Hybrid ventilation in new and refurbished school buildings – the future of ventilation

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ABSTRACT

More than 64 million pupils spend more time in school than in any other place except home in Europe (European Commission, 2014). The indoor air quality is often a challenge in existing school buildings and the lack of proper ventilation often leads to negative effects like increased absenteeism and sick building syndrome symptoms as well as lowered performance amongst students compared to new buildings.

For this study a comparison of automated Natural Ventilation (NV), balanced Mechanical Ventilation (MV) with heat recovery and Hybrid Ventilation (HV) with heat recovery has been made by means of detailed modelling applied to an existing school building using the simulation program IESVE. The energy demand for heating and ventilating the building using the three different ventilation methods was calculated for three key European cities; Munich, Copenhagen and London. Control strategies were set to achieve the same indoor climate for all three ventilation systems, and the indoor climate targets were set according to European Standard EN 15251 (EN15251, 2007).

The results show that the energy performance of the MV and NV systems are nearly the same in terms of primary energy, while demonstrating that HV enables energy savings of 44-52%.

Total costs of the different systems including capital expenditure (products and installation), operation (electricity and heating) and maintenance over the first year and a 20 year life cycle were calculated. This showed that in the first year MV was 2.5 to 4 times more expensive than NV. By selecting HV and taking advantage of NV reducing the load on the mechanical ventilation, 25% of the cost could be saved compared to a pure MV system, and this was similar over a 20 year life cycle.

KEYWORDS

Hybrid ventilation; natural ventilation; mechanical ventilation; ventilation in schools; Indoor Air Quality (IAQ).

1 INTRODUCTION

Studies have shown that the combination of automatic NV and MV offers a promising opportunity to achieve significant energy savings in buildings while maintaining a comfortable indoor climate. HV might, as such, be a key technology to enable designers to fulfil ever stricter energy requirements while at the same time providing the user with a healthy and comfortable indoor climate.

The Reshyvent project (Reshyvent, 2004) investigated HV in residential buildings, while the Hybvent project (Heiselberg, 2006) studied the application for non-residential buildings. Several case studies investigated in the international project IEA ECBCS-Annex 35 (Heiselberg, 2006) show that significant energy savings can be achieved in hybrid ventilated buildings, especially through reduction in fan and cooling energy demand. The case studies for school buildings show that the HV system saves 17-55 % in a year compared to a mechanical system alone. Examples also include Cron (Cron, 2003) who investigated classrooms and found the best results for HV (fan assisted stack ventilation) were in the warmer regions, saving up to 42% energy consumption compared to MV without heat recovery. Comparing HV with MV with heat recovery the results were only better in the warmest regions where there was no requirement for heat recovery. Emmerich (Emmerich, 2004) compared NV, MV and HV and found for HV that heating demand is reduced most in cold regions, and maximum reductions in fan electricity are realised in warm regions compared to purely NV and MV. Sowa (Sowa, 2007) found a reduction of about 60 % for heating demand and about 40 % for fan electricity in a HV simulation for a real school. Heikkinen et al. (Heikkinen, 2002) who investigated ventilation concepts for a school in Finland, found only a limited potential reduction in heating demand, but also a reduction of 70 % in fan electricity.

Thus, the literature contains several findings and in general, HV is demonstrated to result in significant energy savings. This study investigates whether this conclusion is also valid in schools, using state-of-the-art MV and NV systems and a school building fulfilling the performance requirements (in Denmark). This requires very low U-values for the building elements and a requirement for the total primary energy frame in kWh/m^2 per year of 41 + 1000/A (A is the gross floor area). The total primary energy use in the energy frame consists of heating, ventilation, cooling, hot water and lighting. In order to give a true comparison between the energy performances of the systems, nearly identical indoor air quality and thermal climates in the buildings have been established. The simulations are carried out for three large European cities with different climates; Copenhagen, London and Munich. The study also calculates the expected CO_2 emissions and the economical costs from selecting the different systems.

2 SCHOOL BUILDING GEOMETRY, PROPERIES AND LOCATION

2.1 Building layout

The one storey school building consists of eight classrooms, four on each side of the corridor and is oriented north/south. The floor to ceiling height varies from 2.8 to 4.5m no matter of ventilation principle and the floor area of one classroom is 76m^2, which gives a total volume of 278m^3. The building geometry can be seen in Figure 1.

