The future of hybrid ventilation in office buildings – energy simulations and lifecycle cost

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ABSTRACT

This study presents a comparison of three ventilation systems; automated Natural Ventilation (NV), balanced Mechanical Ventilation (MV) with heat recovery and Hybrid Ventilation (HV) with heat recovery for a new build office building.

The energy demand for heating and electricity as well as the indoor climate of the building were simulated using IESVE. Three key European cities were selected (Copenhagen, Munich and London) in order to investigate the applicability of the principles to different climatic conditions in Europe.

Ventilation control strategies were set to achieve identical indoor climate for all three ventilation system. Thermal comfort and indoor air quality targets were set according to Category II of the European Standard EN 15251 (EN 15251, 2007).

The results show that the total primary energy demand (sum of heating and fan electricity demand multiplied by the primary energy factors) for NV was 9-11 kWh/m^2/year, MV 20-25 kWh/m^2/year and HV 7-8.5 kWh/m^2/year. HV enables energy savings of 20-25% compared with NV and 60-70% compared with MV.

The total investment of the different systems including capital cost (products and installation), operation (electricity and heating), and maintenance was investigated for a 20 year period. Overall NV was found 4 to 5 times cheaper compared to MV and HV was found 2.5 times cheaper than the MV system.

The results demonstrate that HV should be considered for offices in addition to NV and MV. Overall the HV solution reduced the energy demand for heating and electricity and saved up to 60% of the CO_2 emissions compared to the NV and MV.

KEYWORDS

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

1 INTRODUCTION

Many studies have shown that HV, combination of automatic NV and MV, offers a promising opportunity to maintaining a comfortable indoor climate and at the same time achieve significant energy savings. HV might, be the key technology to enable designers to fulfil ever stricter energy requirements and provide 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) showed 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.

Dong (Dong, 2010) compared a MV system with a combination of NV and MV supply an office building in Scotland (Glasgow). The calculated energy savings for HV was found to about 12% utilising NV for 69% of the time. Heikkinen (Heikkinen, 2002) did a simulation for a comparison of two balanced MV systems with three types of HV for an office building. The result shows that the net energy consumption during one year for the cooling load and fan electricity could be reduced from an index 100 using MV to an index 82% and 8%, respectively, for a HV system. Ji (Ji, 2009) investigated the potential of HV for an office building in a very humid region in China. The study concluded that HV could enable 30 to 35% of the energy savings for fan power compared to the MV system.

Thus, the literature contains several findings and in general, HV is demonstrated to result in significant energy savings. This current study investigates if this conclusion is valid for an office building using state-of-the-art MV and NV systems. Identical indoor climate was realised for all three ventilation systems, as this would give a true comparison between the energy performance of the systems. The simulation was performed for three large European cities with different climates; Copenhagen, London and Munich. CO_2 emissions and the economical costs from selecting the different systems was also investigated from selecting the different systems.

2 OFFICE BUILDING GEOMETRY, PROPERIES AND LOCATION

2.1 Building layout

The simulated office has three storeys with each three open-space-offices. The building is oriented East-West. Each office has windows in both directions and no openings or transparent façade elements to the north or south. Two meeting rooms, a kitchenette and a printing room are arranged along the main façade of each storey. Toilettes and staiways are placed in the two building cores.

The floor to ceiling height of each storey for the simulation with MV and MV is 2.8m below the suspended ceilings. For the simulation with NV the ceilings are less suspended, resulting in a room height of 3.0m. The gross room height is the same for all ventilation types. The net area is 233m^2 for the corner offices, 287m^2 for the middle offices and 17m^2 for the meeting rooms. The geometry of the building can be seen in Figure 1.

