ENERGY IMPACT OF VENTILATION IN BUILDINGS

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SYNOPSIS

The relative importance of ventilation in the energy balance of buildings has been increasing, as a consequence of control of heat exchanges through the envelope and internal gains. It is therefore very important to clearly understand the main factors that affect energy consumption due to ventilation and potential ways to decrease the energy demand without affecting IAQ.

This study was developed within the European project TIP-VENT (JOULE). An analysis was made to study the impact of the following issues: (1) ventilation rates mandated by regulations and standards in Europe; (2) ventilation control strategies; (3) fan power consumption; (4) Other issues such as heat recovery and air tightness of the building envelope.

The methodology consisted of computer simulation using mainstream programs such as ESP-r and Visual DOE as well as other more specific tools. Six real buildings were selected as case-studies: An hotel, an auditorium, an office building, a single-family dwelling, an apartment and a large office building. They were all simulated in a mild, a moderate and a cold climate.

Results show that the energy impact of the different minimum ventilation rates stated in regulations in different countries can be large. They also confirm the large potential energy saving by using variable ventilation (e.g., CO_2 controlled) and free-cooling. In terms of fan power consumption, the energy saving potential is also very large. Combining several techniques, it is shown that, in many cases, a "best system" can allow an energy saving of up to 70% over a "common system".

1. INTRODUCTION

The buildings sector represents more than 40 % of the total energy consumption in the European Union (Energy in Europe, 1996). Although the energy efficiency of equipment is increasing, the number of new systems and appliances is also increasing, e.g., the demand for HVAC systems is fast increasing in many countries, especially in Southern Europe. So, energy consumption in the built environment still has a tendency to increase. Taking into account the EU energy policy and the Kyoto agreements, it is very important to identify energy saving opportunities in the buildings sector. After the effort to increase insulation in the past decades, it is clear that energy use due to air change is now the area with more potential for further savings. Orme (1998) estimated that, for the non-industrial building stock of the then 13 AIVC countries, the total annual energy needs for heating due to air change amounts to 48% of delivered space heating energy.

Regulations directly or indirectly concerning ventilation are now in force in most countries. These try to take in account both human health and energy consumption considerations. Qualitatively, the energy consumption and indoor air quality (IAQ) relate to ventilation rates as shown in figure 1. Quantification of IAQ and health requirements, however, is not yet technically clear. For this and other reasons, different countries have adopted, for the same type of buildings, different minimum ventilation rates. Moreover, many regulations do not usually stimulate energy-efficient solutions. For example, most regulations do not require advanced strategies such as heat recovery and free-cooling. If the regulation of air flow rates has been used as a way to establish a compromise between energy and IAQ, there are other means available to decrease energy consumption without a penalty in IAQ, namely demand controlled ventilation, free-cooling and heat recovery.

This study developed over this background. Its objective was to study the impact of ventilation rates upon energy consumption as well as the potential for energy savings resulting from the use of innovative technologies. Together with other measures, this could help creating a positive environment for the development of innovative and smart ventilation systems.

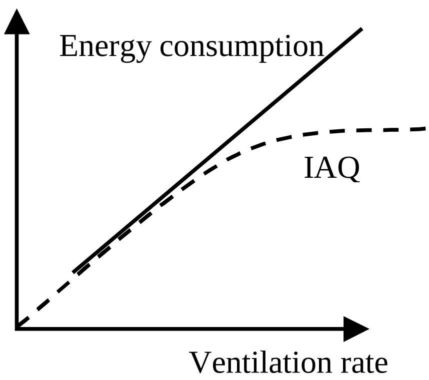
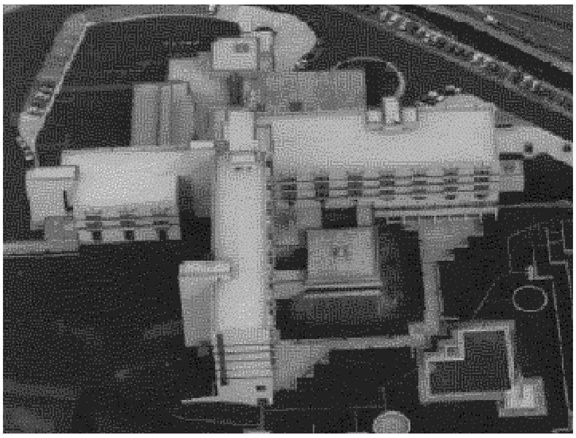


