

A SENSITIVITY ANALYSIS OF NATURAL VENTILATION DESIGN PARAMETERS FOR NON RESIDENTIAL BUILDINGS

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ABSTRACT

Designers can use natural ventilation to reduce building energy use and improve occupant comfort. This study aims to provide guidance for designers of naturally ventilated buildings on the impact various design parameters have on natural ventilation performance.

We modelled a naturally ventilated reference office building, under a range of climate conditions and ventilation strategies. We performed a sensitivity analysis of a range of unknown design parameters used in the early design stage.

The results underline the most important parameters and their effect on natural ventilation strategies in different climate types. Of the parameters assessed, airflow network parameters had the most significant impact on improve thermal comfort. Envelope characteristics were found to have a significant impact also on night cooling strategies in climates with large diurnal swing.

The results showed a dominant influence of the parameters that directly impact solar and internal gains on natural ventilation performance.

Quantitative measures of the impact of various input parameters are presented here which, with the use of dynamic building simulation, can be used to support natural ventilation design.

INTRODUCTION

Natural ventilation offers potential benefits to building owners and operators, both in terms of reduced energy use, resulting in lower operating costs, and improved occupant satisfaction. However the performance of any natural ventilation strategy is highly dependent on factors that are decided on early in the design process. Many of the key design decisions, including the aspect ratio of a building, the presence of courtyards or atriums, and the size and locations of windows and openings, have a significant impact on whether or not natural ventilation is feasible. To exploit its full potential, natural ventilation design has to be considered throughout the complete design process, particularly in early design stages.

Dynamic building simulation tools can be applied during early design phases to inform natural ventilation design and test design strategies. Coupled

building energy and airflow simulation software, such as EnergyPlus can be used to simultaneously model building energy use, natural ventilation airflow, and occupant comfort. Often however many of the building design parameters that impact natural ventilation performance, are not defined during the early design stages. This uncertainty presents a significant challenge for simulation engineer when modeling potential ventilation strategies.

Parametric analysis can be used to some extent to give a range of potential outcomes given uncertainty in the model input parameters. However performing a parametric analysis that includes all of the unknown design parameters requires significant time and resources. Several prior studies have attempted to identify which simulation parameters have the most impact on building performance (Dominguez-Munoz F., 2010) (Hopfe C., 2009) (Breesch H., 2010) (De Wit S., 2001). These studies focused primarily on simulation variables rather than the building design parameters that are likely to evolve throughout the design process. No prior studies have been identified that focus on the uncertainty in building energy models that are coupled with an airflow network model.

This study aims to provide guidance for designers of naturally ventilated non-residential buildings on the impact various design parameters have on natural ventilation performance. We performed a sensitivity analysis on key design parameters that cannot be clearly specified during early design stages, these include, internal and solar gains, envelope characteristics and window geometry and opening type. The results of this work can be applied to support natural ventilation design using building simulation.

METHOD

Reference building

The sensitivity analysis is performed on a four-storey office building north-south oriented, intended to be representative of a typical European medium sized office. The building layout is symmetric around the central stairway and services.

Figure 1 shows the plan view of one of the four stories. Each floor has four open plan office zones connected through vents to the stairwell passive stack. An opening at the ground floor and openings

on the roof allow the stack effect. Table 1 gives geometric characteristics of the building and Figure 2 shows the building model in Sketchup.

*Table 1
Building geometry characteristics.*

Window to Wall Ratio (WWR)	35%
Net conditioned area	2734 m ²
Volume (50m x 15m x 15m)	11250 m ³

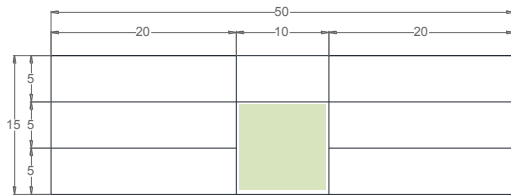


Figure 1 Building plan view.



Figure 2 Building model geometry.

Each window frame has two panes, the left one for natural ventilation and the right one for daylighting. Overhangs have been added to the south façade to reduce the solar gains during summer. Automatically controlled windows have been added to the south and north façade. Vents between the hallways and the offices allow air movement even if the doors are closed.

Modelling method

We modelled two commonly used passive ventilation strategies using the multi-zone airflow network model with the EnergyPlus building energy simulation program: night stack driven cross ventilation, to reduce cooling needs (Strategy A), and wind driven cross ventilation during the day, to improve thermal comfort (Strategy B).

