.3. The heat use and the free cooling energy produced by an AHU can be calculated using the heat balance model. Accuracy is much higher in the calculation of heat use compared to the calculation of the free cooling energy. That is because the heat use depends only a little on the properties of valves and its control principles is easy to understand. On the other hand control of the free cooling system is complicated and its energy balance is totally dependent on properties of valves. We do not fully know control of them yet.

Results of the model are presented in tables 1 and 2. According to the heat balance model the heat use of ventilation system has been 30% less than the simulated heat use in February. However, the actual heat use has been 1.7 times than the estimated heat use in March, and three times more in April. The same has continued even in May but the difference has not been calculated. This gives more evidence to the hypothesis that the rotating heat recovery system does not work as designed.

The correlation between feedback signals of electronic actuators was determined using information of the valves, temperature measurements of liquids (Figure 15) and simulation results.

Table 1 shows that temperature of exhaust air T_{r3} has been relatively high and temperature of supply air after recovery T_{r2} had been relatively low according to the model. This leads to low efficiencies of heat recovery system compared to the design efficiency 0,79 in March and April.

The difference of the heat use calculated with simulation model compared to heat use calculated with the heat balance model is about 6 MWh in March and about 8 MWh in April (see Table 2). The additional capacity of heat recovery system seems to be even more, when actual efficiency and design efficiency are compared: 8 MWh in March and 10 MWh in April. A part of the difference may be because of the idealized properties and parameters in the models.

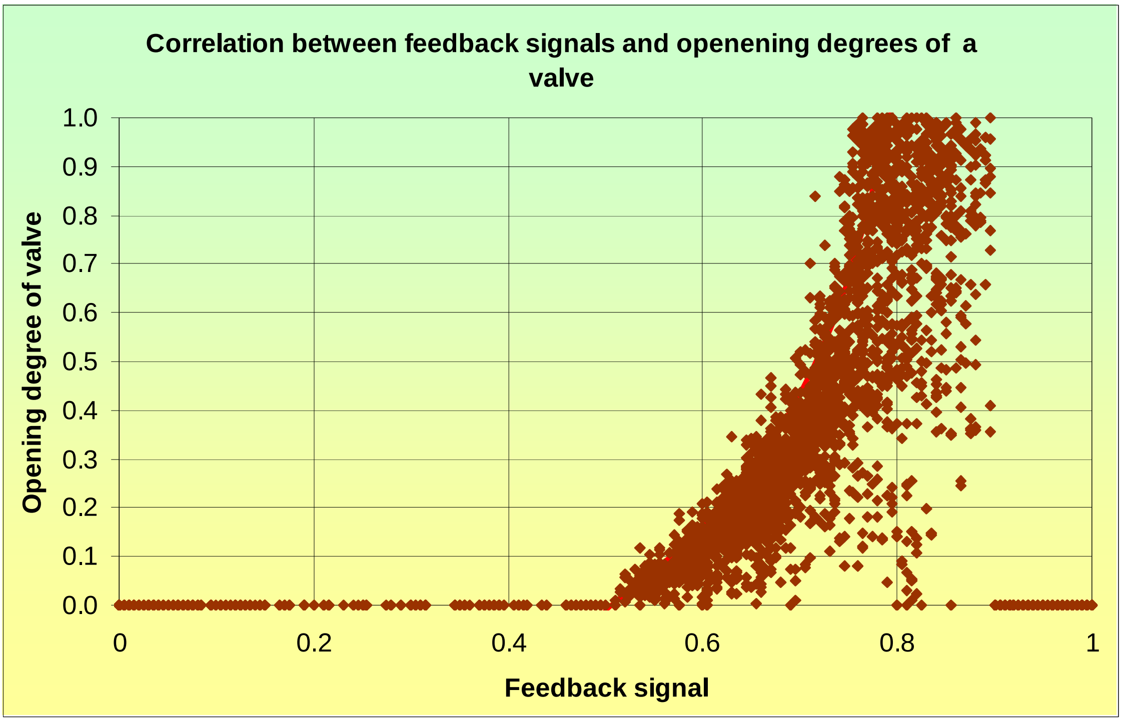


Figure 15. Determination of valve properties

If all the AHUs have performed at the same manner, the most part of the difference between the simulated and the measured heat use, 34 MWh in March and 32 MWh in April, can be explained by the problems in the heat recovery systems.

