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Characteristic values of natural ventilation and air conditioning

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Summary

This investigation is part of project NATVENT™, a concerted action of nine institutions of seven European countries under the Joule-3 program. It aims to open the barriers that blocks the use of natural ventilation systems in office buildings in cold and moderate climate zones.

The choice to apply natural ventilation in office buildings is very arbitrary: it depends very much on the personal preference of the architect or taken for budgetary reasons, even sometimes not considered at all. This article proposes a method to compare natural ventilation with more complicated mechanical ventilation systems based on reliability, comfort, initial and maintenance costs and energy consumption. It shows clearly the strong points (cheap, reliable) and the weak points (limited cooling capacity) of natural ventilation.

1. Introduction

NATVENT™ is a Pan-European project under the Joule-3 program. It aims to open the barriers that block the use of natural ventilation in office buildings. One of its actions is the integration and maintenance of natural ventilation systems.

In practice the choice to apply natural ventilation with night cooling is very arbitrary: it depends very much on the personal preference of the architect or taken for budgetary reasons, even sometimes not considered at all. In many cases natural ventilation can still be a very competitive alternative. One reason for this ignorance for natural ventilation is the lack of tools to compare it with other ventilation systems.

This article proposes a method to develop such a tool. First the basic concepts of reliability and maintainability will be discussed. Afterwards other performance characteristics are introduced, such as air quality (AQ), comfort performance (CP_x), where 'x' stands for the maximal allowable internal load per square meter, budgetary performance (BP) and energy performance (EP)

Finally these performance characteristics are used to choose the appropriate ventilation system for certain conditions.

2. Performance features

A (ventilation) system can be assessed by the success at which it will obtain the design objectives. These objectives can be reached completely or sometimes only to a certain extend. By giving each system a characteristic value (between 0 and 1), one can rank the success of that system for that specific feature. By summing up these characteristic values an overall performance characterization is obtained that can be used to compare the different systems. Performance features that can be used to categorise a ventilation system are: reliability, overall comfort criteria, costs (first and maintenance), energy consumption and safety features.

* Reliability: Without any numerical calculation it can be said that traditional natural ventilation systems are far more reliable, because they do not need power and have a small number of components. Of course when these systems will become more complicated by adding motors and sensors for better control, the performance may increase but the reliability will eventually approaches that of ordinary mechanical ventilation systems.
* Overall comfort criteria: The factors that are typical in natural ventilation systems and that should be discussed in relation with air conditioning systems, are air motion (draught), space humidity, noise level, air cleanness, and psychological effects (acceptance of higher temperatures with openable windows).
* Costs: The costs can be divided in first costs and maintenance costs. For automatic controlled natural ventilation systems the actuators and control system require maintenance. Because the actuators are not concentrated in one place, but spread out through the whole building, the personal costs are higher then the component cost.
* Energy consumption: The outside air supplied by the ventilation system should be heated to room temperature. Here natural systems have the drawback that heat recovery is very difficult to apply. Mechanical ventilation and air conditioning systems can be equipped with heat recovery units. But on the other hand mechanical ventilation systems need fans to transport the air and therefore they use electricity. Air conditioning systems not only need energy for transport, but also use a substantial amount of energy for conditioning the air. In general the energy costs of air conditioning systems are about three times higher than for mechanical ventilation systems [1].
* Safety features: Other features that are difficult to quantify are fire and smoke control and safety against burglary. These are very complex and beyond the scope of this paper.

3. Theoretical background [2]

A system that cannot fulfill the function for which it is designed, fails. The reliability of the system depends on the period in its life cycle, in which it fails; when this occurs in the first period of its life cycle, the system is not reliable. On the other hand, when it fails at the end or over it's (theoretical) life cycle, the system is said to be reliable.

The reliability R(t) of a system or a component is defined as the probability of failure free functioning in a certain time interval (0 to t) under defined conditions. When f(t) is the failure probability density function (the probability that the system fails in time interval (t, t+dt)), then

$$F(t)=\int_0^t f(t)*dt$$

is the unreliability function. The reliability R(t) is defined as the complementary function of the unreliability function F(t):

$$R(t) = 1 - F(t)$$

The conditional probability density function or failure degree z(t) is the probability that the system fails in the time interval (t, t+dt), given, that it has not failed till time t under certain conditions. It is defined as:

$$z(t) = \frac{f(t)}{R(t)}$$

The discussed quantities above are related to distribution functions, which can be characterized by certain parameters. One of the most important distributions is the negative exponential distribution, given by

$$R(t) = e^{-\lambda * t} \qquad \text{with} \qquad \lambda = \frac{1}{MTBF}$$

λ is the failure rate, defined as the fraction with failure of tested pieces within a period dt. MTBF is Mean Time Before Failure.