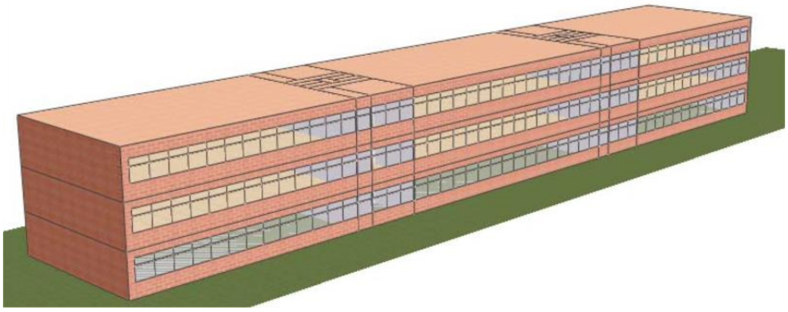

Figure 1: Layout of the building

2.2 Construction properties

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

Glass ratio of the east/west façade is 42% and 41% in the meeting rooms. The glass selected have a g-value of 0.63 and light transmittance of 0.74.

External solar shading is provided for all three ventilation types. The lower level windows, which aren't used for natural ventilation, have an external sun screening with a shading coefficient of 0.1. In Munich, all windows were equipped with solar shading.

Table 1: Constrution properties

Building element	**U-Value [W/m^{2}K]**
Ground Slab	0.08
Exterior Walls	0.12
Roof	0.07
Windows	0.9-1.07

2.3 Internal heat loads

The occupant density in the office rooms is set to 10m^2 floor space and in the meeting rooms 2.25m2 per employee.

The maximum occupant density during the day is 90% from Monday to Friday from 7 am to 18pm, see Figure 2.

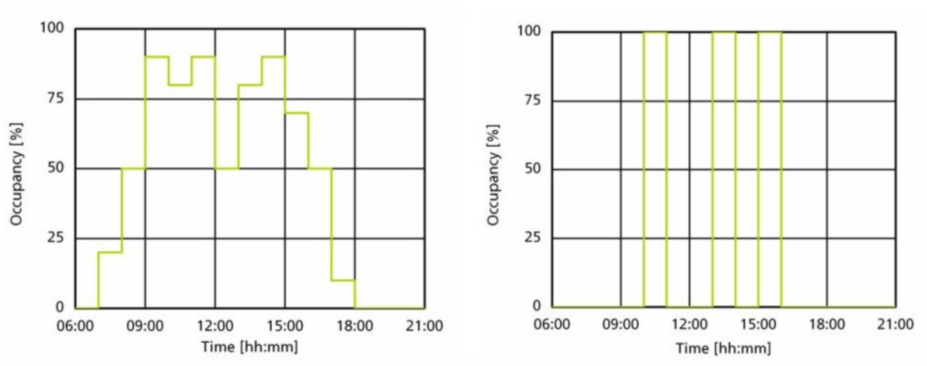

Figure 2: Occupant schedule for the open-plan-offices (left) and meeting rooms (right)

Vacation time is 7 weeks per year in total (week 14, 20, 27 - 29, and 51 - 52). The occupancy during vacation is set to 35 % adopting the same daily profiles as for the rest of the year. No occupancy is assumed during weekend.

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/m² skin surface and a skin surface of 1.8 m².

Each employee is expected to have technical equipment (computers etc.) with 100 W heat load. This is a typical heat load by equipment in offices according to EN 13779 (EN 13779, 2007). The lighting (fluorescent lighting) shall provide a luminance intensity of 500 lux at the table and has a maximum heat load of 8 W/m² including a desk lamp for each person.

The variation of the heat loads is adopted to the occupancy schedule.

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

The requirements for thermal comfort and indoor air quality are based on EN 15251 (EN 15251, 2007) and Category II was applied to assessment of the indoor climate. The values might exceed the category up to 5% of the occupied hours. Category II is deemed an acceptable level of expectation and a target of 900ppm is applied for the assessment of indoor air quality.