Figure 1: Energy consumption and IAQ relation to ventilation rates

2. METHODS

The analysis consisted of a set of sensitivity studies performed by computer simulation. A set of case-studies was selected to represent the diversity of the built environment in Europe. Buildings selected were a hotel, a university auditorium, an office building, a semi-detached dwelling, an apartment and a large office building. These buildings can be seen in figure 2.



Hotel (Portugal)

University auditorium (Portugal)

Office building (Belgium)

Semi-detached dwelling (The Netherlands)

Apartment (The Netherlands)

Large Office Building (Portugal)

Figure 2: Case-study buildings at their original locations

Although the buildings are located at a specific place, it was decided to evaluate their energy requirements in a mild, a moderate and a cold climate. Figure 3 shows the temperature distribution for the locations of Lisbon (Portugal), Trappes (France), Uccle (Belgium), Kew (U.K.), Zurich (Switzerland) and Stockholm (Sweden). In the distributions there are clearly two climates that differentiate themselves from the others: Lisbon with a higher number of hours at higher temperatures and Stockholm with a higher number of hours at lower temperatures. All the other climates are somewhat similar. It was so decided to take Lisbon as the mild climate (hot in Summer), Uccle as the moderate climate and Stockholm as the cold climate. Each building was thus studied as if located at each of these three locations.

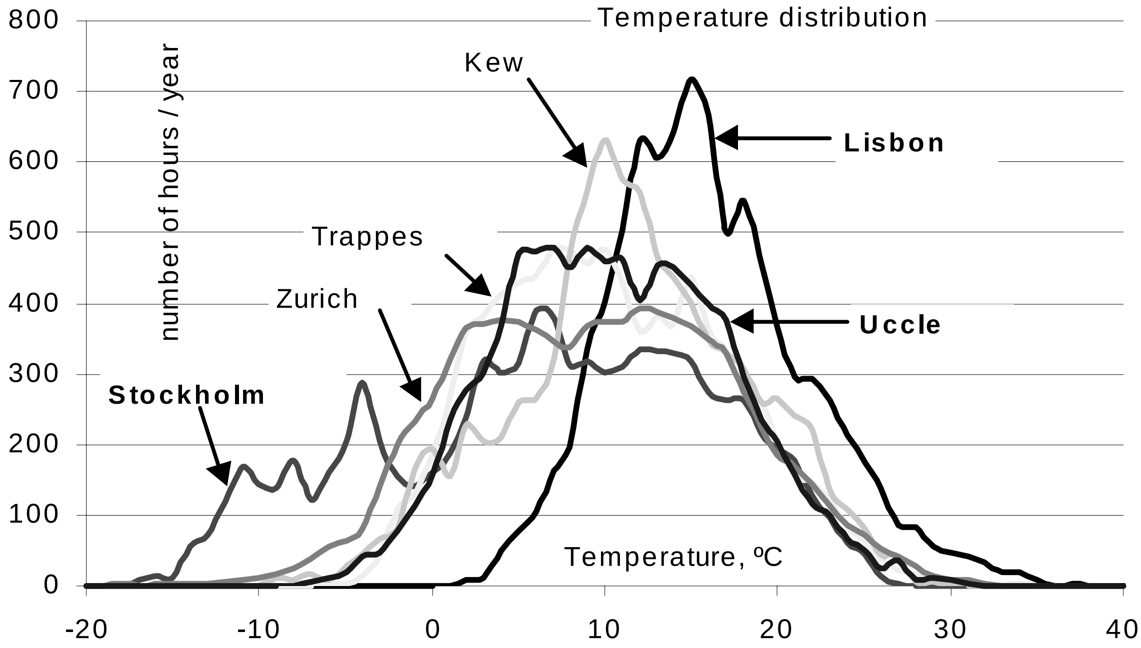


Figure 3: Histogram of local temperature distributions

In order to make the simulations of a building in different climates realistic, they were adapted to the local construction practice and utilisation habits. To do so, local experts in each country provided typical values for each of the main characteristics of each building in their countries. Table 1 shows the average U-value of exterior walls and the heating and cooling set-points for all buildings at each studied location. Other characteristics taken into account were U-values for other envelope components, air-tightness and internal gains (Leal et al, 1999).