The main characteristic of this distribution is that failures occur at random. This means that the probability of failure in each interval of the duration of its life time is the same, so the failure degree is a constant. When the MTBF is reached, there are only 37% survivors of the initial population, see figure 1 for some examples of the negative exponential distribution.

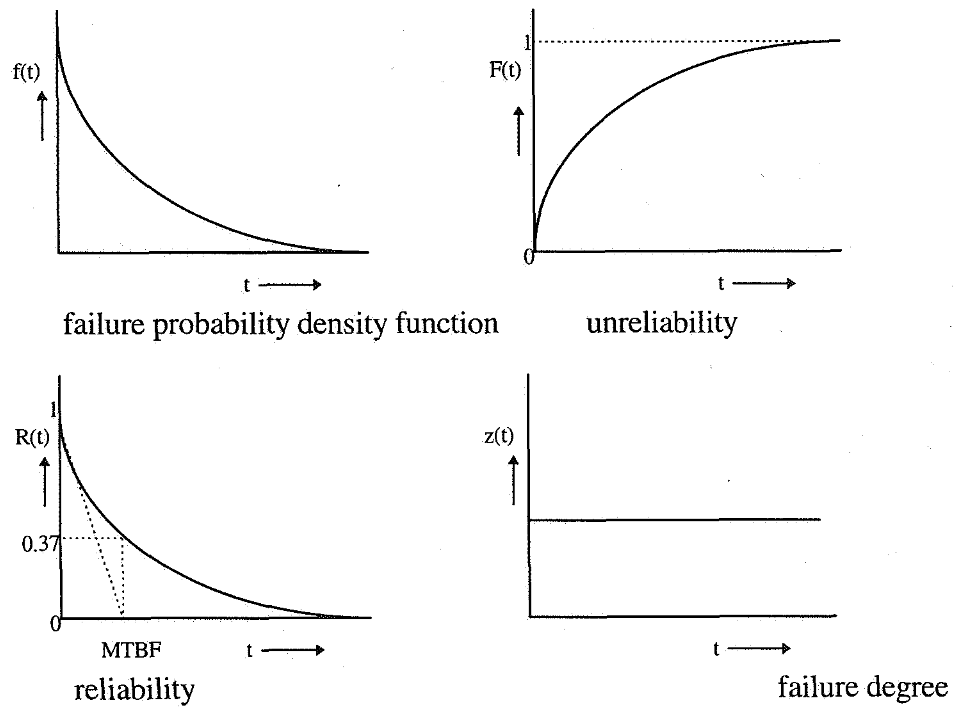

Figure 1   The negative exponential distribution

4. Reliability analysis

For every function of a technical system the demand for reliability needs to be described in the demand specification. When the reliability's of all the separate components of the system are known, the reliability on system level can be determined with a reliability model and rules from mathematics. Fig 2 shows the reliability's of the components of a simple system.

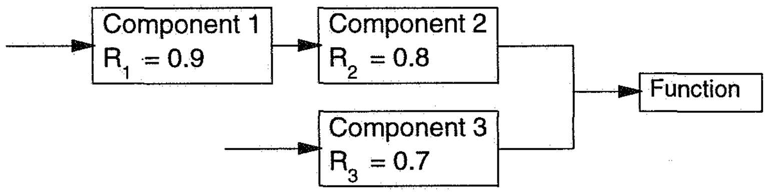

Figure 2   Example of a reliability model for a simple system

This system functions when the components 1 and 2 function or when component 3 functions or when all 3 components are functioning. The reliability of the branch that consists of component 1 and 2 is:

$$R_{1,2}(t) = \prod_{i=1}^{n} R_i(t) = R_1 * R_2 = 0.9*0.8 = 0.72$$

The system reliability now becomes:

$$R_{syst}(t) = 1 - \prod_{i=1}^{n} F_i(t) = 1 - (0.28*0.3) = 0.92 \qquad \text{(F=1- R)}$$

This procedure is called a reliability analysis.