In Strategy A, we assume windows are closed during office hours, and that cooling loads are met using mechanical cooling. Windows and vents open autonomously if the indoor temperature exceeds 26°C, allowing night-time free cooling through the stairwell passive stack. The modelled strategy varies the opening area depending on the inside-outside temperature difference, in order to reduce the possibly large fluctuations in temperature. We

modelled stairwell passive stack as four vertically stacked zones connected to each other through horizontal openings and to the office floors through vents.

In Strategy B, we assume windows are operated during normal office hours by occupants based on their thermal comfort. When windows are in use, ventilation cooling is provided via naturally driven cross ventilation. The modelled control strategy is based on CEN 12521 adaptive comfort model and allows window opening during the day if the indoor operative temperature is greater than the adaptive comfort temperature. We assumed in this case that the building is in free-running mode with no mechanical heating or cooling.

For both simulation scenarios we used wind pressure coefficients from the AIVC dataset for semi-sheltered low-rise rectangular buildings (Liddament M.W., 1986). We modelled unintentional infiltration by applying Equivalent air Leakage Areas (ELAs) evenly over the exterior envelope surface area of the building model.

We applied four different ELAs derived from the four classifications of building envelope performance specified in the KlimaHaus build regulations. We calculated ELAs from the maximum ACH at 50 Pascals, as defined in KlimaHaus, using translation equations defined in ASHRAE (TC, 2001).

Window position and dimension were not considered variables. We developed hourly lighting schedules to represent the use of artificial lighting. We generated these schedules by first performing a building simulation run using the daylighting controls option in EnergyPlus. This option uses the anticipated availability of daylight coming through the windows, to moderate electric lighting on needed basis. Performing building simulations using this option is computationally costly, and so this option was only used to generate our electric light usage schedules. Simulations performed for our parametric analysis used EnergyPlus's FullExterior shading mode which assumes no daylighting modeled; resulting in significantly quicker simulation run times. We used 15 minute simulation run time steps based on analysis by (Zhai J., 2011) that demonstrated 15 minute time steps were sufficient to the coupling of airflow and thermal models.

Parameter selection and variable range assessment

Our sensitivity analysis took into account only uncertain building properties due to lack of information during early design stage. Input parameters that were primarily simulation environments parameters (i.e. convection coefficients, zone air heat balance algorithm) were not varied in our analysis, as these type of parameters would typically remain constant throughout the design process.

We assigned value ranges for the envelope thermal insulation, air tightness (ELA) and density based on a

combination of building regulations (D.Lgs.192/05), energy performance requirements (KlimaHaus energy certification) and technical feasibility. For instance, the upper bound U-value was the U-value required by the local building regulation and the lower bound was set by taking into account the technical and economic feasibility of the envelope construction.

Table 2
Input parameter variables

	DESCRIPTION	MIN	MAX
F1	Exterior wall insulation thickness [m]	0.1	0.25
F2	Exterior roof insulation thickness [m]	0.16	0.28
F3	Exterior window U-value [W/m ² K]	0.5	1.7
F4	Exterior window Solar Heat Gain Coefficient (SHGC)	0.3	0.9
F5	Exterior wall density [kg/m ²]	230	430
F6	Slab density [kg/m ²]	150	415
F7	Overhang depth [m]	0.3	1.5
F8	Inside reveal depth [m]	0	0.24
F9	People fraction radiant	0.3	0.6
F10	Lights fraction radiant	0.18	0.72
F11	Effective Leakage Area	0.5	2
F12	Window opening factor	0.4	1
F13	Window discharge coefficient	0.3	0.9
F14	Vent discharge coefficient	0.3	0.9
F15	Number of people per Zone	7	16
F16	Lighting Watts per Zone Floor Area [W/m ²]	5	20
F17	Electric equipment Watts per Zone Floor Area [W/m ²]	5	20
F18	Wind velocity profile: Exponent α , Boundary layer thickness δ [m]	$\alpha=0.10$ $\delta=210$	$\alpha=0.33$ $\delta=460$

We varied electrical equipment gains and lighting gains between the most efficient equipment available on the market (LED lighting and new electrical equipment) and a reference one based on the EU technical background report on indoor lighting (BRE, 2011). We varied the number of people in the zone assuming two different office layouts, open space (7.14 m²/p) and single office (12.5 m²/p) (SIA 2024-

2006). This resulted in average daily total internal gains of between 12 W/m² and 40 W/m². We varied the people fraction radiant (ASHRAE, 2009) and the lights fraction radiant, taking into account different luminaire configurations (IES, 1993).

