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REDUCING COMPLEXITY IN OUTDOOR AIR SYSTEMS

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ABSTRACT

The outdoor air system is a major subsystem of any heating, ventilating and air conditioning (HVAC) system. In this paper, the most used outdoor air systems are described and the usual design recommendations are enounced. Good indoor air quality is the highest-level functional requirement of an outdoor air system. Its accomplishment depends on indoor pollution control, as for example CO_2 control, and on the outdoor airflow rate. Reducing the complexity of outdoor air systems may be as easy as increasing the outdoor airflow rate to take into account the worst operating scenario. This solution affects the system dimensions, initial cost and energy consumption, which in some instances may be difficult to handle.

The system range of indoor air quality might be evaluated in terms of independence and information content. On the other hand, the dedicated outdoor air system can be regarded as an independent design for which the outdoor airflow rate and the filtration efficiency must be defined. The present paper proposes a new computation method for the information content that is based on the fuzzy definition of membership, instead of probability density function.

Keywords: Ventilation, Complexity, Fuzzy Sets.

1 INTRODUCTION

In the western countries, 90% of people spend 90% of their time inside closed buildings, a fact that makes indoor air quality an important asset for public health. Nonetheless, the effort that is made in the definition of design specification of HVAC systems just represents 5% to 10% of the full design effort, even though it is known that around 90% of the system cost and 90% of the customers' satisfaction are implicitly defined by the design specification [11].

European Union member countries might implement the Energy Performance of Buildings Directive (EPBD) [1] in their national legislation at latest on the beginning of 2006. This directive imposes to the designers of new buildings the issuing of a statement on energy consumption that takes into account the ventilation needs.

As it is intentionally stated in the 11th consideration of EPBD, its implementation will indirectly influence the HVAC industry in what to indoor environments concerns.

Subsequently, EN 13779 [2] has defined several categories of comfort in terms of indoor air quality. Whatever will be the chosen category for a design, it will influence significantly the sizing of the HVAC equipment and consequently the required energy.

As a regulation for indoor environments has not yet been published, this paper may be regarded as contribution for establishing the ventilation rates using Axiomatic Design (AD) for environments intended for human occupancy.

The present study is based on office buildings but may be used for other buildings with similar characteristics.

2 THE CURRENT VENTILATION STANDARDS

The required outdoors air supply rate of the HVAC ventilation subsystems has changed significantly along the last two decades.

After the 1973 and the 1979 oil crises, the typical outdoor air rate has dropped down to as low as 5 $m^3/(h.person)$, but such a low rate has been found as the main cause of the sick building syndrome (SBS).

Later, in prENV1752 [6], Fanger proposed that the ventilation rate could reach 80 $m^3/(h.person)$. In turn, EN 13779 sets the default value for medium indoor air quality for human occupancy to 45 $m^3/(h.person)$, DIN 1946 Teil 2 01-94 specifies a outdoor air supply of 60 $m^3/(h.person)$ for high-class office premises. In addition, ASHRAE 62-1999 [4] specifies a outdoor air supply of 36 $m^3/(h.person)$ for office premises, and calculations based on the latest ASHRAE 62.1-2004 [3] usually yields to a lower value of around 30 $m^3/(h.person)$.

Therefore, what ventilation rate might one adopt? Why is it so hard to find out the appropriate ventilation rate? The answers depend on the design goal.

In fact, EN 13779 aims at providing *comfortable and healthy indoor environment*, and defines four categories for indoor air quality (from IDA1, the highest indoor air quality, to IDA4, the lowest indoor air quality, while ASHRAE 62.1 objective for acceptable

indoor air is *not to have known contaminants at harmful concentrations as determined by cognizant authorities, and with which a substantial majority (80% or more) of the exposed people do not express dissatisfaction.*
Although the difference in objectives, ventilation rates prescribed by ASHRAE are similar to the ones of EU's IDA3 or IDA4.
In addition, the answers also depend on method: rates in former standard are targeted toward satisfying un-adapted visitors. This is also the approach of Fanger's prENV1752, and of the 1989 to 2001 versions of the ASHRAE 62. The new ASHRAE 62.1, however, takes into account the perception of adapted persons.
On the other hand, a EU study of 56 office buildings showed that the ventilation rates varied by a factor of two above or below the designed ventilation rates [5].
This is caused by accumulation of uncertainty that can be summarized as follows:

a. Number of people:

Usually, the sizing of ventilation systems is based on the number of exposed people. Floor area per person is considered, which may vary from 7 to 20 m^2/person for landscape type office rooms. On the other hand, ASHRAE 62.1 requires the definition of the actual number of exposed people and introduces a diversity factor to take into account the random presence of people in spaces other than their own. It is usually hard to have an accurate definition of number of people.

b. Building emissions:

Materials in buildings have a substantial disparity in what composition and emission concern, and it is likely to have emissions of the same compound caused by similar brand new materials in a range of 1 to 1000. The range is narrower for a steady-state condition, but finding out the time that is required to reach steady state has been the issue of several studies. Low polluting buildings that use low emission materials need half the ventilation rate comparing to other kinds of buildings. Typically, office buildings require about 6 times the ventilation rate of low polluting ones, with a deviation of 1 to 30 times [6].

c. Emissions of people and building:

For buildings intended for human occupancy, it is usual to take into account the ventilation rate per person. The ventilation might remove the people's emissions as well as the building's emissions, and it is usual to consider that the indoor air quality is related to the difference between the CO_2 concentrations at indoors and at outdoors [4]. A CO_2 concentration of 1000 ppm, or a difference of 700 ppm to the outside is widely used, which roughly corresponds to 36 m^3/(h.person). This corresponds to 15% of the dissatisfied people, which is the better category proposed by CR1752 [7]. EN 13779 proposes 18 to 72 m^3/(h.person) as default values, depending on the air quality category.
The impact of air contaminants on human beings can be either additive, independent, synergetic or antagonistic [12]. ASHRAE 62.1 has adopted a conservative reasoning: adding the effects, which decreases the probability of under-ventilation.

d. Filters and particles:

Particles may cause severe allergic reactions and may carry viruses. When deposited in highly moisturised ducts, those particles create good conditions to raise colonies of all kinds of mold and bacteria.
Therefore, the particles might be filtered, and the humidity inside ducts should be kept lower than 80%, usually by means of air re-heating.
According to the Environment Protection Agency (EPA), the long-term geometric average for outdoor air should not exceed 50 μg/m^3 for PM_{10} particles, that is, particles which aerodynamic diameter do not exceed 10 μm. The threshold limit value (TLV) is usually around 10 mg/m^3, but depends on the nature of the particles. In the lack of an accurate specification, one tenth of TLV is usually allowed for indoor air, which yields to around 1000 μg/m^3. However, the typical value for healthy environments is around 100 μg/m^3, and Health Canada refers 40 μg/m^3 as a mean value for residential applications. The allowed size for indoor particles is regulated for industrial and laboratory applications, but there is no same similar regulation for offices.
The filters for particulate matter should be located either upstream of all cooling coils (or at the entrance of the treatment unit) of buildings located in areas with a high concentration of PM_{10} particles.

e. Room ventilation effectiveness:

Non-homogeneity of the air in a room depends on the flow pattern and on the kind of pollution sources. The ventilation effectiveness equates to one when there is a uniform mixing of air and pollutants. This is a common situation when the cooling airflow is supplied close to the ceiling. If heating is needed, then the ventilation effectiveness decreases to 0.8, or even to a lower value, depending on the air temperature [7].

f. System efficiency:

The ability of the ventilation system to deliver outdoor air to the breathing zone depends on the zone ventilation effectiveness and on the type of ventilation system [3].
In a single-zone HVAC system, all the outdoor air coming from outside is delivered to that zone. In a 100% outdoor air system, all the outdoor air is delivered to the multiple zones in a way that depends on the ventilation effectiveness of each specific zone and on the system balancing.
Otherwise, systems that serve multiple spaces by partially re-circulating the air from those spaces will deliver a different fraction of outdoor air to each specific space. The nature of such systems can be of either constant or variable volume (flow).
In constant volume systems, the airflow depends on the cooling requirement of each space. A space with a larger cooling requirement would receive a larger amount of air and consequently a larger amount of outdoor air. Outdoor air supply would depend on the cooling or heating requirement, and the space with the lowest ratio between the total air supply and the outdoor air requirement must be identified in order to define the appropriate outdoor air volume rate. These systems may have temperature control through a re-heating system.
Variable air volume systems (VAV) require a minimum supply flow when the temperature control is achieved. In such a case, a major concern is to find out the minimum air supply that carries the required outdoor airflow.
Exact values of ventilation efficiency can be determined, usually varying from 0.6 to 1.0.

g. Monitoring and balancing outdoor air flow:
Finally, there is uncertainty in monitoring and balancing the airflow. An accuracy of 200 m^3/h is a typical target. Therefore, for small installations of 200 kW, one should expect a outdoor airflow error of ± 5%, and a similar error for the air supply.