Figure 1: Layout of the school building.

2.2 Construction properties

The main construction properties attached to the models are listed in Table 1.

Table 1: Constrution properties

Building element	U-Value [W/m^2K]
Ground Slab	0.08
Exterior Walls	0.12
Roof	0.08
Windows	0.9-1.1

Glass ratio of the outer façade is 45 % and the g-value is 0.63 and light transmittance is 0.74. Only the windows which aren't used for natural ventilation have an external sun screening with a shading coefficient of 0.2.

2.3 Internal heat loads

There are 28 students and one teacher in each classroom, resulting in an occupancy density about 2.6 m^2/person. The occupancy during lessons are 95 % from Monday to Friday from 8 am to 2:50 pm. Vacation time is 12 weeks per year in total (week 7, 14, 20, 26 - 31, 42 and 51 - 52). The occupancy during vacation is set to 10 % from 8:00 am to 2:50 pm from Monday to Friday, as summer courses or maintenance might occur. There is no occupancy during weekends.

Each person has a heat load of 75 W sensible heat and 50 W latent heat corresponding to an adult with an activity level of 1.2 met. This assumes a heat emission of 70 W/m^2 skin surface and a skin surface of 1.8 m^2. Children with a lower body mass normally also have a higher level of activity of about 1.4 met (81 W/m^2skin surface). Assuming a skin surface of 1.5 m^2 per child, the heat emission for all persons is quite the same.

Each student and teacher is expected to have a computer, which is switched on 50 % of the time during occupancy. As it is expected that the use of computers will increase in the future.

The lighting (fluorescent lighting) shall provide a luminance intensity of 300 lux at the desk and has a maximum heat load of 15 W/m^2, which corresponds to an effective lighting system (a luminous efficacy of 20 lumens per watt).

2.4 Outdoor climatic conditions

The locations chosen for the comparison are Copenhagen, Munich and London. These three cities are typical European cities with different climates and therefore different possible opportunities for HV. Copenhagen has a cold winter and a cool summer, whereas Munich has a colder winter and a warm summer. London, located near the sea, has a maritime climate with a mild winter and a cool summer.

3 REQUIREMENTS FOR INDOOR AIR QUALITY AND THERMAL COMFORT

Several studies have shown that many of the existing schools have a poor indoor climate with CO_2 levels sometimes exceeding 2-4,000 ppm (Byg DTU, 2009). These levels are clearly adversely affecting the learning ability of the school children (Mendel, 2005. Wargocki, 2007. Wargocki, 2007) - and must be improved. However, general adoption of the current Category II requirements in EN 15251 with a maximum CO_2 concentration of 900ppm seems unrealistic in schools for two key reasons: Firstly, the air exchange rate for a 60 m^2 classroom with a room height of 2.8m and 29 persons needs to be at least 6-7 air change per hour. This can create problems with air speeds in the comfort zone in the majority of existing schools. Secondly, it is also noted that the financial abilities of the public authorities in most countries does not support such strict requirements. In fact, they could prove to be a barrier against improving the indoor climate in existing schools simply because the systems become too expensive.

The classification of the thermal comfort and indoor air quality in the buildings are based on EN 15251. Category III is deemed an acceptable level of expectation and a target of 1200ppm is applied for the assessment of indoor climate.

4 DIMENSIONING OF VENTILATION SYSTEMS

To maintain the air quality according to Category III of EN 15251 (EN 15251, 2007) the necessary air flow rate was calculated by the air flow rates per m^2 given in the standard for persons in a classroom and low emissions from the building. This results in a flow rate of 2.4 l/sm^2 and a total air flow rate of 180 l/s, 648 m^3/h. The total flow rate for all 8 classrooms is 1,440 l/s or 5,148 m^3/h. For maintaining temperature, different air change rates were tested in the simulation. Due to these results a maximum air exchange of 4.6 per hour was chosen for summer and night ventilation. This is a flow rate of 360 l/s or 1,296 m^3/h for one classroom and 2,880 l/s or 10,368 m^3/h for all eight classrooms.

4.1 Natural ventilation

For the NV every second high level window on both sides of the room can be opened with motors to realize cross ventilation. The resulting openable window area for the automated windows is 4.1 m^2 representing 5.4 % of the room area.

