ASSESSMENT OF NATURAL VENTILATION POTENTIAL FOR SUMMER COMFORT IN BUILDINGS ON MEDITERRANEAN COASTAL ZONES

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ABSTRACT

Natural ventilation in building is a common way to ensure indoor air quality, thermal comfort in summer and reduce energy consumption due to air conditioning. However, efficiency of such a system is highly dependent on climatic conditions.

In this paper we review the different ways to use natural ventilation in buildings and then we propose indicators to assess the potential of a site. The study focuses on the Mediterranean climate and especially the coastal zones, characterized by the occurrence of thermal breezes which can be used to improve natural cross ventilation.

INTRODUCTION

In France, the building sector is the largest energy consumer, accounting for over 45% of the total energy consumption. It is also the sector where the most important energy savings can be done. Rehabilitation or conception of a building must take into account the environment in which it is or will be located : evolution of temperatures and relative humidity, wind profile, solar resource, shadings... As shown in the ANR project VALERIE (Chesné et al., 2012) energy consumption of a building can be greatly reduced if it effectively exploits the resources of the environment. The design of "typical" low energy buildings, usually focused on thermal insulation, deprives them of these resources. We have to examine the problem more generally and focus on the availability of these resources accorded to the needs of the building, which evolve during days and seasons. To investigate the potential of the different resources it is necessary to define indicators to assess their contribution. It is therefore imperative to characterize the different climates and thus have reliable and available meteorological data over a sufficiently long period.

France has a great climatic diversity. As defined in the thermal regulation of buildings (RT), it is composed of eight climate zones. Joly et al. (2010) also propose a map based on an abstract partition of the factorial space organized by the order structure (Figure 1). Using a local interpolation method performed on a time series of 30 years, eight climates have been identified and mapped on the french territory. A coefficient involved in regulatory calculations to obtain labels such as the BBC (low-energy consumption building), varying the maximum

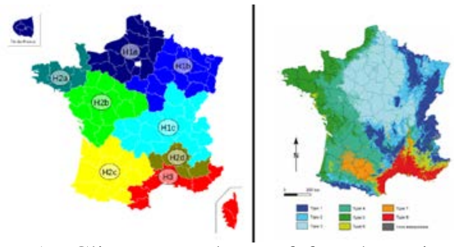

Figure 1: Climate typology of french territory in 8 classes : according to the RT (left) and Joly et al. (2010) (right)

consumption of primary energy between 40 and 75 $kWh.m^{-2}.year^{-1}$ depending on the climate zone. This significant variation shows the impact of climate on the energy consumption of buildings and the will to take it into account. However, even within the same climate zone, all regions are not subject to the same climatic conditions and therefore can not benefit from the same resources. This diversity shows the great importance of adopting a bioclimatic approach.

Among these different climates we focus on Mediterranean climate which is characterized mainly by hot and dry summers and mild and wet winters. It is a temperate climate, whose characteristics are found mainly around the Mediterranean sea (Figure 2). It also presents significant temperature differences between day and night. In terms of energy these

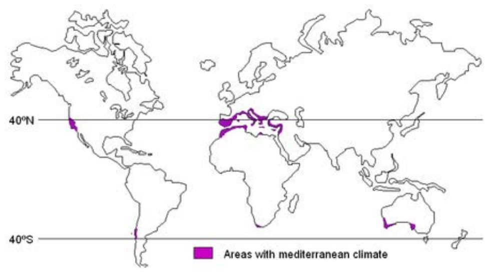

Figure 2: Mediterranean climatic zones

conditions induce specific needs, air conditioning needs being the most important for this type of climate. Taking into account the summer climate and its consequences in terms of comfort is a characteristic of Mediterranean buildings.

The problem of summer comfort is one of the major issues for this type of climate. For this purpose, we focus in this study on the potential of passive cooling which exploits free resources to reduce the temperature inside the building and provide a comfortable atmosphere.