3 DEDICATED OUDOOR AIR SYSTEM

Two basic types of ventilation systems may be used as part of HVAC systems: the dedicated outdoor air system (DOAS) and the multiple zone re-circulating system (MZRS). Variable air volume (VAV) and constant volume systems are variants of MZRS.

DOAS is extensively used in Europe in association with terminal units, such as fan-coil boxes, chilled ceilings or induction units. For this reason, DOAS will be analysed in detail in the present paper.

The role of a DOAS is to treat the outdoor air and deliver the required airflow to single or multiple spaces [9]. Fig. 1 depicts a DOAS that serves multiple spaces. Each one of those spaces is provided with a dedicated fan-coil, so that the air can be conditioned in an independent way for each space.

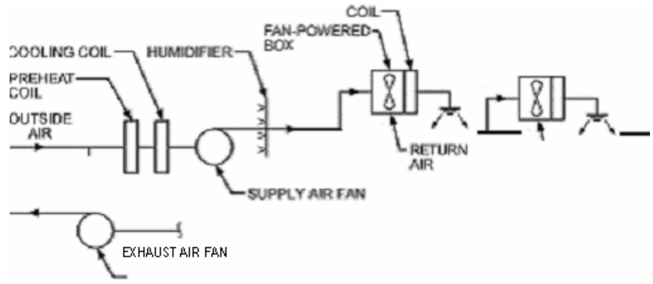

Figure 1. The Dedicated Outdoor Air System (DOAS)

First, the outdoor air is processed in an air-handling unit, passing through processes of filtration, heating, cooling and humidifying, so that the air comes close to the required indoor condition.

Next, the air is mixed together with return air in the dedicated fan-coil. Low efficiency filters are usually included in the mixed air paths.

The mixed air is subsequently cooled or heated as required and supplied to the various spaces in order to take away the thermal load. Adjusting the coil temperature and the fan speed sets the temperature and the air velocity of each space. During the design process, only the mean air velocity is usually considered.

Finally, an exhaust fan removes the air at the same flow rate as the air-handling unit supplies it.

The highest-level functional requirement of a HVAC system is to provide treated air to one or more spaces to ensure thermal comfort and a healthy environment. In a DOAS system, the air-handling unit and ducts form the ventilation system and the terminal units the active system.

Since each space is conditioned in an independent manner, just the functional requirements and design parameters of one room are depicted, although each room has its own functional requirements and design parameters. Nevertheless, placing them in the figure would not increase our understanding about the entire system.

Fig. 2 summarises a possible zigzag decomposition [13] of a DOAS.

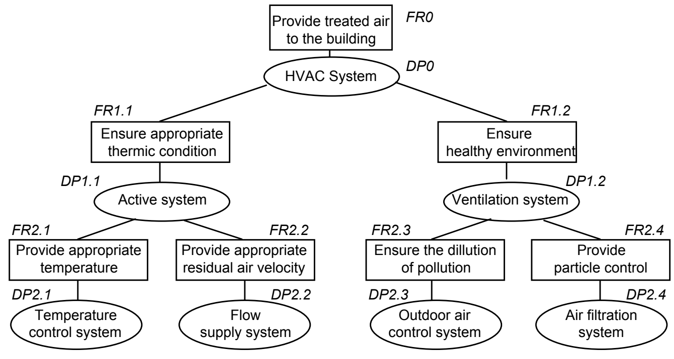

Figure 2. The HVAC decomposition trees

Changing the airflow rate through the fan speed of the fan-coil will just cause minor effects in the filtration state and in the temperature of the air. Therefore, the design equation for the DOAS is:

$$\begin{bmatrix} \mathrm{FR0} \\ \mathrm{FR1.1} \\ \mathrm{FR1.2} \\ \mathrm{FR2.1} \\ \mathrm{FR2.2} \\ \mathrm{FR2.3} \\ \mathrm{FR2.4} \end{bmatrix} = \begin{bmatrix} X & & & & & & \\ & X & & & & & \\ & & X & & & & \\ & & & X & x & & \\ & & & & X & & \\ & & & & & X & \\ & & & & x & & X \end{bmatrix} . \begin{bmatrix} \mathrm{DP0} \\ \mathrm{DP1.1} \\ \mathrm{DP1.2} \\ \mathrm{DP2.1} \\ \mathrm{DP2.2} \\ \mathrm{DP2.3} \\ \mathrm{DP2.4} \end{bmatrix} \qquad (1)$$

where X and x denote strong and weak relationships, respectively. Eq. 1 shows that the system can be developed in an independent way if these minor effects are not taken into account during the design development process, which is quite usual.