A temperature difference of 1 K and 5 K between inside and outside results in almost 4 and 9-fold air exchange respectively. A wind speed of 0.5 m/s and 1 m/s results in a 5 and 10-fold air exchange rates respectively - calculated according to the British Standard Method (Allard, 1998). Outdoor conditions with 0.5 m/s wind speed and a temperature difference above 1 K should be available most of the time throughout the year for all three locations and would also be sufficient for delivering adequate ventilation to maintain temperatures in summer.

4.2 Mechanical ventilation

For the MV in the school building, four smaller decentralized units are utilized. The system was dimensioned for the maximum air flow rate according to air quality and indoor temperature (10,368 m^3/h). The specifications of the four units have been selected from those products currently available in the market place, resulting in a total flow rate of 15,680 m^3/h.

The pressure loss for the supply and the exhaust ductwork of the system is only 80 Pa for the supply system and 80 Pa for the exhaust system. The filter classes were F7 for supply air and F5 for exhaust air causing an additional pressure of 40 Pa due to dirt. The Specific Fan Power (SFP) value for each of the four units is 993 J/m³ - which is probably among the best currently available in the market. No additional heating or cooling units were utilised. As the 'Demand Controlled Ventilation operates with a constant pressure loss in the main ductwork, the setting for the external pressure was held constant.

The heat recovery system is a state-of-the-art counter-flow plate heat exchanger with low-energy de-icing function, and the sensible heat effectiveness in the simulation was set to 92 %, which is the temperature efficiency including the effects of the motor heat at 1800 m³/h, 75 % of the design flow rate.

4.3 Hybrid ventilation

For the HV two decentralized units are utilised and dimensioned for the air flow rate only according to air quality (5,148 m³/h). To maintain indoor temperature in summer NV is utilized with a flow rate of 10,368 m³/h. Hence the mechanical element of the system can be of significantly lower capacity than that used for pure MV.

The pressure loss in the MV element of the system for the supply and the exhaust ductwork is then about 132 Pa for the supply system and 143 Pa for the exhaust system. Pressure loss from filters, sensible heat effectiveness and heating/cooling unit is the same as the MV. SFP value for each of the two units is 1135 J/m³.

5 CALCULATION METHOD

The energy demand and the indoor climate of the building were simulated in the widely recognised simulation program VE-Pro (version 6.4.0.7, Integrated Environmental Solutions Limited, Glasgow, UK). This program has a special function for calculating more complex HVAC systems (ApacheHVAC) and also a very reliable calculation tool for NV (MacroFlo), which is able to calculate NV and effects from wind turbulence on air exchange, considering special features like the aspect ratio and sash type of the opening. The calculation was done in 1 minute steps to achieve realistic results for natural and especially natural pulse ventilation. The results are derived from 6 minute averages of the calculation. This is mainly due to the pulse ventilation when using natural ventilation, which has to be controlled very precisely in order to avoid over cooling of the room during cold periods.

For the assessment of indoor climate, CO_2 levels inside the building were used as an indicator for indoor air quality, and operative room temperature was used as an indicator for thermal comfort. The values were obtained during occupancy in one representative room, and the requirements for thermal comfort and indoor air quality were based on EN 15251 (EN 15251, 2007).

6 CONTROL STRATEGIES

The operational parameters of the control strategy for the simulation models were input to reflect as closely as possible WindowMaster's control strategy. Sometimes changes were necessary due to the restrictions of the simulation software or to obtain a similar thermal comfort and indoor quality.

6.1 Natural ventilation

NV is defined as automated NV through high level windows on both sides of the rooms utilizing cross ventilation. The windows are opened and closed by a specific amount with small MotorLink™ chain drive actuators. The opening distance is defined by a controller, which uses indoor and outdoor climatic parameters to calculate the appropriate opening distance. This precise opening is necessary, because the resulting air flow rate is not only dependent on the climatic conditions, but also very much on the opening distance of the windows. A precise control of air flow is necessary to avoid too high ventilation rates, which cause additional heat loss or poor thermal comfort due to low temperatures or high draughts, while still providing good air quality at the same time.