For most buildings, some measured data were available, thus allowing a calibration of the simulation model before performing any sensitivity studies. Figure 4 shows the comparison of the simulation results for the hotel (ESP-r calibrated model, base-case configuration) with the measured data. A good agreement was found in all cases.

Most of the simulations were performed with a well-validated, widely used software, the European reference program, ESP-r (ESRU, 1997). For some particular sensitivity studies where ESP-r is not particularly efficient, Visual DOE (Eley Associates, 1996) and STEVE (Lima et al., 2000) have also been used. Although good agreement was found between simulation results and measured data, when available, conclusions from the BESTEST IEA project (Judkoff and Neymark, 1995) must always be kept in mind, especially those stating that all programs revealed modelling limitations, faulty algorithms and significant differences in results.

Table 1: Exterior walls U-Value and heating and cooling set-points at each reference location

	Country					
	Belgium		**Portugal**		**Sweden**	
Building	U-value ($W/m^2.K$)	Set-points (heat.–cool.) (ºC)	U-value ($W/m^2.K$)	Set-points (heat.–cool.) (ºC)	U-value ($W/m^2.K$)	Set-points (heat.–cool.) (ºC)
Hotel	0.51	20 - 25	0.50 - 0.63	21 – 24	0.26 - 0.29	20 – 26
Auditorium	0.57	20 - 25	0.97	20 - 25	0.26	20 - 25
Dwelling	0.51	20/18 - none	0.56	20/16 – none	0.24	21 – none
Apartment	0.75	18- none	0.56	20/16 - none	0.22	21 – none
Large Office Building	0.50	20 – 24	0.50 - 1.10	20 – 24	0.24	20 – 24

Following the make-up of a calibrated model, sensitivity studies could be performed. These focused essentially on the analysis of the energy impact of the following issues:

(a) Ventilation rates stated by different regulations and standards;
(b) Ventilation control strategies, such as demand-controlled ventilation and free-cooling.
(c) Fan power consumption.
(d) Other issues such as heat recovery and building air tightness.

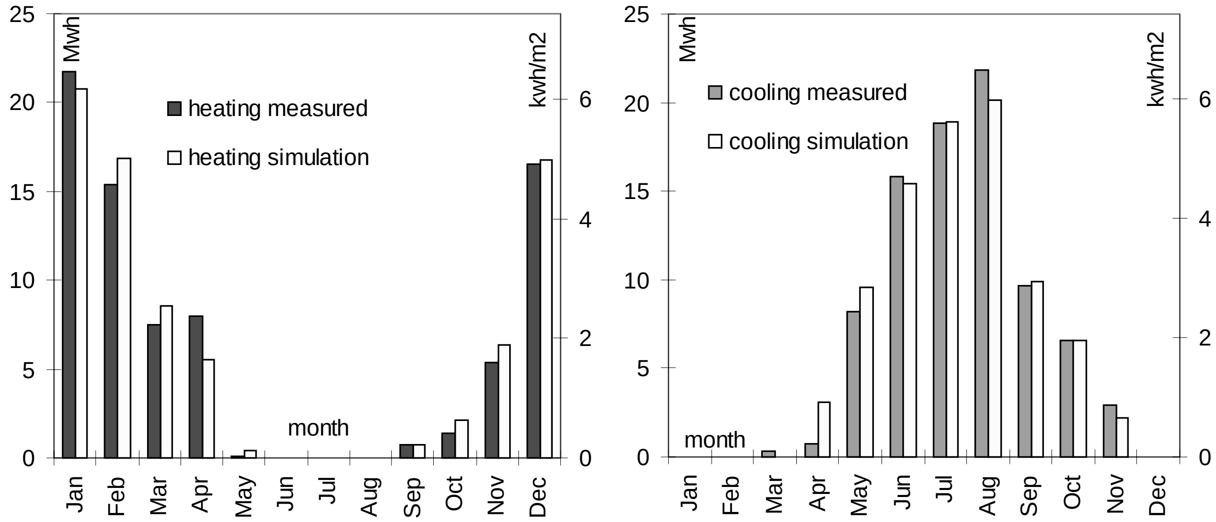


Figure 4: Results of energy demand measured and simulated with a calibrated ESP-r model