4 DESIGN FOCUS

By the end of section two, one could realise how unclear is to set an airflow rate specification. Therefore, a new sizing procedure is proposed for DOAS. The new method uses a combination of Axiomatic Design, fuzzy definition of the variables, and data that is strongly inspired in both EN13779 and ASHRAE 62.1. The questions to be answered: what ventilation rate should be set and what kind of filters should be used?

4.1 VENTILATION RATE

As we could realise, estimating the number of exposed persons in a zone is a difficult issue. In addition, buildings usage may significantly change with time, and it is important to take into account their entire lifetime.

The summative effects of people and of building environment are modelled using fuzzy variables. The membership functions are of triangle form, μ_A = triangle(a, b, c), where a and b are the lower and upper bounds of the universe of discourse of variable A for which the membership is zero, and c is the value belonging to the universe for which the membership is one. The membership value of one will be assumed as the default value.

The ventilation rate per person should be substituted by the ventilation rate per occupied area. The ventilation rate per 10 m², V_{10}, is the proposed variable, which is given by:

$$V_{10} = \frac{(D.P.R_p + A.R_A)U}{E_v}, \qquad (2)$$

where D is the diversity factor applied to the number of exposed persons P that are expected in the area A; R_P and R_A are the ventilation rates per person and per area, respectively; U is the accuracy of measurement and E_v the ventilation effectiveness.

Table 1 contains the rate per person R_P and the rate per area R_A according to the required indoor air quality.

Table 1. (a,b,c) for variables R_P and R_A

Category	R_P [m³/(h.person)]	R_A [m³/(h.m²)]
V1	(24,36,48)	(3.5,5,6)
V2	(20,22,24)	(2.5,3,3.5)
V3	(9,15,20)	(1.5,2,2.5)
V4	(5,9,16)	(0.5,1,1.3)

Categories V1 to V4 in Table 1 are strongly inspired on EN13779, and similar percentages of dissatisfied persons are expected. Categories are named V1 to V4 instead of IDA 1 to IDA 4, since they do not exactly correspond to the EN13779 categories.

Table 2 summarises the remaining variables.

Table 2 – Variable definition

Variable	Name	Units	(a,b,c)	Section 2 paragraph
D	Diversity factor	---	(0.7,0.9,1.0)	a.
P	Number of persons	person	(.5, .8, 1.4)	a.
A	Area	m²	(10,10,10)	a.
E_v	Ventilation effectiveness	---	(0.8,0.9,1.0)	e.
U	Accuracy	---	(0.9,1.0,1.1)	g.

Using Eq. (2) as a fuzzy operation and fuzzy variables as defined in Tables 1 and 2, one can obtain the required ventilation rate per area. The computation was achieved using only the membership values zero and one. Table 3 expresses the computed V_{10} values for each category:

Table 3 – (a, b, c) for ventilation V10

Category	V_{10} [m³/h] per 10m²
V1	(39,85,176)
V2	(29,52,95)
V3	(16,35,73)
V4	(6,19,49)

Table 3 clearly shows how difficult it is to define a ventilation rate in the lack of accurate data. ASHRAE 62.1 tries to supersede this uncertainty with more data on building usage, but one feels every day how uncertain and ephemeral this approach is.

4.2 FILTERS

According to EN13779, the recommended air matter filters for IDA1 to IDA4 air quality categories are shown in Table 4. Filters are identified according to EN779, where G group filters are rated according to *average arrestance of synthetic dust* and F group filters are rated according to *average efficiency of 0.4 μm particles.*

Table 4. Required Filters

Category	Filters From ... to ...
IDA 1	F7 F9
IDA 2	F6 F8
IDA 3	F6 F7
IDA 4	G4 F6

Initial fractional efficiency (E_i), which is measured by means of an optical particle counter [10], allows indicating the degree of filtration as a function of particle size. Class F6 filters and above keep around 100% of particles with aerodynamic diameter above 5 μm. Therefore, 5 μm was chosen as the upper bound of discourse. As for the lower bound, it will be 0.5 μm because this is the lower particle size of interest for demanding applications [8]. Membership is zero for both bounds (0.5 and 5.0 μm). Membership of one is the weighted average of filtration efficiency. Table 5 contains the values of a, b and c for the five filter classes of Table 4. They are identified as FF4 to FF9 as Table 5 presents the fuzzyfied filters that correspond to G4 to F9.