The relief of the Mediterranean which is often uneven, also introduces additional nuances, creating microclimates. Corsica is a good example, with both plains, mountains and different coastal areas. The coastline is particularly interesting because the sea/land interface allows the creation of thermal breezes which can be exploited for applications in building natural ventilation.

NATURAL VENTILATION IN BUILDINGS

Building ventilation, both mechanical or natural, can occupy several roles such as ensure the indoor air quality, improve thermal comfort in summer and reduce energy consumption. Natural ventilation has the advantage of exploiting a free and abundant resource, remaining easy to use and cause no additional cost to the building design. It improves occupant comfort by creating air movement in the building and by cooling the building structure at night with lowest outdoor temperatures. Neglected since the 50s for mechanical systems of ventilation and air conditioning they tend to disappear from constructive methods. Natural ventilation, however, fits perfectly with the current issue which is to design low-energy buildings with low emissions of greenhouse gases.

Phenomena of natural ventilation

There are two types of physical phenomena which induce naturally an airflow in the building, one by wind effect and the other by stack effect. These two phenomena can occur simultaneously but at a given moment the effect of one of them generally predominates over the other.

Natural ventilation by wind effect
Natural ventilation by wind effect is simply done by openings positioned in the axis of the wind (Figure 3). The pressure difference induced can be described by :

$$\Delta_p = \frac{1}{2} C_p \rho v^2 \qquad (1)$$

Where C_p is the pressure coefficient, ρ the air density and v the wind speed. Only one opening is needed to create an airflow inside the building, but higher flow rates are achieved with cross ventilation. Facades containing the openings do not necessary need to be perpendicular to the wind axis. According to Givoni (1976) an angle between 30 and 60° allows better ventilation. Potvin and Demers (2005) also announced that a building at 45° relative to the prevailing winds will maximize high and low pressures improving natural ventilation. However, the effectiveness of a such system depends strongly on the wind profile of the site, the design of the openings and the building geometry. Sobin (1980) studied the effect of the shape of the openings and the wind direction on air velocities inside the building with wind tunnel experiments. Ji et al. (2011) also studied the effect of fluctuating wind direction on natural cross ventilation. It appears that under real conditions these parameters fluctuate constantly and have a significant impact on airflow rates and therefore on the efficiency of the system.

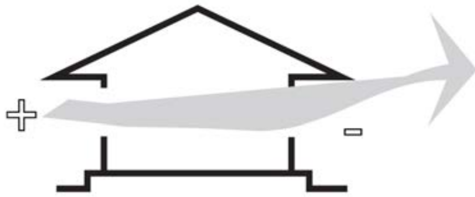

Figure 3: Natural ventilation by wind effect (Sharag-Eldin, 1998)

Natural ventilation by stack effect
Natural ventilation by thermal buoyancy is due to the difference in density between the air inside and outside the building :

$$\Delta_p = \rho_i g h \frac{T_i - T_o}{T_o} \qquad (2)$$

Where ρ_i is the inside air density, g the constant of gravity, h the vertical distance between the two openings, T_i the inside temperature and T_o the outside temperature. This technique is possible as there is a temperature difference between the inside and the outside. However, it does not achieve the high ventilation rates obtained by wind effect. Moreover, the position of the openings must respect more accurate guidelines. Here we must focus on a lower opening and a upper opening such as a roof evacuation (Figure 4). It is also possible to use the two phenomena but it requires opening management and building design a little more complex.

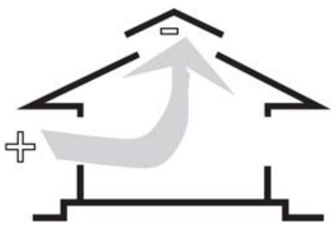

Figure 4: Natural ventilation by stack effect (Sharag-Eldin, 1998)

Uses of natural ventilation

Natural ventilation can be used in two distinct ways : for comfort ventilation, used during day, and for night ventilation to cool the building. However, according to Givoni (1991) these two techniques are not compatible.