3. RESULTS

3.1 Impact of ventilation rates mandated by standards and regulations

The main reason for having ventilation requirements is human health and building conservation. However, clear, objective, uncontroversial and widely accepted criteria to define ventilation rates based solely on health considerations are still not available. Under these circumstances, each country defines ventilation rates taking into account different criteria. Assuming that the outdoor air quality is about uniform throughout European cities, it makes sense to ask why the ventilation rates stated by different regulations and standards are so different. There several possible reasons for this:

(1) The typical finishing materials in the interior of buildings in different countries are not the same and thus have different pollution loads, requiring different ventilation rates.
(2) Some regulations can allow higher ventilation rates because they compensate with other measures, e.g., compulsive heat recovery or efficiency of the equipment and systems.
(3) Different cultural and political attitudes towards the energy consumption vs. IAQ balance.

If all those aspects are taken in account to study the energy impact of regulations and standards, a comparison between different regulations and standards becomes difficult to be made and there is a risk of loosing clarity in the analysis of the results. So, in this approach, the study is made only in terms of the energy impact of ventilation rates mandated by standards and regulations. In future work, more integration can be attempted, but this present analysis could already provide some interesting results.

As an example, table 2 shows how ventilation rates in the hotel change from country to country, which, in turn, raises the question of how they impact upon energy demand.

Table 2: Criteria for defining ventilation rates in different countries for the hotel

Belgium	**Portugal**	**Sweden**	**France**	**UK**	**Switzerland**	**Netherlands**
Bedroom : 3.6 $m^3/h.m^2$ (min. 25 m^3/h, max. 36 m^3/h per person) Bathroom : 3.6 $m^3/h.m^2$ (min : 50 m^3/h) (max: 75 m^3/h)	35 m^3/hr per person	*Minimum 0.35 l/sm^2 and minimum 15 l/s in guest rooms, 7 l/s.person*	25 m^3/h per person	*with no smoking: 8 l/s/person with some smoking: 16 l/s/person with heavy smoking: 24 l/s/person with very heavy smoking: 32 l/s/person*	*Smoking not allowed: 12-15 m^3/h.person (0.15 % CO_2) 25-30 m^3/h.person (0.10 % CO_2) Smoking allowed: 30-70 m^3/h.person*	*Bedroom : 3.6 $m^3/h.m^2$ (min. 25 m^3/h, max. 36 m^3/h per person) Bathroom : 3.6 $m^3/h.m^2$ (min : 50 m^3/h) (max: 75 m^3/h)*

This study investigated what would happen if the mechanical ventilation rates for some buildings in a particular location were changed to those mandated by other countries' regulations. Figure 5 shows the heating and cooling energy demand for a hotel located in Portugal when applying the air-flow rates required by different regulations and standards. It shows that the difference between the lowest and the highest heating demand is 90 %. If the hotel were really located in Belgium or in Sweden, this maximum difference would still be 70% and 82% respectively.