As conclusion, the heat recovery system could perform in more efficient way than it has performed in last winter.

Table 1. Temperatures in ventilation system and efficiency of heat recovery based on the model (symbols are presented in Figure 5)

	Supply air			Exhaust air			Efficiency
Month/ year	**Temperature before heat recovery**	**Temperature after heat recovery**	**Temperature of supply air**	**Temperature after heat recovery**	**Temperature before heat recovery**	**Temperature of outdoor air**	**of heat recovery**
	T_{r1}	T_{r2}	T_s	T_{r3}	T_{r4}	T_o	η
2/2004	-5.5	14.9	21.1	2.4	22.4	-5.8	0.71
3/2004	-0.9	14.8	20.2	7.3	22.4	-1.8	0.62
4/2004	5.9	16.8	19.9	12.0	22.2	4.3	0.57

Table 2. The results of simulation and measurements based component model concerning heating and cooling energy

Month/ year	**Heat use of ventilation**			**Free cooling energy**			**Cooling energy**		
	Simulated	**Model**	**Diff.**	**Simulated**	**Model**	**Diff.**	**Simulated**	**Model**	**Diff.**
2/2004	19650	14979	-4671	631	639	8	64	1228	1164
3/2004	8585	14282	5697	1776	1955	179	336	842	506
4/2004	3652	11298	7646	2768	4640	1872	774	1192	417
Sum	31887	40559	8672	5175	7234	2058	1174	3261	2087

5. DISCUSSION

Both whole building simulation and component models were used in commissioning of an advanced educational building. It was found out, that use of the models is an efficient way to evaluate if building is working as designed. This can be done comparing the actual use and the results given by the models. However, the modeling of the buildings and the calculations take plenty of time and need special skills.

The pilot of an educational building is modeled concerning commissioning using both purely computational simulation and component models and the measurement based component model. The whole building is modeled with two simulation models, which have given almost equal results. One of the models has been calibrated using the measured electricity use and the information of the ventilation rates and the user profiles. The calculated and the measured electricity consumption and the heat use differ much from each other. The reason for that has been tried to find out using the simulation model, the component models, and measured data from the building automation system.

Simulation is a fruitful way to estimate whole energy consumption of the building. It gives the heat and the electricity use divided in the heat use of the ventilation and the space heating and the cooling energy need for cooling of the spaces and the supply air. It also gives an estimation of the indoor temperature, CO2-content and the moisture content. These simulated values can be compared to the measured values whenever it is available.

The component models give more detailed information of the special systems. Programs like MagiCad, EES, and Matlab can be used to evaluate the design principles, especially the sizing and the adjusting of the systems. Also the producers of the blowers and the pumps have special programs, which are useful in the commissioning. They can help to estimate if the component is working in an allowed operation range or if it is oversized or undersized concerning the actual use of the building.

We have plenty of appropriate programs for simulations and for modeling the systems, the components and the sub-components. They should be used more widely in the commissioning in future.

NOMENCLATURE

c_{pw} specific heat capacity of water, J/(kg K);
c_{pa} specific heat capacity of air, J/(kg K);
T_o temperature of outdoor air, °C;
T_s temperature of supply air, °C;

T_{r1} temperature of supply air before heat recovery system, °C;
T_{r2} temperature of supply air after heat recovery system, °C;
T_{r3} temperature of exhaust air after heat recovery system, °C
T_{r3} temperature of exhaust air before heat recovery system, °C;
T_1, T_2, T_3, T_4, T_5, T_6, T_7, T_8 temperatures of liquids in the circulating loop, °C;
$\dot{m}$ mass flow rate of circulating liquid, kg/s;
$\dot{m}_c$ mass flow rate of cooling liquid, kg/s;
$\dot{m}_a$ mass flow rate of air, kg/s;
v_{11}, v_{12} relative flow rates of free cooling valve
v_{21}, v_{22} relative flow rates of heating and cooling valve

Greek symbols

η temperature efficiency of heat recovery system

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