Three different opening strategies were implemented; continuous ventilation with a varying opening degree, pulse ventilation with the maximum opening degree calculated due to weather for a short time, and night ventilation. The first strategy is utilized for control of air quality during the whole year and indoor temperature in summer. The second strategy is only for additional control of indoor air quality during winter and transient times, where the opening distance for continuous ventilation needs to be restricted for comfort reasons. The third strategy is utilized for additional cooling of the rooms in summer. In addition, the windows are opened to maximum after occupancy to purge ventilate the rooms completely with fresh air until outdoor air quality is reached.

6.2 Mechanical ventilation

The flow volume of the MV is defined by the need to achieve the required improvement of indoor air quality and reduction of overheating. Therefore, the maximum flow volume is utilized when either the carbon dioxide level or the indoor air temperature rises above a certain point. Furthermore, night ventilation is only active during the warmer periods

6.3 Hybrid ventilation

The HV control strategy is a combination of the natural and mechanical control strategies. The main strategy is to use the best aspects of both systems in order to reach the best possible values for energy consumption and indoor climate quality.

During winter season, only MV is activated as the heat recovery of the system helps save energy to heating. NV has best results during summer where good indoor air quality and temperatures can easily be reached. In addition, the motors of the windows need much less electricity than the fans for MV and the flow rate can be raised by simply increasing the window openings a little more without using further energy. This is also the benefit from NV during night time for ‘free cooling‘.

During the transient season, it mainly depends on internal conditions as to whether MV or NV is the best solution. Therefore, the system automatically chooses between NV or MV depending on indoor temperature as an indicator of demand for heating or possible cooling.

6.4 Heating, shading and lighting

The heating is activated from October to May. The heating is set to avoid too low temperatures in accordance to Category III during occupancy (8 am - 2:50 pm). During hours with no occupants in the building the set-point is 18°C.

The operation of automated external blinds is according to outdoor and indoor parameters. This is done to avoid overheating, which may affect indoor temperature and thermal comfort for up to a few days later. The blind rises with a wind velocity above 12 m/s and/or an outdoor temperature below minus 6°C to avoid damage to the blinds. The blind lowers with a solar radiation above 100 W/m² and if the indoor temperature is above 23.5°C.

The dimming of artificial light is controlled due to occupancy and to maintain 300 lux in the rooms.

7 RESULTS

7.1 Temperature and CO_2

The results of thermal comfort and indoor air quality were evaluated for one south facing classroom, as negligible differences were found between a north and south facing classroom. Figure 2 shows the percentage of occupied time where indoor temperature achieved the different performance categories according to EN 15251 (EN 15251, 2007). This is displayed for all three ventilation types in each location.

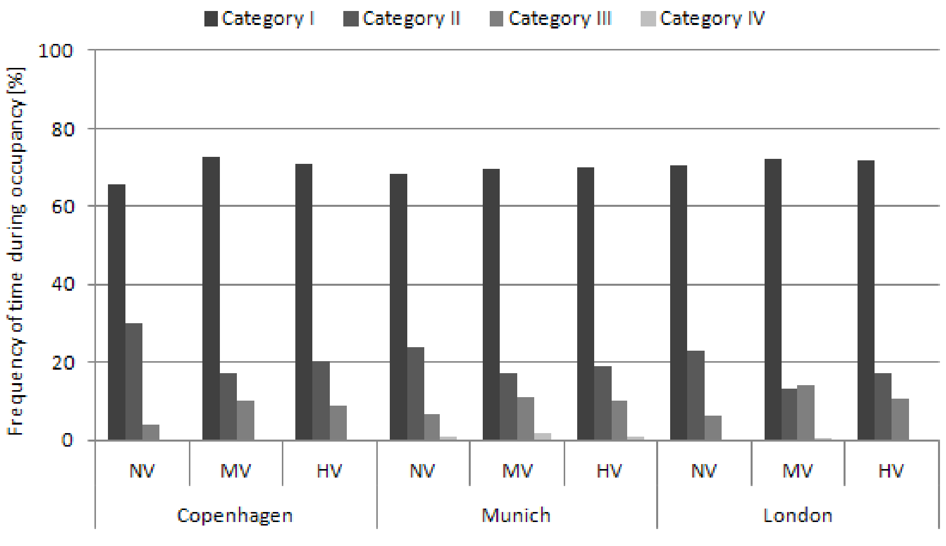

Figure 2. Percentage of occupied time where indoor temperatures achieved the different performance categories according to EN 15251

Only very small temperature variations were found for the different locations. This implies that each of the three ventilation systems would achieve similar levels of thermal comfort in each location. A similar picture was found when comparing the CO_2 levels. The result showed that Category II performance could be achieved 45-55% of the time depending on the ventilation system, while the remainder of the time fulfilled the requirements according to Category III.