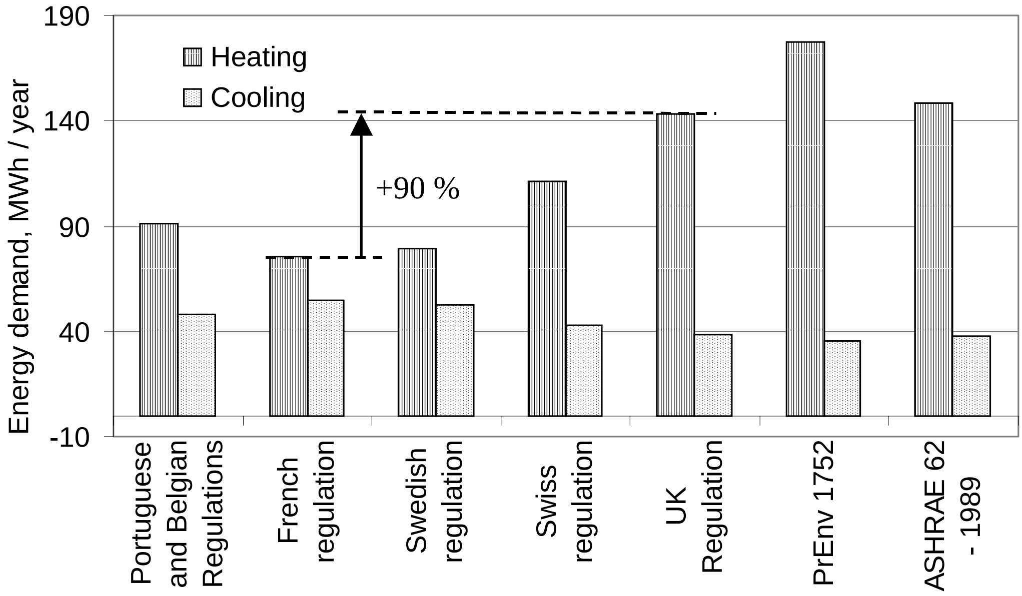


Figure 5: Energy demand of the hotel in Portugal applying ventilation rates stated by different regulations or standards[1]

Table 3 shows the same type of results for this hotel and for the other buildings studied. It can be confirmed that the ventilation rates stated in regulations and standards can have a large impact upon heating energy demand. It also shows that the current differences of ventilation rates in European regulations and standards have important consequences in terms of energy demand.

The effect upon cooling can also be seen, although it goes in the opposite direction: increasing ventilation rates decreases cooling energy demand. In effect, this is equivalent to reducing free-cooling, which will be shown in the next section to be a desirable option everywhere. This inverse behaviour of heating and cooling energy demand thus suggests that a good system must always allow the possibility to control the ventilation rate, providing a certain minimum for IAQ control in Winter but allowing it to increase when this is beneficial in Summer.

[1] In the UK regulation, the ventilation rate depends on whether smoking is allowed or not. In the hotel, smoking was considered allowed, but not allowed in the school auditorium.

3.2 Impact of Control Strategies

One of the good principles of ventilation design should be to provide air "where needed, when needed" and not more than necessary. Unfortunately, most installed systems still provide a constant ventilation rate, assuming that the maximum number of people is always present.

In section 3.1 it was seen that, on average, the cooling energy consumption decreases with the increase of ventilation rates. The correct way to take advantage of this effect is to increase the ventilation rate when the outside air temperature (or enthalpy) is lower than the indoor temperature (or enthalpy), i.e., to use "free-cooling". However, to take advantage of this, the system needs to have special components and an appropriate control, which usually are not installed to reduce investment costs.

Figure 5 shows the impact of having demand-controlled ventilation, i.e., ventilation proportional to the number of people actually present in a room, and free-cooling upon heating and cooling energy demand. The same type of data were obtained for other buildings. Values vary depending upon each specific case, but the main conclusions are in line with qualitative expectations:

- Demand controlled ventilation has a potential that is as high as the variation of the occupancy during the day increases;
- Free-cooling provides an effective way to decrease the cooling demand, for all types of climates, although it is only economically viable in buildings with high cooling demand.

Table 3: Minimum ventilation rates and impact upon heating energy demand

	Minimum ventilation rates in reg. & standards l/(s.person)		**Heating energy demand** (MWh/year)			
Building	**Lowest (A)**	**Highest (B)**	**Virtual location**	**(A)**	**(B)**	**Difference between (A) and (B)**
Hotel	7	10	Portugal	76	143	+ 90%
			Belgium	210	357	+ 70%
			Sweden	278	506	+ 82%
Auditorium	5	10	Portugal	1.5	3.5	+128 %
			Belgium	6.5	11.8	+81 %
			Sweden	12.1	19.6	+62 %
Dwelling	a)	a)	Portugal	1.6	3.9	+ 152%
			Belgium	6.7	12.0	+ 79%
			Sweden	6.9	20.2	+ 193%
Large Office building	7	10	Portugal	111	182	+ 64%
			Belgium	427	612	+ 43%
			Sweden	543	789	+ 45%

a) ventilation criteria could not be expressed in these units. Some were expressed in terms of flow/area, while other were just dependent of the type of room.