We varied the shading overhangs, inside reveal depth and solar heat gain coefficients as per Table 2. Variation in these three parameters impacted the internal solar heat gains. In addition, we also varied the window and vent opening factors and their discharge coefficients (Karava P., 2004). Variation in these parameters was based on typical window performance, representative of a range of different window types, operation and wind direction. We considered different wind velocity profiles based on the rationale that the location or orientation of the building might be subject to change during early design stage, which we considered likely to impact cooling loads.

Table 2 lists all the considered variables and their ranges.

Because the principle objective of Strategy A is to provide space cooling, we used the cooling loads as our metric to assess the performance. In Strategy B no cooling system was modelled, therefore our metric of performance was the number of comfortable occupied hours. We calculated the comfort hours based on the three categories of adaptive comfort described in the European Standard EN15251-2007.

Climate dependency

Prior work by (Zhai J., 2011) indicated that simulated building performance is significantly impacted by the use of locally measured weather, as compared to weather station data. Zhai recommends the use of local weather data when available, particularly for buildings with high solar gains. We performed parametric analysis using three different weather files: Bolzano, Palermo and San Francisco (DOE, 2011).

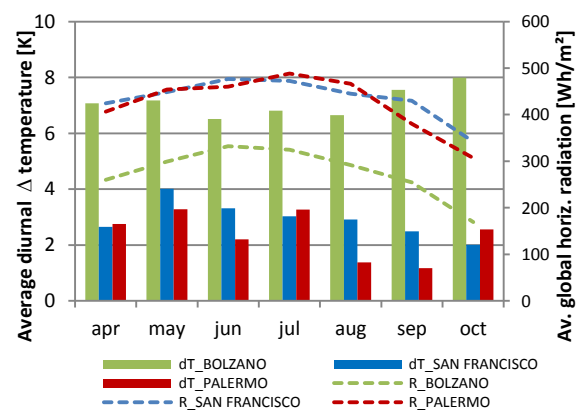


Figure 3 Day-night temperature difference and solar radiation of the three selected locations.

Figure 3 compares average day-night temperature differences and solar radiation in the three locations. Bolzano represents a typical continental climate with large diurnal swing and low wind speed (see Figure 4). Palermo represents a typical Mediterranean climate with hot summers and low wind breezes (see Figure 5). San Francisco has mild summers and higher wind speeds (see Figure 6).

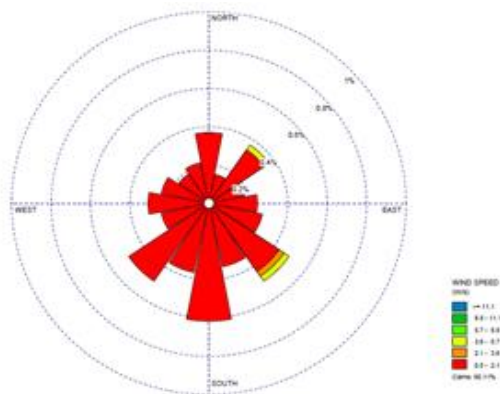


Figure 4 Wind rose for the Bolzano climate.

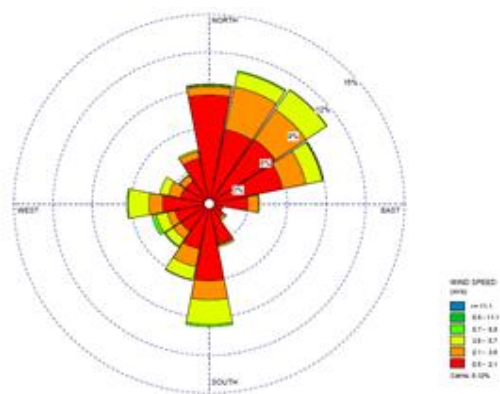


Figure 5 Wind rose for the Palermo climate.