7.2 Primary energy

For the calculation of the total primary energy consumed (sum of heating and fan electricity demand multiplied by the primary energy factors) the nationally adopted primary energy factors have been used for the different locations; Munich (district heating: 0.7; electricity 2.6), Copenhagen (0.8; 2.5) and London (1.2; 2.92).

Figure 3 shows the primary energy consumption. Comparing the primary energy consumption figures it can be seen that heating energy demand can be reduced by nearly 70 % for HV compared to NV. Fan electricity can be reduced by 75 % for HV compared to MV. Total primary energy is almost the same for MV and NV, but can be reduced by up to 50 % by utilising HV.

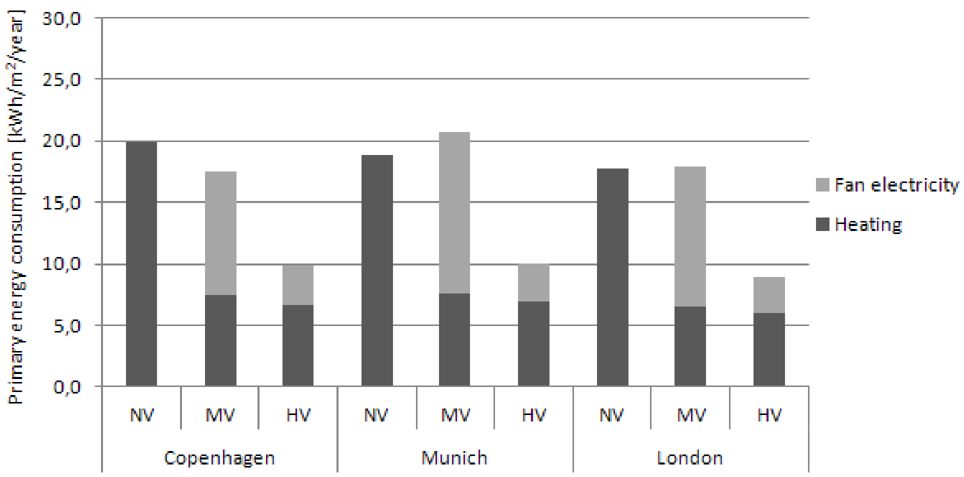

Figure 3. Primary energy consumption

8 CO_2 EMISSION

Calculation of CO_2 emissions are based on the following figures; Munich (district heating 200 g/kWh and electricity 606 g/kWh), Copenhagen (104; 425) and London (206; 517). CO_2 emissions due to electricity and heating are almost the same for NV and MV. Depending on the location the total CO_2 emission ranges from 2.6-5.4 kg CO_2/m^2 per year. HV makes it possible to reduce this CO_2 emission by up to 50%.