4 DIMENSIONING OF VENTILATION SYSTEMS

To maintain the air quality according to Category II of EN 15251 (EN 15251, 2007) the necessary air flow rate was calculated by the mass balance of the target carbon dioxide level of 900 ppm and a carbon dioxide emission per person of 18 l/h. This results in a total air flow rate of 230 l/s (828 m^3/h) for the corner offices, 280 l/s (1008 m^3/h) for the middle office and 80 l/s (288 m^3/h) for the meeting rooms. The total flow rate for all meting and office rooms is 3180 l/s (11,448 m^3/h).

For maintaining temperature in summer different air change rates were tested. Due to these results a ventilation rate of 5 air times the air quality rate was selected for the summer and night ventilation. The total flow rate for all meeting and office rooms is 15,900 l/s (57,240 m^3/h).

4.1 Natural ventilation

For the NV every second high level window on both sides of the offices can be opened with chain drive actuators to realise cross ventilation for Copenhagen and London. For Munich, every high level window on both sides can be opened. In the meeting rooms, every high level window was set automated for all simulated locations with regard to the single-sided ventilation.

The resulting openable window area for the automated windows is 4.3 m^2 representing 1.8% of the floor area for the corner rooms and 4.9m^2 corresponding to 1.7% of the floor area (both doubled for Munich).

A wind speed of 0.5 m/s and 1 m/s results in a 2 and 4-fold air exchange rates respectively - calculated according to the British Standard Method (Allard, F., 1998) for open plan office space. Outdoor conditions with 1 m/s wind speed should be available most of the time throughout the year for all three locations and would also be sufficient for delivering adequate ventilation.

4.2 Mechanical ventilation

One centralised unit is utilised for the MV in the office building. The system was dimensioned for the maximum air flow rate according to air quality and indoor temperature (57,240 m^3/h). The specification of the unit has been selected from those products currently available in the market place, resulting in a total flow rate of 70,200 m^3/h.

The Specific Fan Power (SFP) value is 1814 J/m^3 and no heating or cooling units were assumed. The pressure loss for the ductwork of the system is 235 Pa for the supply and 170 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. 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 sensible heat effectiveness in the simulation was set to 80 %, which is the temperature effectiveness including the effects of the motor heat.

4.3 Hybrid ventilation

The HV combines a smaller decentralised MV system with automated NV.

The NV system is mainly utilised to maintain indoor temperature during summer and the transient seasons (57,240 m^3/h), whereas the MV system is dimensioned solely to maintain air quality (11,480 m^3/h). Hence the mechanical element has a significantly lower capacity compared to the pure MV.

The pressure loss in the MV element of the system for the supply and the exhaust ductwork is then about 235 Pa for the supply system and 170 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 the system is 1814 J/m^3.

5 CALCULATION METHOD

The simulation program IESVE-Pro (version 6.4.0.7, Integrated Environmental Solutions Limited, Glasgow, UK) was used to simulate the energy demand and the indoor climate of the office building. The program has a special function for calculating more complex HVAC systems (ApacheHVAC) and a very reliable calculation tool for NV (MacroFlo), which can 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 should be controlled very precisely 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

The definition of NV is automated windows on both sides of the rooms utilizing cross ventilation. Small MotorLink™ chain drive actuators are used to open and close the windows by a specific amount. 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, pulse ventilation, and night ventilation. Continuous ventilation with a varying opening degree is utilized for control of air quality during the whole year and indoor temperature in summer. The opening distance for continuous ventilation is restricted for comfort reasons. Pulse ventilation with the maximum opening degree calculated due to weather for a short time for additional control of indoor air quality during winter and transient times. Night ventilation 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 air flow rate of the MV is defined due to improvement of the indoor air quality and reduction of overheating. Hence, the maximum air flow rate is utilized, when either the air flow rate due to carbon dioxide level or due to indoor air temperature raise above a certain set point. Night ventilation is activated during warmer periods.

6.3 Hybrid ventilation

Combining the natural and the mechanical control strategies leads to the HV control strategy. The overall strategy is to use the best aspects of both systems to achieve the best indoor climate at the lowest energy consumption.