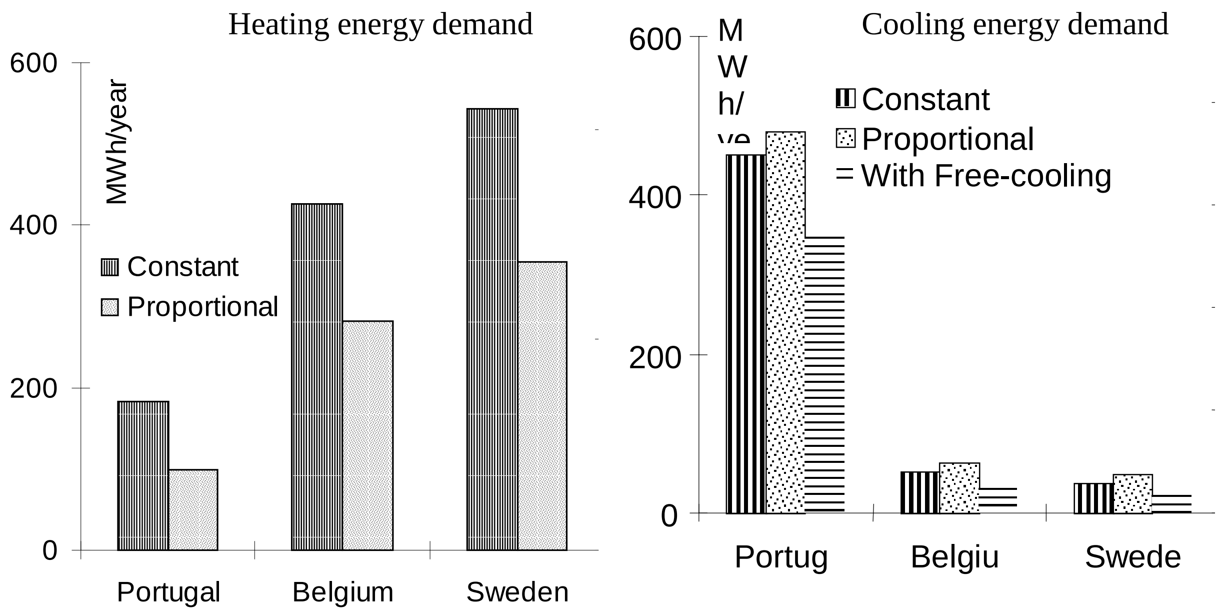


Figure 5: Heating and cooling energy demand of the large office building as a function of the control strategy, for different virtual locations.

3.3 Importance of Fan-Power Consumption

The range of specific fan power consumption (SFP) in existing and even in new buildings seems to be very large. The specific fan power consumption values in existing and in newly designed buildings vary between 5.5 and 13 W/(l/s), while a good system can have about 1.0 W/(l/s) and a very good one can go as low as 0.5 W/(l/s) (Blomsterberg, 2000).

Table 4 shows the fan power consumption and its weight in total HVAC energy consumption (electricity equivalent, assuming COP 3.5 for refrigeration system) for three scenarios of SFP in the large office building . This is a building with 100% fresh air, i.e., without recirculation. Heating and cooling loads are removed by fan-coils. It is observed that, with a good SFP, the energy consumption by fans can be kept below 15% of total HVAC energy, but with a bad system it can represent more than 50 % of HVAC energy consumption. Of course, in all-air systems with recirculation, these values can be much higher.

The results thus show that care taken in the design of ducts and specification and selection of fans is of utmost importance.

3.4 Impact of Heat Recovery

The consequences of heat recovery were also studied. Taking a simple 50% efficiency, results showed a saving potential in heating energy demand of up to 40% in the hotel (in Portugal), 50% in the auditorium (in Belgium), 20% in the dwelling (in Stockholm) and 38% in the large office building (in Portugal). All these buildings have mechanical ventilation systems that centralise exhaust. They also pressurise the building, in practice eliminating infiltration.