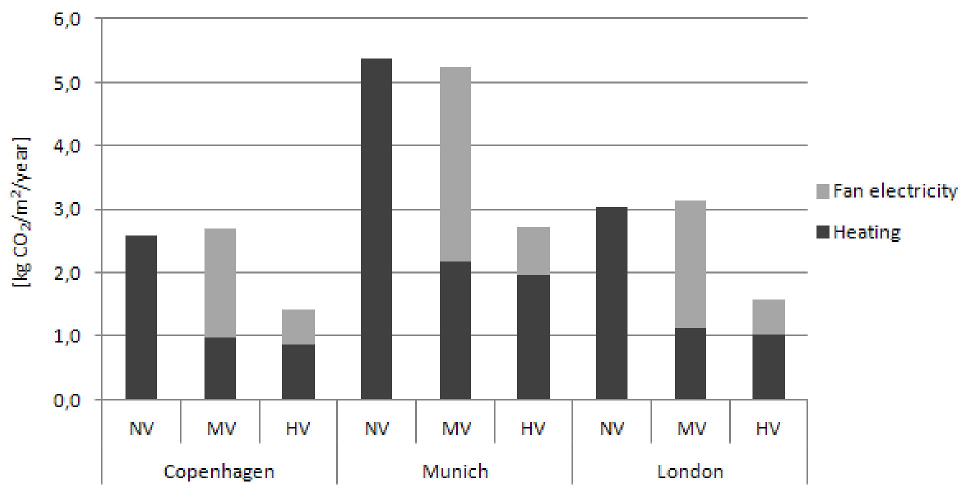

Figure 4. CO_2 emission

9 COST

The total investment required by the different systems has been evaluated including capital cost (products and installation), operation (electricity and heating), and maintenance costs for the first year of operation (Figure 5) and during a period of 20 years (Figure 6). The prices are calculated by WindowMaster in close collaboration with a Danish ventilation contractor (Roth, 2012). The maintenance cost for HV is almost the same as MV. Choosing NV this cost could be reduced by 70%. No significant difference was found between NV and MV for the operation cost during the first year. However, using HV the operational cost could be reduced by 50%.

One of the major differences of the three systems is the capital cost. Here it was found that a MV system is more than four times as expensive as a NV system. For HV this was only a factor of three. As a result of these large capital costs, the total investment for the first year is still in favour of NV by a factor of four compared to MV and a factor of three compared to HV. Accordingly, HV was found to be 25% cheaper than a full MV system.

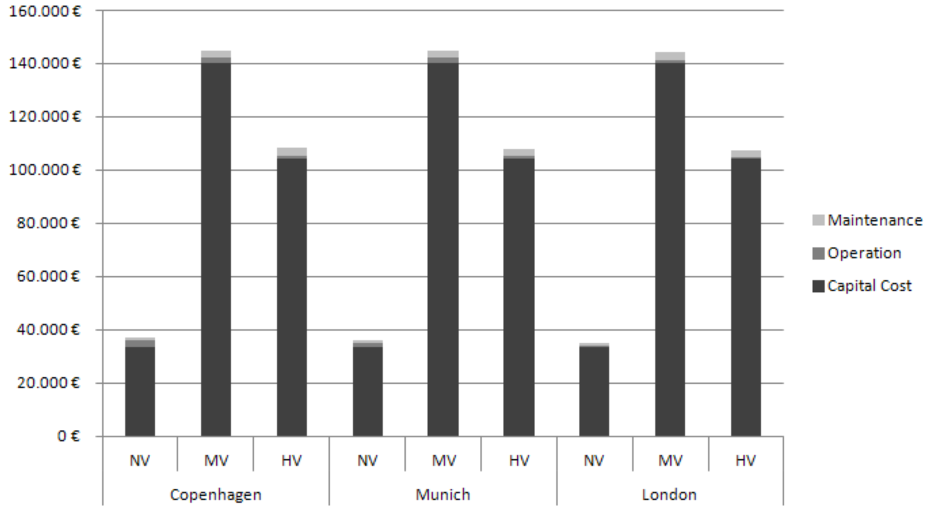

Figure 5. The total investment during the first year of operation

The total investment over a period of 20 years showed almost the same pattern as the first year of operation. MV was found to be 2.5 to 3 times more expensive than NV on the total investment during a 20 year period. 25% could be saved over 20 years by choosing a HV system compared to a MV system.