Comfort ventilation
Comfort ventilation does not allow to reach a set

temperature but improves the physiological comfort of the occupant by creating an airflow. To obtain sufficient airflow rates by natural ventilation it is necessary to use cross ventilation. For optimal use of day time comfort ventilation the building should not absorb and store heat, so we have to focus on lightweight structures (wood, lightweight concrete, perforated brick ...). In terms of climate, the maximum temperature should not exceed 28-32 $°C$ depending on acclimation of the occupants (Givoni, 1992). This strategy is preferred if the difference between day time and night time temperatures is less than 10 $°C$. It is used especially in tropical climate characterized by a low thermal amplitude. The CSTB (Scientific and Technical Centre for Building) studied consideration of climatic parameters in the habitat on humid tropical climate (Sacré et al., 1997). It appears from this study that, with wind speeds greater than 1 m/s at the openings of the building, it is possible to effectively remove heat gain due to the sun and internal loads and improve the comfort feeling. If the use of natural ventilation is not possible, a similar comfort can be achieved by using a fan. However, it will cause an additional cost due to power consumption and will not evacuate the internal loads.

Night ventilation

Night ventilation allows to cool the building structure by convection and store cold to ensure thermal comfort during the day. To optimize its efficiency the building must not be opened during the day to not let enter warmer air. It should also benefit from adapted solar protections to minimize solar gain. Furthermore, the structure of the building must allow cold storage (heavy structure) and have a good thermal insulation. In terms of climate, it is necessary that the thermal amplitude is the greatest possible for better efficiency. The use of this technique is very interesting for amplitudes of 10 $°C$ and more.

Many studies have shown the interest of night ventilation, based on experimental and numerical results (Kolokotroni and Aronis, 1999; Blondeau et al., 1997). According to a study in the UK this process allows up to 40 % energy savings if the building is optimized for natural cross ventilation (Kolokotroni and Aronis, 1999). Blondeau et al. (1997) are also interested in the impact of the set temperature on system performance. In this study, if natural ventilation is not sufficient, the set temperature is reached by a mechanical cooling system. The contribution of natural ventilation is only 12% for a set temperature of 22 $°C$ but reaches 54% for a set temperature of 26 $°C$. Performances vary greatly depending on local climate and type of building (structure, orientation, geometry of the building and its openings...) so these figures can not be generalized but they demonstrate nevertheless the interest of this type of system.

Examples of buildings cooled by natural ventilation

Apartment building in Catania (Italy)

Allard and Santamouris (1998) present an example of use of thermal breezes for passive cooling on an apartment building in Catania (Italy). The building has two openings on opposite walls and is cooled by natural ventilation without any mechanical assistance. This allows a temperature decrease of about 3 $°C$ for standard use of the building. The local climate is very hot in Catania with average monthly temperatures up to 30 $°C$. The temperature, however, fall at night which gives an average thermal amplitude of approximately 10 $°C$ and allows efficient use of night ventilation. The authors specify that this strategy is particularly suitable for buildings with two openings in opposite walls allowing to exploit the sea and land breezes with high thermal amplitudes.

Residential building of IESC in Corsica (France)

This building was selected as a case of application in the framework of the ANR project 4C (comfort in hot climate without air conditioning). It is located on the site of the IESC (Cargse Institute of Scientific Studies) close to the sea and where the climate is well suited to passive cooling (IESC). One of the aims was to have a comfortable building in summer without the use of active cooling in order to minimize energy consumption. The building, composed of several traversing rooms, has an east-west orientation to allow natural cross ventilation. It appears that the thermal inertia of the building coupled with night ventilation significantly improves the thermal comfort in the building (Stephan et al., 2011).

THERMAL BREEZES AND WIND REPRESENTATIONS

Thermal breezes and their observation

The sea/land interface allows the creation of thermal breezes caused by the difference between the cooling of water and land (Figure 5). During the day, by clear sky , the air above the land warms up and rises by convection, creating a local low pressure area. This is reflected by the occurrence of a breeze circulating from the sea to the land. At night, the opposite phenomenon occurs and the breeze will circulate from land to sea.