Table 5. (a,b,c) for filters

Filter	Efficiency, Ei [%]
FF4	(5,27,96)
FF6	(22,35,98)
FF7	(62,76,100)
FF8	(72,82,100)
FF9	(95,98,100)

5 FUZZY COMPLEXITY

Since the independence axiom is satisfied, design simplicity should be achieved by minimizing the design information content, as per Axiom 2.

In order to achieve this objective, the DOAS system range must intercept the system range. The interception area, called common area, is the zone where the system behaves according to the design range. The probability *p* of achieving the objective is defined as the ratio between the common area and system area of the functional domain. The information content for an event of probability *p* is:

$$I = -log_2 p = log_2 \frac{\text{system area}}{\text{common area}} \qquad (3)$$

The total information content of a design with n independent FRs is the sum of the information content that is associated to each FR. If the information content is very large then the system will never work. On the other hand, if the probability of success is one, then the design's information content is zero and the system will surely achieve its objective [14].

Although the design range is usually specified, the system range may be very difficult to define. The proposed solution is to use all data in fuzzy requisites and implications in linguistic terms, defining the system range "as built" from the implications. Membership functions replace pdf functions and the overall implication process defines the system range.

The target of this paper is to analyse function $FR_{1.2}$, that is, to ensure a healthy environment. As it is impossible to guarantee that an environment is healthy, a parallel metric is used: the Satisfaction. This is a psychological measure taken by a trained team. This evaluation method has ever been used and is probably the best way to evaluate office environments. For this purpose, CR1752 adopts three categories of dissatisfaction, from 15 to 30%, which are used to define the overall satisfaction according to Table 6.

Table 6. (a,b,c) for satisfaction

Satisfaction	(a,b,c) [%]
High (H)	**(85,95,100)**
Medium (M)	**(75,85,90)**
Medium Low (ML)	**(70,80,85)**
Low (L)	**(60,70,80)**
Very Low (VL)	**(0,45,65)**

$FR_{1.2}$ is decomposed in two lower level functional requirements which achievement depends on $DP_{2.3}$ (Outdoor Air Control System) and $DP_{2.4}$ (Filtration System), which control the Ventilation Rate and the Filtration Efficiency, respectively.

The crisp values of Ventilation Rate and Filtration Efficiency are used to determine a function for satisfaction membership that is similar to a probability density function (pdf) [15], and the information content is obtained through Eq. 3.

The computation process starts by fuzzyfying the inputs, i.e., by using Tables 3 and 5 to estimate the degree of fulfilment for a given pair of ventilation airflow rate and filter efficiency. The following example illustrates the process. Suppose that the pair (V_{10}, Filter) = (50, 85) is used: the airflow rate of 50 m^3/h. per $10m^2$ belongs to categories V1, V2 and V3 of ventilation (see Table 3), although with different degrees of fulfilment represented by $\mu_{V10}(50)=(0.24\ 0.91\ 0.61\ 0)$. A similar reasoning applies to $\mu_{Filter}(85)=(0.16\ 0.21\ 0.62\ 0.83\ 0.00)$. Each one of the possible fuzzy pairs will have implication on satisfaction. The proposed implication rule is described in Table 7, following an EN13779-like format, e.g., the fuzzy ventilation V3 and a the fuzzy filter FF6 will cause a medium/low fuzzy satisfaction.

Table 7. Implication rule

	V1	V2	V3	V4
FF4				**L**
FF6		**M**	**ML**	**L**
FF7	**H**	**M**	**ML**	
FF8	**H**	**M**		
FF9	**H**			

The proposed crisp pair has a membership of 0.61 to V3 and 0.21 to FF6, causing some effect in medium/low satisfaction.

Based on the conservative assumption that the minimum membership will have a decisive influence, the fuzzy relation "minimum" is applied, yielding to min (0.61, 0.21) = 0.21. Therefore, this pair of values yields to a medium/low membership with a degree of fulfilment of 0.21.