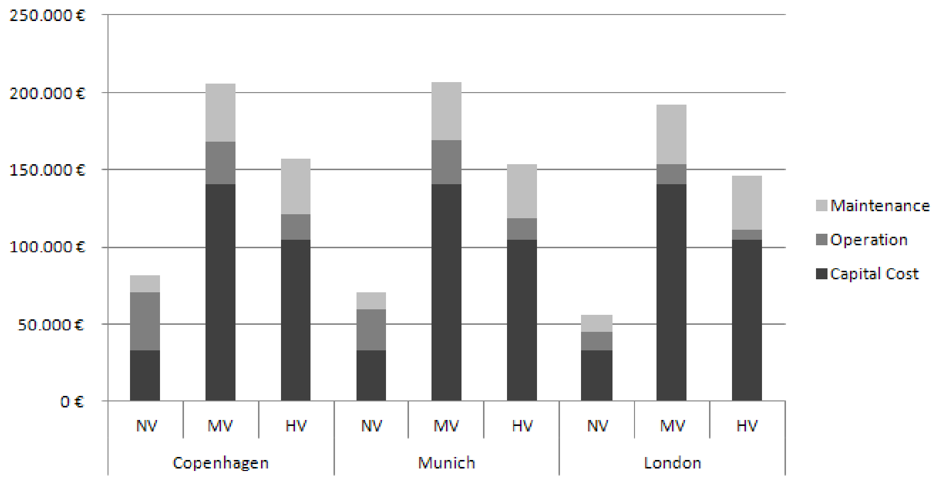

Figure 6. The total investment during a period of 20 years

10 DISCUSSION

The main ambition for the control strategies is to obtain the desired thermal comfort and indoor quality defined in EN 15251 Category III and to obtain very similar indoor air quality for all three ventilation types. This is necessary for a useful comparison of energy demand resulting from the different ventilation types. It should be noted that better relative indoor air quality and thermal comfort performance could have been achieved for all three ventilation systems if other benchmarks for CO_2 and temperature performance had been chosen.

To make the study as realistic as possible, it was decided to use real, commercially available products. Likewise, is the product specifications selected corresponding to these products. The approach avoids a discussion about whether the results can be transferred in practice. However, the actual products are only available in certain sizes, so it is not possible to select a product for all locations that just fits the exact requirements. Instead, we have chosen a product that can meet the requirements of the most heavily loaded location - and this product is used at all locations. It avoids that the choice of commercially available product affects energy calculations. The only effect can occur at the cost side, where the MV in London and Copenhagen could possibly be a more customized MV product.

The transfer of the control strategy to the simulation models was done as close as possible to WindowMaster’s control strategy. Sometimes changes were necessary due to the restrictions of the simulation software or to obtain a similar thermal comfort and indoor quality. It is believed that these simulations still closely reflect the WindowMaster control system.

HV control strategy is a combination of the NV and MV control strategies. The overall objective is to use the best aspects of both systems, in order to optimise the balance between indoor climate and energy consumption. This is possibly the greatest challenge with HV and it is therefore necessary to have a control strategy that can take this into consideration.

During winter and summer the HV control strategy is almost straight forward; MV gives the best results during cold periods, when there is a heating demand. The heat recovery of the system helps save heat energy from the building. During the summer period, it is NV that has the best results. Good indoor air quality and thermal comfort can easily be reached without using any fan energy. The ventilation rate can be increased only by opening the windows a little more without using additional energy. NV also has the ability to benefit from night ventilation/cooling without using any additional energy.
The transient season is, however much more complicated and most of the time it depends on internal conditions to dictate whether MV or NV is the best solution. Therefore, it is very important to have an automatic system that can choose between the two systems depending on indoor temperatures as an indicator for heating or possible cooling demand. This is perhaps not that complicated. The complex part is to know, when, for instance, to make the MV stop and then start up the NV system due to the fact that the internal environment has changed throughout the period where MV has been used. This strategy has been developed in these calculations.

11 CONCLUSION

The total primary energy demand (sum of heating and fan electricity demand multiplied by the primary energy factors) for the NV and MV systems ranges from 18-21 kWh/m² per year in all three locations. For HV the total primary energy demand was only 9-10 kWh/m² per year.

The result shows that HV enables energy savings of 44-52% compared with MV. Compared to NV an energy saving of 46-50% could be achieved. The heating demand can be reduced by nearly 70% for HV compared to NV. Fan electricity usage can be reduced by 75% for HV compared to MV. Overall, total primary energy consumption is almost the same for MV and NV, but can be reduced by up to 50% using HV.

One of the major differences was to be found in the total investment of the different systems including capital cost (products and installation), operation (electricity and heating), and maintenance. Looking at both the first year of operation and during a period of 20 years, MV was found to be 2.5 to 4 times more expensive than automated NV. By selecting HV, 25% of the total investment could be saved compared to a MV system.

The results demonstrate clearly that effective automated NV can deliver similar indoor climates and energy performance to MV, but with significantly reduced capital costs. However, HV should be more widely considered for schools in addition to NV and MV. Overall HV makes it possible to save on capital costs compared with MV, and delivers ongoing savings for heating and electricity during operation while reducing CO_2 emissions by up to 50%.

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