MV is activated during the winter season, as the heat recovery of the system helps save energy to heating. NV is enabled during summer time to secure a good and stable indoor air quality and temperatures. Additionally, the chain drive actuators of the windows need much less electricity compared to the fans for MV and the flow rate can easily be increased by simply increasing the openings of the windows. Same benefit applies for NV during night time - exploiting the 'free cooling' potential.

In the transient season, most of the time the internal conditions determine, whether MV or NV is the best solution. The indoor temperature is used as an indicator of whether there is a heating or cooling demand and based on this the system automatically chooses between NV or MV.

6.4 Heating, shading and lighting

The heating is enabled from October to May and if the outdoor temperature is below 12°C The heating is set to avoid too low temperatures in accordance to Category II during occupancy (7 am - 6 pm). During occupancy, the set-point is 21°C and in times with no occupants the set-point is 19°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 24°C.

The dimming of artificial light is controlled due to occupancy and to maintain 500 lux in the rooms.

7 RESULTS

7.1 Temperature and CO_2

The results of thermal comfort and indoor air quality were evaluated for a middle office space on the upper floor, as this was found to be the worst-case office space. Figure 3 shows the percentage of occupied hors where indoor temperature achieved the different performance categories according to EN 15251 (EN 15251 2007). This is displayed for the three ventilation types in each of the three locations.

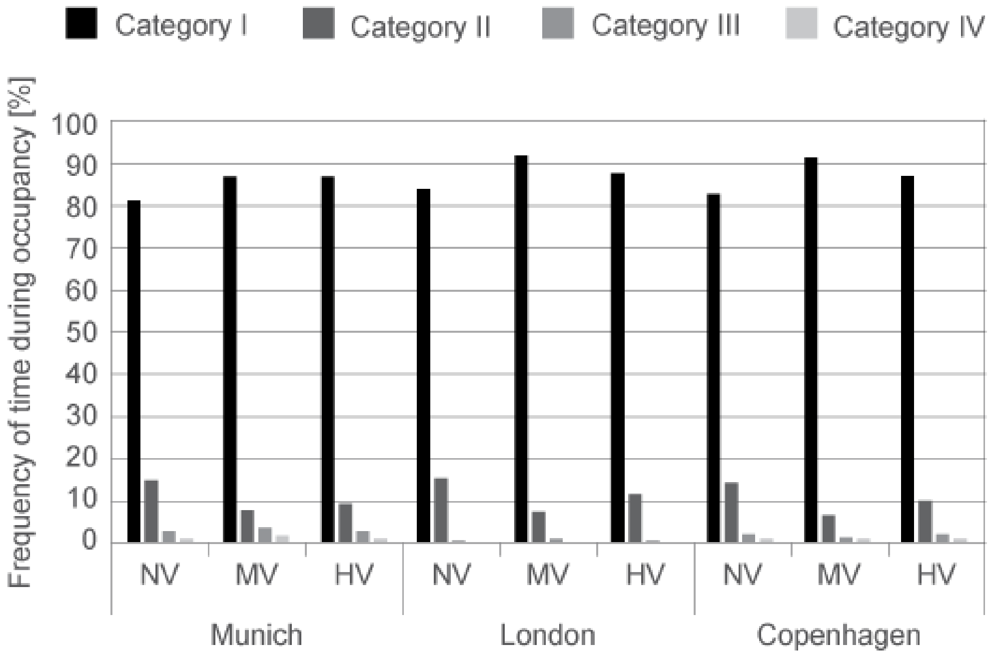

Figure 3: Percentage of occupied hours where indoor temperatures achieved the different performance categories according to EN 15251

Thermal comfort levels were found almost to be identical for the three ventilation types and at the different locations. This implies that each ventilation systems would achieve similar levels of thermal comfort in each location.

The results for the indoor air quality showed comparable figures for the three investigated ventilation types. The result demonstrated that Category II performance could be achieved 98.4-100% of the time depending on the ventilation system.