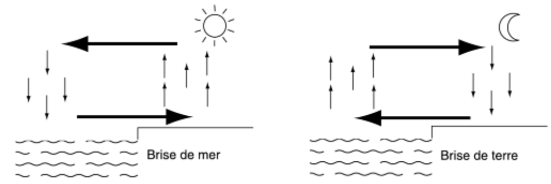

Figure 5: Sea and land breezes (De Parcevaux and Huber, 2007)

Breezes phenomena are generally available up to the local scale, which include areas of the order of tens of kilometers. More precisely, these two phenomena are observed between the ground and about 150 m of height, in a range which rarely exceeds 15 km on both sides of the coast (Stephan et al., 1999). However, it is possible to observe sea breezes penetrate up to a hundred kilometers inland (Simpson, 1994; Tijm et al., 1999). The main advantage of these breezes is that their direction remains constant (sea/land axis). For the building, it allows to develop optimal strategies with natural cross ventilation.

The speed of the breezes, most important during day time, promotes comfort ventilation and lower temperatures at night allow efficient cooling of the building. Moreover, breezes are observable all along the coast, thus offering similar strategies for a large housing stock. The synoptic wind, however, can have a great influence on these breezes, up to cancel the phenomenon (Arritt, 1993).

Meteorologists typically use hodograph to represent the cycle of breezes. An example is shown in Figure 6. This representation is useful to visualize the existence of breezes and highlight their start and end times. It also shows their speeds, pointing here that the sea breeze has a much higher speed than the land breeze. However, this representation does not guide a design choice for an optimal natural ventilation. It is possible to determine the best orientation of the building hour by hour but not on the entire period. Moreover this type of representations only displays one day at a time and therefore does not allow to draw conclusions on a long time.

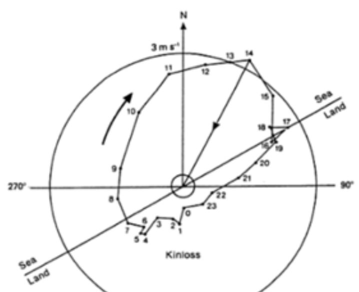

Figure 6: Example of hodograph (Simpson, 1994)

To highlight the phenomenon of breezes, we plot the graph in Figure 7 with meteorological data of the site of Campo dell'Oro in Ajaccio (Corsica) on 6 days. The data used come from an approved Meteo-France station and measurements of wind speeds and directions are realized at a height of 10 m. Both sectors called "sea breeze" and "land breeze" are opposite and have a resolution of 30°, i.e. we consider a range of ± 15° centred on the main axis for each of the two sectors. Here we observe the alternation of breezes and their speed difference. The addition of the outside temperature also allows to correlate the cooling needs and the availability of the wind resource : when temperatures are high, the wind speeds are also high, thus allowing effective comfort ventilation.

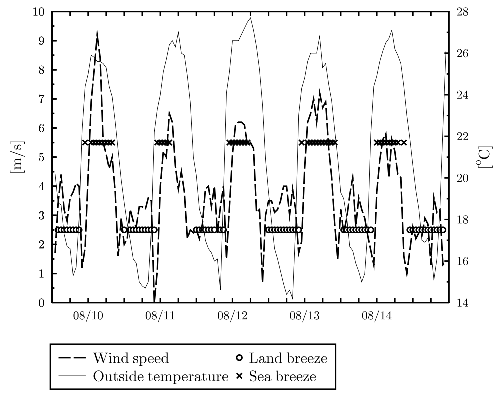

Figure 7: Example of thermal breezes on the site of Campo dell'Oro, Ajaccio

Wind representations

More generally the wind profile of a site is represented on a wind rose. A classical wind rose can bring together the three essential informations in one graph : speed, direction and frequency of the wind by sector. It is possible to draw the entire studied period in order to obtain a global information or to use shorter period to visualize the evolution of the wind during the day. Two examples, Figure 8 and Figure 9, from the meteorological station of Campo dell'Oro are plotted using a Matlab - GLE processing.