Table 4: Energy consumption in MWh/year and Fan power portion of HVAC energy consumption for the large office building (10 l/s.person, constant flow, 100% fresh air)

	Portugal	**Belgium**	**Sweden**
Heating	182	427	543
Cooling	129	15	11
Fans	56	56	56
(Good, FSP=1 W/(l/s))	15%	11%	9%
Fans	279	279	279
(average, FSP=5 W/(l/s))	47%	39%	34%
Fans	560	560	560
(bad, FSP=10 W/(l/s))	64%	56%	50%

3.5 Integrated impact of the best technologies

The effects of a series of variables have been considered individually in the previous sections. Now we compare the "common system" and the "best system", taking the large office building as the selected case-study. Table 5 lists the main assumptions made for each of the cases and table 6 indicates the results, in terms of energy consumption (electric equivalent, COP 3.5 for refrigeration system). The study shows that the "best system" can allow an energy saving larger than 60%.

Table 5: Main properties of Common system and "best system"

	Common system	**Best system**
Ventilation rate & control	10 l/s.p constant	10 l/s.p proportional
Free-cooling	No	Enthalpy control
Heat Recovery	No	heat rec. 80% efficiency
Specific fan power consumption	5 W/(l/s)	1 W/(l/s)

Table 6: Energy consumption for "common system" and "best system", MWh/year

	Portugal			**Belgium**			**Sweden**		
	Common	*best*	*saving*	*Com.*	*best*	*saving*	*Com.*	*best*	*saving*
heating	182	61	67%	612	277	55%	789	340	57%
cooling	129	91	29%	12	9	30%	9	7	27%
fans	279	38	86%	279	47	83%	280	47	83%
total	590	190	68%	903	333	63%	1078	394	63%

Of course, the best system is also more expensive in terms of first cost (investment). The selection of the best case should be made on the basis of life-cycle cost (Blomsterberg,

2000) or, at least, in terms of payback periods. Table 7 shows the maximum investment cost acceptable for each of these technologies, for the same building, if the maximum payback period acceptable is set to be 7 years (interest rate assumed as 4%, and inflation assumed as 2%).

Table 7: Maximum acceptable investment for several energy-efficient technologies for the large office building, assuming a payback period of 7 years (in k•).

	Portugal	**Belgium**	**Sweden**
Heat recovery	19.4	30.7	43.2
CO_2 control	19.6	33.2	43.6
Free-cooling	21.5	8.8	6.9
All	62.1	66.1	83.0

So, ventilation regulations should be critically evaluated to ensure sufficiently good IAQ and energy efficiency at the same time. Good regulations should go much further than just specifying minimum ventilation rates. They should be performance based and promote the use of efficient ventilation techniques, i.e., variable ventilation, free-cooling and heat recovery.

4. CONCLUSIONS

Ventilation rates mandated by standards and regulations can have a very large impact upon the energy consumption in a building. If ventilation rates mandated by regulations and standards from different countries are applied to a certain building at a certain location, differences of nearly 100 % in cooling and heating energy demands can be found. As minimum ventilation rates should be established based on health criteria, these results call for a critical evaluation of the existing standards and regulations toward a certain degree of uniformity.

The use of control procedures that allow adjusting ventilation rates to the real and time-dependent occupancy can have an extremely important impact on energy consumption. This is especially applicable for service buildings with a highly variable occupation pattern during the day. The energy saving potential for this technique can be significantly larger than the savings potential for heat recovery. This is thus an area with great potential for development. Regulations and standards should clearly make a reference to this issue and promote this type of techniques. In general, heating energy consumption is proportional to ventilation rates, but cooling consumption increases if ventilation rates are smaller. In Summer, the optimum ventilation pattern is low ventilation rates when the outdoor temperature is high and large ventilation rates otherwise, i.e., free-cooling.

Energy consumption due to fans can be small in the total HVAC energy consumption if good design and specification take place, representing up to 15% of total HVAC needs, but, in some particularly badly designed cases, it can easily exceed 50% of total consumption. Electricity to run the fans is an expensive form of energy, and it should thus be reduced through a careful selection of components and careful design.

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