7.2 Primary energy

The total primary energy (sum of heating and fan electricity demand multiplied by the primary energy factors) was derived from the detailed energy modelling of the net energy. The nationally 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).

The primary energy consumption is shown on Figure 4. The result shows that NV uses 9-11 kWh/m^2/year, MV 20-25 kWh/m^2/year and HV 7-8.5 kWh/m^2/year. HV enables energy savings of 20-25% compared with NV and 60-70% compared with MV.

The energy performance for the HV was calculated based upon the calculations and following improvements suggested by Fraunhofer.

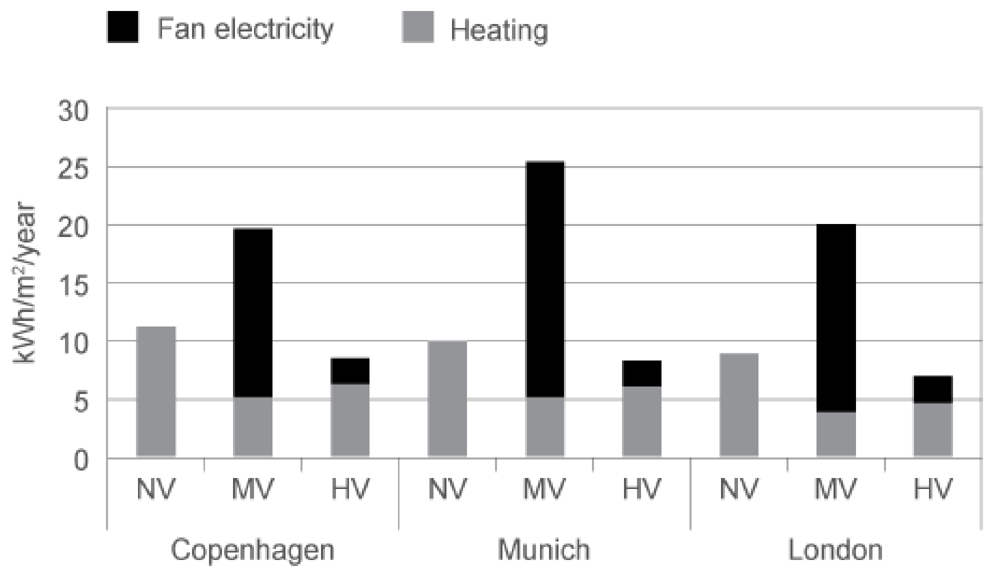

Figure 4: Primary energy consumption

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 ranges from 1.6-6.2 kg CO_2/m^2 per year depending on location. The CO_2 emissions are much less for NV and HV comped to the MV system. HV emits approximately 20% than NV.