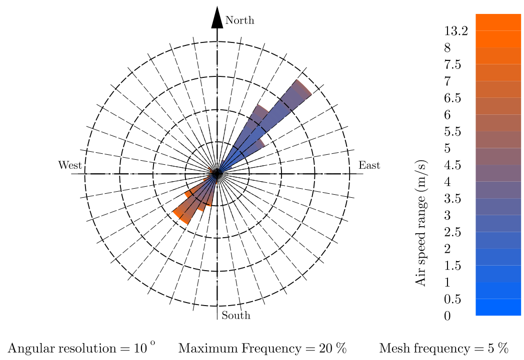

Figure 8: Wind rose of Campo dell'Oro, Ajaccio (summer 2011) - resolution 10°

Figure 9 allows to visualize the alternation of breezes and their speed range when they are present, providing similar information to the hodograph. The disadvantage of this type of representation for an application in natural ventilation is that it gives us little information on the fluctuation of speed that will have a very significant impact on system performance.

A new representation for natural ventilation in buildings

To provide more information on the speed fluctuations a representation involving the statistical tool boxplot

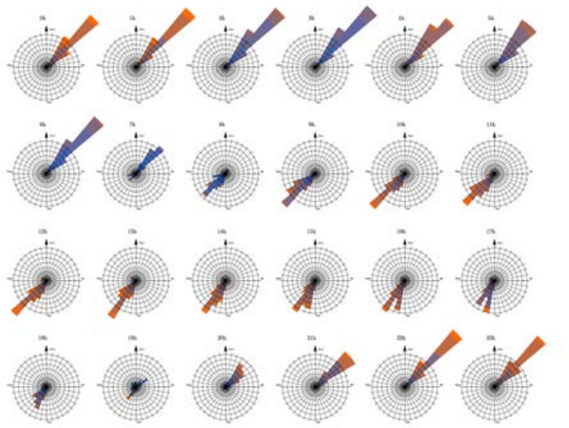

Figure 9: Hourly wind rose of Campo dell'Oro, Ajaccio (summer 2011) - resolution 10°

is proposed in Figure 10. This wind rose consists of nine sectors of 40°. Using a Matlab processing we identify the sector where the frequency is the highest then we determine the eight other sectors. Each sector is associated with a gray level that allows to quickly identify his frequency. A very low sector will almost be not visible, while an important sector will appear very clearly. A scale also shows the exact value of the frequency. Unlike a classical wind rose the main axis of the graph gives here the wind speed. To provide more information on the speed distribution we plot in each sector the quantiles at 0.025, 0.25, 0.75 and 0.975. The "box" thus contains the full range of speed which is between 25 and 75% of the sample. Higher speeds to the last quantile are also plotted as singular points. Finally we display in the background an image of a classical wind rose normalized.

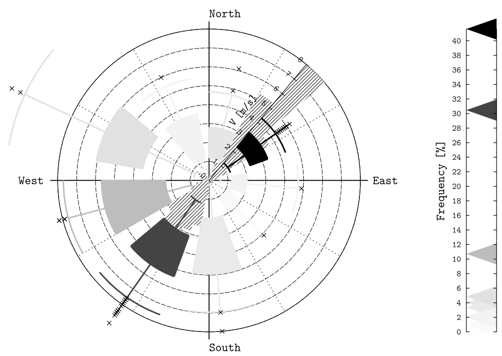

Figure 10: Statistical wind rose of Campo dell'Oro, Ajaccio (summer 2011) - resolution 40°

We also propose a representation of the same type but entirely focused on natural cross ventilation (Figure 11). Here we focus on the main axis of the wind. We are no longer looking for the sector with maximum frequency but the sum of two opposite sectors. For greater clarity this representation contains only the minimum necessary information. We observe that the speeds of the two sectors vary little. The majority of speeds from Southwest sector (sea breeze) are between 3 and 6 m/s and those in the Northeast sector (land breeze) are between 2.5 and 3.5 m/s. In the case of the rehabilitation of a building, it is also possible to draw the axis corresponding to its orientation. This will help to know the frequency and the range and fluctuations of wind speeds that will benefit the building.