All the other pairs of values corresponding to Table 7 are calculated using the same fuzzy relation. This set of values is called the antecedent of the implication expressed in Table 7. The consequent (i.e., the satisfaction) will be scaled in a basis of antecedent values using the Larson Product implication operator [16]. In the example, medium/low satisfaction (70, 80, 85) will be scaled by a 0.21 factor. The consequent set is represented in Fig. 3.

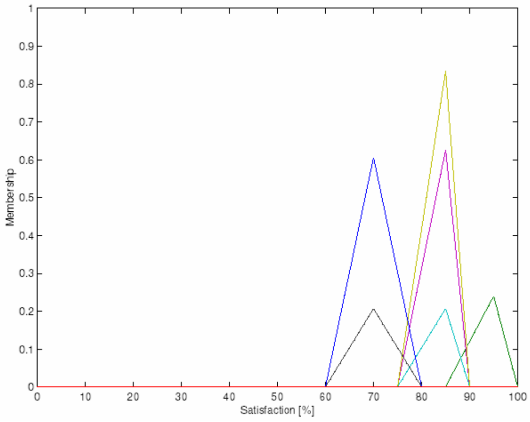

Figure 3 – Consequent Set of Fuzzy Rules

Next, the outputs are aggregated using a max function that represents the system behaviour caused by the input crisp values. The design range is linguistically defined as "more than 90% satisfaction" and is represented by a trapezoidal function which membership equates to zero at 85 and 100%, and to one from 90 to 95%. The design range function and the satisfaction membership function allow for computing the information content through Eq. (3).

Fig. 4 depicts the design, the system and the common ranges for the present example.

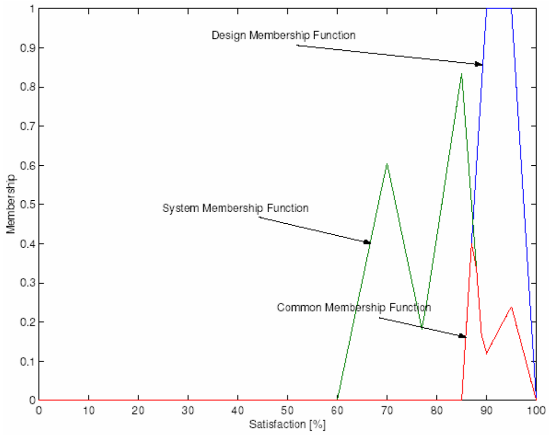

Figure 4 – Design, System and Common Ranges

6 RESULTS AND CONCLUDING REMARKS

A computer simulation was run for airflows rates ranging from 45 to 175 m^3/h per 10 m^2 and for average initial filter efficiency ratings that range from 50 to 100%. A surface representing the information content was obtained as shown in Figure 5.

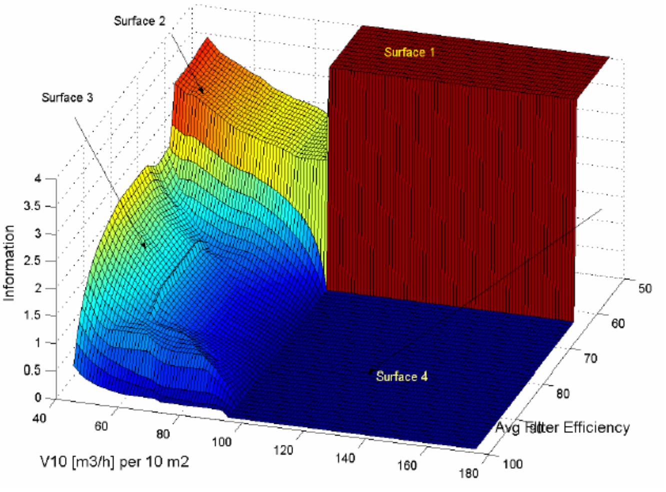

Figure 5 – Necessary Information

Surface 1 of Fig. 5 is out of scale and represents a void common area, for which the information content is infinite. The effect of the implication rule for low efficiency filters is depicted by the scarped surface 2, for which the information content ranges from 2 to 3. The valley surface 3 reflects the effect of high efficiency filters combined with low airflow rates. Finally, the horizontal flat surface 4 at the bottom of the valley, for which information content is zero, is the region of interest. Surface 4 corresponds to the combination of a filter of average initial efficiency above 64% with ventilation rates above 95 m^3/h per 10 m^2, and delimits the best design specifications for the system under design. Notice that this corresponds to 3 renovations per hour for a typical 3 m high space office, instead of the 2 renovations per hour commonly used as a design guideline.

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