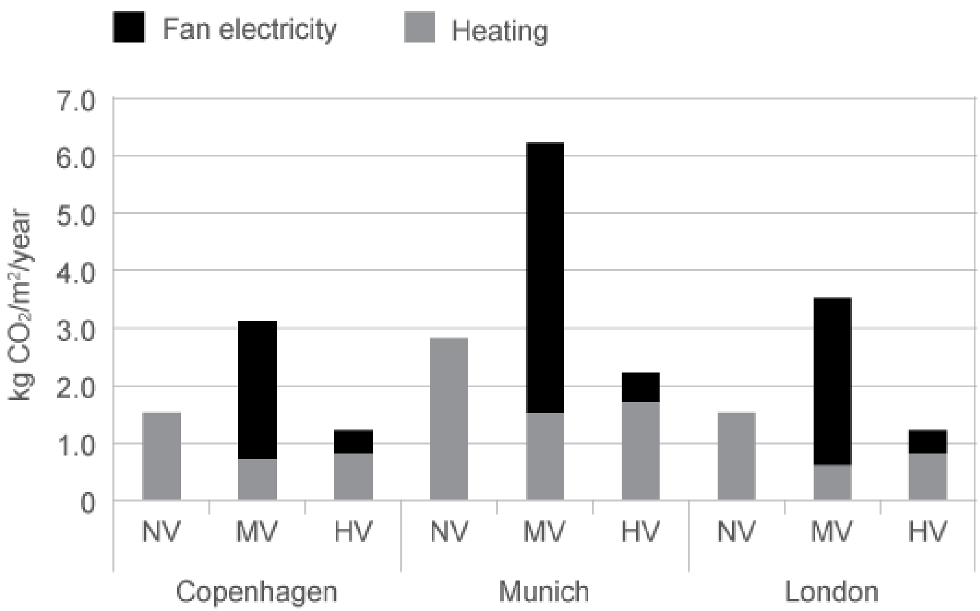

Figure 5: CO_2 emission

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 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 around 40% lower compared to the pure MV system. Choosing NV this cost could be reduced by 75%. For the operation cost NV was found in the range of 30-60% cheaper compared to MV depending on location. Using HV the operation cost could be reduced in the range of 50-70% compared to MV.

One of the major differences of the three systems is the capital cost. Here it was found that a MV system is 4 to 5 times as expensive as a NV system. For HV this was a factor of 2.5.

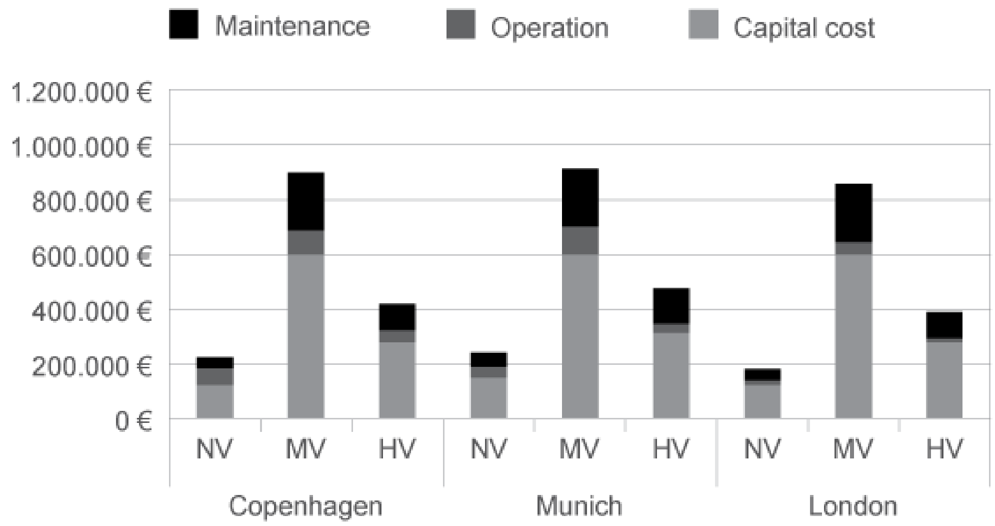

Figure 6: The total investment during a period of 20 years

10 DISCUSSION

The main goal was to have almost identical indoor environment for all three ventilation types in order to compare the energy demand. It should be noted that the indoor environment could have been improved for all three ventilation systems if other benchmarks for CO_2 and temperature performance had been chosen. The requirements for thermal comfort and indoor air quality are based on the Category II of EN 15251 with the possibility to exceed the criteria with 5% of the occupied hours. It was chosen not to use the adaptive comfort model, as it was found more easy to compare the results to fixed temperature levels.

Real, commercially available products and their specifications was chosen to make the study as realistic as possible. This method avoids a discussion about whether the results can be transferred in practice. Nevertheless, 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, it was chosen to use a product that can meet the requirements of the most heavily loaded location – which was used at all locations. The only effect can occur at the cost side, where the MV in London and Copenhagen could possibly be a more customized MV product.

WindowMaster’s control strategy was adopted to a large extent as possible for the simulated models. It was to a minor degree necessary to do smaller restrictions of the simulation software or to obtain a similar thermal comfort and indoor quality. It is believed that these simulations still reflect the WindowMaster control system.