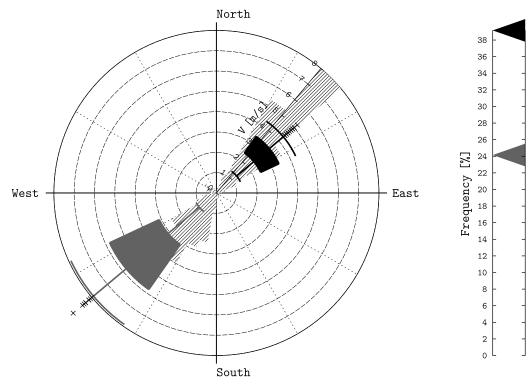

Figure 11: Statistical wind rose of Campo dell'Oro, Ajaccio (summer 2011) : main axis of the wind - resolution 30°

The main difficulty in adapting this type of representation for building is the choice of the sectors resolution that will depend directly on the frequency. Indeed, the frequency can have very significant variations by slightly modifying the resolution. However, it is difficult to determine from which range of orientation the building will be able to benefit from the wind. The limit for use of these representations in space is also subject to numerous conditions. In real conditions if the measures were not performed directly on the site, this will depend on the surrounding environment (presence of obstacles . . .).

These different representations still allow us to characterize more precisely the wind properties of the site and begin to introduce the notion of building. Clearly observing a main axis (Northeast/Southwest) in the site of Campo dell'Oro with favourable speed ranges for the use of natural ventilation shows its interest.

More generally these graphical representations do not allow to give a definitive conclusion. Indeed, the performance of a natural ventilation system involves many parameters and the knowledge of the main axis of the wind and the fluctuation of speeds is not enough to guide a design choice. For this it is also necessary to use indicators taking profits from the different information available.

INDICATORS

Data required

In order to design a naturally ventilated building several meteorological data are required. Since we only want to characterize the potential of passive cooling, we will not take into account either the level of pollution of the site or noise. However, it is clear that these two criteria will have an important role in the decision making for the building design choices. As an example, Germano and Roulet (2006) offer a potential assessment using a semi-qualitative multicriteria analysis to take them into account.

The indicators proposed subsequently exploit the following data : *wind speed*, *wind direction* and *outside temperature*. We have then to define the overall limits for the use of natural ventilation. These threshold values are difficult to determine because they depend on the acclimatization of occupants. Roaf et al. (1998) suggest to use as a criterion for passive cooling by night ventilation an outside temperature up to 20 $°C$ at night and a mean outside temperature up to 31 $°C$ during the day. These figures are in agreement with those of Givoni (1992) recommending a thermal amplitude of about 10 $°C$. Givoni also gives similar orders of magnitude for comfort ventilation during the day, with a maximum external temperature between 28 $°C$ and 32 $°C$. In this study, the maximum outside temperature has been set to 30 $°C$ during the day and 20 $°C$ at night. The thermal amplitude criterion is considerate to be optimum with a day/night temperature oscillation at least greater than 10 $°C$.

These criteria are used to identify suitable sites for natural ventilation but even if values below these thresholds will give lower potential it may still be beneficial to the building. Moreover, the characterization of thermal comfort is difficult to generalize. Adaptive comfort is the established method to assess thermal comfort in naturally ventilated building where comfort zones are dynamically affected by the external temperature history as presented in Figure 12.