The reliability of the separate components can be determined with historical data, by registration of occurred failures or by testing of the components in a laboratory under simulated operation circumstances. In [2] are given life spans and failure rates (failures per 10^6 h) of some selected components and equipment's. In this study reliability is considered as a measure for maintenance costs.

5. Reliability analysis of HVAC systems

Based on the procedure described in the foregoing paragraph four HVAC systems will be analyzed. These systems are:

1. Natural ventilation with radiators for heating
2. Same as 1 but with motorized windows and vents for night cooling
3. Mechanical ventilation with radiators
4. Variable Air Volume (VAV) system

The reliability analysis is based on the following assumptions:

* The system only functions when all components are functioning
* The system is used non-stop 24 hours a day, 365 days a year
* All components have an exponential reliability distribution
* The components which are not likely to fail have a reliability of 1
* Only components which are considered important are included

The reliability for a period of 1 year is calculated. This means that the installation is used for 1 * 365 * 24 = 8760 hours. So the reliability of a component is given by: $R(8760) = e^{-\lambda \cdot 8760}$, with λ is the failure rate of the component.

The reliability of the entire system is the product of the reliability's of its components.

To illustrate the procedure, the reliability of a natural ventilated system with motorized windows and vents for night cooling and radiators for heating (see figure 3) is determined.

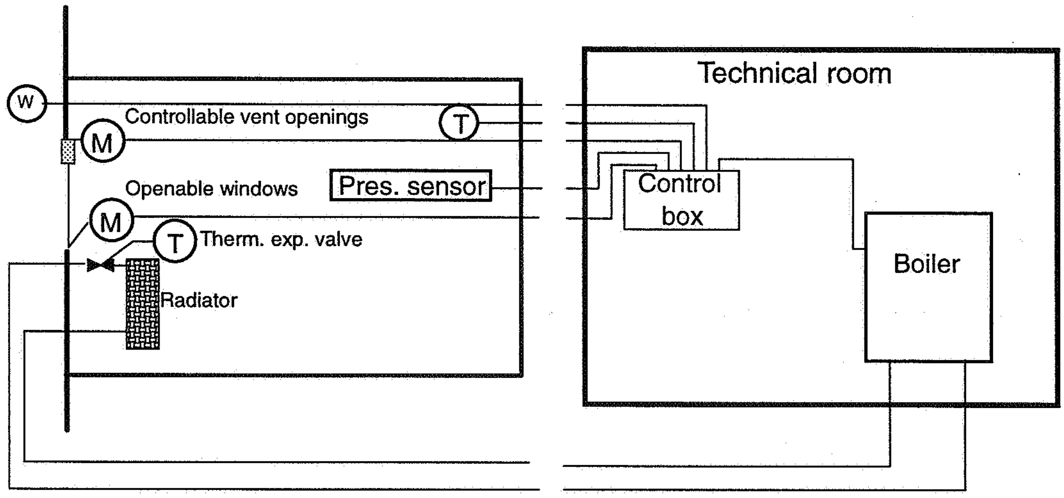

Figure 3. The ventilation system with motorized windows and vents and radiators for heating

Components	Failure rate : λ	Reliability
controllable ventilation opening		1
openable windows		1
tubes		1
radiator		1
boiler		
elec. controller		
thermostatic expansion valve	10^{-5}	0.916
elec. servo motors (2 x)	2×10^{-5}	0.839
presence sensor	10^{-6}	0.991
weather sensor	10^{-6}	0.991
temp. sensor	10^{-6}	0.991

Total system reliability (rough estimate !): R= 0.648

In the same manner the reliability's of the other systems are determined. The results are given in Table I. As expected, the reliability of the Variable Air Volume System drops dramatically because the number of its components is much higher.

Table I. Reliability's of some HVAC systems → open mechanic.

System	Description	Reliability
1	Natural ventilation + radiator heating	0.8
2	As 1 + controlled windows and vents for night cooling	0.6
3	Mechanical ventilation + radiator heating	0.6
4	Variable Air Volume System	0.3

6. Other characteristic values

Other features that can be used to compare the system performance besides reliability are:

Air Quality: $$AQ = \frac{\text{Fresh air supplied by the system}}{\text{Fresh air required according specifications}}$$

Although simulation studies showed that well-designed natural ventilation systems in general can easily satisfy the specifications, there are periods with too low/too high rates [3]. Considering the number of hours with too low ventilation rates the AQ-value is set at 0.8. System 2 has an AQ-value equal to 1. It has a rule based control system [4] that adjusts the window opening as a function of wind speed and wind direction, so that on average a constant flow of outside air is supplied. Because mechanical- and VAV-systems deliver the right ventilation rates under all circumstances, AQ = 1 for these systems.