The overall objective of HV is to use the best aspects of NV and MV, in order to optimise the balance between indoor climate and energy consumption. The control strategy of HV is one of the greatest challenge, as it is a combination of the NV and MV control strategies. During winter and summer the HV control strategy is straight forward; MV gives the best results during winter, and NV gives the best results during summer period.

The transient season is, much more complex and most of the time it depends on internal conditions to dictate whether MV or NV is the best solution. Therefore, it is essential to have a control strategy that can choose between the two systems depending on indoor temperatures as an indicator for heating or possible cooling demand. This is, however not the most complicated part. The complex part is to know, when, for instance, to make the MV stop and then start up the NV system since the internal environment has changed throughout the period where MV has been used. This strategy has been developed and applied in the present study.

Even though it was out of the scope of these calculations, it was investigated if a mechanical cooling system would be more energy efficient compared to the relatively high air flow rates for the MV system especially during summer time. The following was based on basic hand calculation based on the previous results. The additional energy demand for electricity for Copenhagen and London is expected to be about 20-25% higher by using mechanical cooling compared to free cooling. For Munich, however, it would have been more effective to use mechanical cooling with the minimum flow rate, due to air quality, which would have saved 10-15% of fan energy. However, it is usually necessary to have higher flow rate with mechanical cooling to avoid too low supply air temperature.

11 CONCLUSION

The aim of this study was to compare the energy demand for heating and electricity for an office building located in one of the three key European cities; Munich, Copenhagen and London using either NV, MV or HV by the means of the simulation program IESVE. Identical indoor climate was realised for all three ventilation systems in accordance to European Standard EN 15251 (EN 15251, 2007).

The total primary energy demand (sum of heating and fan electricity demand multiplied by the primary energy factors) for the NV uses 9-11 kWh/m^2/year, MV 20-25 kWh/m^2/year and HV 7-8.5 kWh/m^2/year. The result shows that HV enables energy savings of 20-25% compared with NV and 60-70% compared with MV.

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. During a 20 year period the NV was found 4 to 5 times cheaper compared to MV. The HV was found 2.5 times cheaper than the MV system.

The results demonstrate clearly that effective automated NV can deliver similar indoor climates compared to MV, but with significantly reduced energy consumption and capital costs. However, HV should be considered for offices in addition to NV and MV. Overall the HV makes it possible to reduce the energy demand for heating and electricity and to save up to 60% of the CO_2 emissions.

12 ACKNOWLEDGEMENTS

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13 REFERENCES

Allard, F. (1998). *Natural ventilation in buildings*. A design handbook. MPG Books Ltd, London

Cron, F. and Inard, C. (2003). *Analysis of hybrid ventilation performance in France*. Proceedings of Eighth International IBPSA Conference, Eindhoven, 243 - 250.

Dong et at. (2010). Simulation-based Hybrid Ventilation System Design and Evaluation. Proceeding of International High Performance Buildings Conference, Purdue, paper 3409, 1-7.

EN 13779 (2007). Ventilation for non-residential buildings. Performance requirements for ventilation and room-conditioning systems

EN 15251 (2007). *Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*.

Emmerich, S. J (2006) *Ventilation Systems in an Office Building*. HVAC & Research 12, 4, 975 - 1004.

Heikkinen, J. et al. (2002). *Performance simulation of hybrid ventilation concepts*. IEA - Technical report in Annex 35 Hybrid Ventilation.

Heiselberg, P. (2006). Design *of Natural and Hybrid Ventilation*. DCE Lecture Notes, Aalborg University.

Ji et al. (2009). Hybrid ventilation for low energy building design in south China. Building and Environment 44, 2245-2255.

Reshyvent (2004) *Demand controlled hybrid ventilation in residential buildings with specific emphasis on the integration of renewables*.

Roth, J. (2012). *Cost calculation for the office investigated in the Fraunhofer study.*