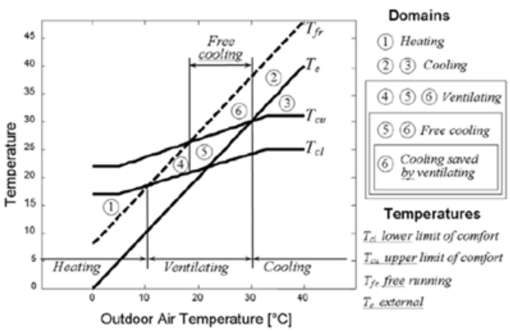

Figure 12: Evolution of the comfort temperature as a function of outside temperature (Germano et al., 2005)

From this minimum data set it is possible to calculate several indicators to assess the potential of the site.

Climate indicators

Even though they are not directly related to the building, these indicators give information on the environment in which the building is or will be located. They do not require complex simulation and time consuming modelling while giving fundamental orientation on building design. Thus, the objective is to define a minimum set of indicators to support decision-making during preliminary design phase.

We have seen the importance of the temperature evolution of the site for the choice of a strategy for passive cooling by natural ventilation. In agreement with the criteria defined above we remove all points where temperatures are respectively greater than 30 $°C$ and 20 $°C$ (Figure 13).

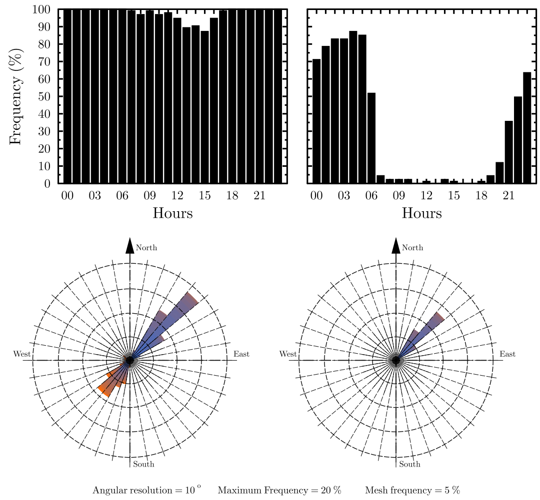

Figure 13: Filtering of temperatures and Wind data at 30 $°C$ (left) and 20 $°C$ (right) on the site of Campo dell'Oro, Ajaccio (summer 2011)

The top left graph shows the periods for which comfort ventilation is favourable. The top right tells us over what period it will be possible to use passive cooling. We observe that the measured temperatures at the site of Campo dell'Oro are very favourable to the use of ventilation comfort. They also provide satisfactory results for night ventilation from 10pm to 6am (UTC). Obviously an essential condition is that the wind profile is also favourable to natural ventilation. Therefore, this filter is also applied to a wind rose to see if the remaining points correspond to a favourable axis and if the range of wind speed is acceptable (Figure 13, bottom left and right). These wind roses must be viewed in conjunction with the unfiltered one (Figure 8). For a filter of 30 $°C$ there is no significant difference, there is still more than 97% of the data. For a filter of 20 $°C$ the data corresponding to the sea breeze (Southwest axis) disappear, leaving 30% of remaining data. This is consistent with the alternation of breezes : sea breeze during the day (higher temperature) and land breeze at night (lower temperatures).

These representations can also be translated as numerical indicators by calculating the number of hours during which the criteria are met :

$$Nh = \sum_i C(i) \quad (3)$$

With, over the entire period, hour by hour :

$$\begin{aligned} C(i) &= 1\, if\, T_o(i) < T_s \\ &= 0\, else \end{aligned} \quad (4)$$

Where T_o is the outside air temperature and T_s take the required value, 30 $°C$ for comfort ventilation and 20 $°C$ for the passive cooling.

The maximum and minimum mean temperatures are also calculated over the period studied, in order to compare the criteria presented above :

$$T_{o,max} = \frac{\sum_d max(T_o(d))}{N_d} \quad (5)$$

$$T_{o,min} = \frac{\sum_d min(T_o(d))}{N_d} \quad (6)$$

Where T_o is the outside air temperature and N_d the number of days. We obtain respectively 27.6 $°C$ and 17.1 $°C$ for the site of Campo dell'Oro. These temperatures are greatly favorable for passive cooling according to the criteria of Roaf et al. (1998).