Comfort Performance: $$CP_x = \frac{\text{Cooling delivered}}{\text{Cooling required}}$$

x = the internal load per square meter floor area

With natural ventilation without night cooling the maximal internal load is only 15 W/m^2 (see Table II); this means, that at CP_{25} (internal load is 25 W/m^2) the comfort performance is only CP_{25}=15/25=0.6. When the internal load is increased to 40 W/m^2, the comfort performance drops to CP_{40}=0.375. With system 2 it has been experimentally found [5], that with night cooling the internal load can be increased to 30 W/m^2; consequently CP_{25}=1($0 <= CP_x => 1$) and CP_{40}=0.75.

Budgetary Performance: $$BP = \frac{\text{Cost of the cheapest system}}{\text{Cost of the system considered}}$$

The budgetary performance (BP) can be determined with Table II

Table II. Costs and allowable internal load (use of outdoor shading)

System		per m^2 net occupied area		
		Investment cost	Maintenance cost	Internal load (max)
		NLG	NLG /year	W
1	Natvent+rad	154	4.4	15
2	As 1 + controlled windows and vents for night cooling	300	9	30
3	Mech. vent+rad	330	8.8	30
4	VAV system	680	18	>50

Energy Performance: $EP = \dfrac{\text{Primary energy of natvent - system}}{\text{Primary energy of system considered}}$

Table III shows typical values of primary energy consumption's for a well isolated, medium heavy office building facing south with outside shading. With these values EP can be determined for the various systems. It is clear, that the air conditioning system has the highest energy consumption. It uses approximately three times more energy than the other systems.

Table III. Energy consumption of some HVAC systems

System		Yearly energy consumption [MJ/m^2]			
		Heating	Cooling	Transport	Total
1	Natural ventilation+radiators	447	0	0	100%
2	As 1 + controlled windows and vents	447	0	0	100%
3	Mechanical ventilation + radiators	447	0	35	108%
4	Variable Air Volume system	756	399	420	350%

7. Characteristic values

Table IV. Characteristic values with an internal load of 25 W/m^2

System		R	AQ	CP_{25}	BP	EP
1	Natural ventilation +radiators	0.8	0.8	0.6	$\frac{154}{154}=1.0$	1.0
2	As 1 + controlled windows and vents	0.7	1.0	1.0	$\frac{154}{300}=0.5$	1.0
3	Mechanical ventilation + radiators	0.6	1.0	1.0	$\frac{154}{330}=0.5$	0.9
4	Variable Air Volume System	0.3	1.0	1.0	$\frac{154}{680}=0.2$	0.3

Table V. Characteristic values with an internal load of 40 W/m^2

System		R	AQ	CP_{40}	BP	EP
1	Natural ventilation+radiators	0.8	0.8	0.4	1.0	1.0
2	As 1+controlled windows and vents	0.7	1.0	0.7	0.5	1.0
3	Mechanical ventilation+radiators	0.6	1.0	0.7	0.5	0.9
4	Variable Air Volume System	0.3	1.0	1.0	0.2	0.3

Je kan van maken als alle factoren even veel! zijn
Andere weegfactoren (bvb comfort x 5)

The characteristic values as defined in the preceding paragraphs can be determined for the various ventilation systems for different conditions and locations. Tables IV and V shows the characteristic values of four ventilation systems for a well isolated, medium heavy office building facing south with outside shading and with internal loads of respectively 25 W/m^2 and 40 W/m^2. It must be emphasized, that these values are rough estimates, based on generally accepted data [1] and personal experience [5]. It shows that natural ventilation with night cooling can still be used with an internal heat load of 25 W/m^2
These tables forms a simple tool for architects and developers to choose the appropriate ventilation system for a certain condition, included natural ventilation.

8. Conclusions

In the preceding paragraphs the characteristic values of various ventilation systems such as reliability, air quality, comfort, budgetary features and energy performance are defined. After these values are tabulated, they can be used to choose the appropriate ventilation system, ranging from simple natural ventilation to more sophisticated air conditioning systems and in doing so bring natural ventilation in the focus of the architect or developer as a comparable ventilation system with its strong (cheap, reliable) and weak points (limited cooling capacity)

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