The thermal amplitude is also defined as the difference between the daily maximum and minimum temperatures :

$$A(d) = max(T_o(d)) - min(T_o(d)) \quad (7)$$

This calculation is performed every day from 5pm to 5pm UTC in order to take into account a full day and night.

For the site of Campo dell'Oro, the mean thermal amplitude, 10.6 $°C$, is within the order of magnitude found in the literature for using night ventilation as passive cooling source.

Next these indicators are grouped in Table 1. Here, they are all favourable to passive cooling by natural ventilation.

Table 1: Summary of indicators

Frequency $T_o < 30°C$ (%)	97.7
Frequency $T_o < 20°C$ (%)	30.0
Mean $T_{o,max}$ ($°C$)	27.6
Mean $T_{o,min}$ ($°C$)	17.1
Mean amplitude ($°C$)	10.6

Finally, to simplify the use of these indicators and to assess the global potential of the site a radar plot is used. For the temperatures three indicators presented above are chosen : the mean maximum temperature, the mean minimum temperature and the thermal amplitude. For the wind profile we focus on the speed range, the frequency of the main axis and regularity of speeds. In order to establish an indicator independent of the wind height measurement, wind speed is given at a normalized height of 1.5m. Following relation gives wind speed at 1.5m height as a function of wind speed (U), wind speed height measurement (z_{met}) and terrain rugosity (α) given in Table 2 (Feustel, 1998) :

$$\frac{U(1.5)}{U_{met}} = \left(\frac{1.5}{z_{met}}\right)^\alpha \quad (8)$$

Table 2: Exponent α as a function of terrain

Roughness type	α
Flat open country	0.14
Rolling hills	0.28
Inner city areas	0.40

Then the frequency of the period during which the wind speeds are within an acceptable range is calculated. We assume here that the building has a control system suited to the regulation of the air flow for a wind speeds range from 0.5 to 10 m/s. In practice this range will depend on many parameters such as the geometry of the building and its openings, its orientation and its use (occupancy period . . .). For the direction, we focus on the frequency of the main axis of the wind in a sector of 40 ° (± 20°). Finally, the regularity is represented by the difference of 0.95 and 0.25 quantiles. This parameter provides information about the fluctuations of the wind. A good regularity is important for a natural ventilation system : a steady wind allows easier management of openings and an optimal comfort ventilation.

A rate between 0 and 5 is then assigned to each criterion and the result is plotted on the radar in Figure 14. For frequencies the maximum rating is between 80 and 100% and decreased in step of 20%. For temperatures and thermal amplitude it varies according to their differences with the orders of magnitude presented above. For regularity, the smaller the gap between the two quantiles, the greater the rating.

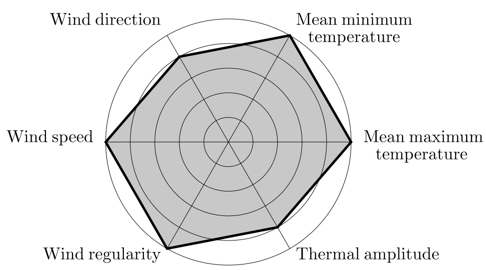

Figure 14: Radar plot for the site of Campo dell'Oro, Ajaccio (summer 2011)

This representation can be used to discuss design choices for the building. Interpretation of the results identifies passive cooling methods which are best suited to the site.

CONCLUSION

Different ways to use natural ventilation in buildings have been reviewed. Through the development of indicators such as the statistical wind rose and the radar plot we proposed an approach to assess the potential of a site. A way to improve natural cross ventilation for buildings using thermal breezes, characteristics of coastal areas, has also been highlighted. Their moderate and low variables wind speeds coupled with favourable temperatures allow to establish optimal strategies, both for comfort ventilation and for passive cooling by night ventilation. This work is a first step to propose a building suited to its environment which can use readily available resources to reduce its energy consumption. One of the perspectives is then to optimize building performances by the use of controlled systems including piloting algorithms and predictive control.

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