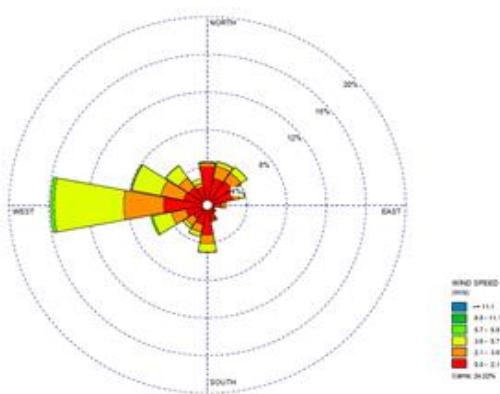


Figure 6 Wind rose for the San Francisco climate.

Limitations

Our building model assumptions should be considered first before applying these study results to real building natural ventilation design. In EnergyPlus, thermal zones are considered well mixed zones, assumed to have uniform temperature

and pressure varying hydrostatically. Therefore temperature stratification is not modelled within an airflow network zone. As long as the zone ceiling height is around 3 m, this assumption is considered reasonable.

The stairwell passive stack modelling method is based on the approach used in prior studies (Hensen J., 2002), but has not been independently experimentally validated by our team.

The convection model used in the analysis is not optimal for use with passive cooling strategies because convection coefficients are indirectly predefined by the adaptive convection algorithm (Beausoleil-Morrison I., 2000). As in an early design stage no other tools are available, our use of the adaptive convection algorithm can be considered valid.

Our analysis was performed on a rectangular building with a single orientation, and so we were able to make use of published wind pressure coefficients. The results of the analysis can be considered generalizable to other rectangular buildings, but could be inappropriate for alternative building geometries or orientations.

Bulk airflow model does not consider the internal space layout. Internal walls and furniture may affect the natural ventilation performance. Designers should consider the impact this may have on limiting cross ventilation during the early design stages.

Sensitivity analysis method

We performed a sensitivity analysis using the Elementary Effects method described in (Saltelli A., 2008). This method determines which input variables have negligible, linear or nonlinear effect on the objective with a relatively small number of samples (combinations of input values).

Rather than testing all possible combinations of the input parameters, the EE method selects representative combinations of input parameters to test. Groups of combinations of input parameters are called “trajectories”. Typically the number of combinations in each trajectory is equal to the number of test parameters plus 1. Within a trajectory, each combination of test parameters differs from the previous by changing only one parameter each time. For a detailed explanation of the parameter selection process see (Saltelli A., 2008).

The EE method subdivides the variable ranges of each input parameter into equal intervals of equal size. The boundaries of these intervals are called levels. For our parametric analysis, we used four levels (three intervals), based on work by Saltelli that showed the four levels have equal probability of being selected. When applying the EE method, the discrete probability distribution for each factor can be user defined. We have selected uniform distributions for all input parameters, because we consider each of the values to be equally likely in an early design stage phase.

When two combinations of sequential input parameters within a trajectory are simulated, only one variable will differ between them; the difference in the output between these two runs is used to calculate a metric called the elementary effect (EE). The elementary effect (EE) is defined for the i^{th} parameter, on the k^{th} input analysed as:

$$EE_i = \frac{[y(x_1, \dots, x_{i-1}, x_i + \Delta, x_{i+1}, \dots, x_k) - y(\bar{x})]}{\Delta} \quad (1)$$

where X_i , $i = 1, \dots, k$ represents the input parameters and Y the output results for the selected parameters combination. p is the number of levels and Δ is equal to $[p/2 (p-1)]$.

The EE of a factor depends also on the values of the other factors. The sensitivity measures proposed by (Saltelli A., 2008) are the mean (Eq. 2), the standard deviation (Eq. 3) and the mean of the absolute values of the elementary effects (Eq. 4).

$$\mu_i = \frac{1}{r_i} \sum_{t=1}^{r_i} EE_{i,t} \quad (2)$$

$$\sigma_i = \sqrt{\frac{1}{r_i - 1} \sum_{t=1}^{r_i} (EE_{i,t} - \mu_i)^2} \quad (3)$$

$$\mu^*_i = \frac{1}{r_i} \sum_{t=1}^{r_i} |EE_{i,t}| \quad (4)$$

μ^* quantifies the influence of the factor on the objective. Parameter ranking is based on these values.

High values of σ demonstrate that the factor interacts with other variables and has a nonlinear effect on the objective. Low values of μ , associated with high μ^* values, indicates that there is no direct correlation between this input value and the output value. Whether this factor has a negative or positive impact on the output depends on value of the other significant factors. If μ is equal to μ^* , an increase of the factor corresponds to an increase in the output. If μ is equal to μ^* in magnitude but they have opposite signs, an increase of the factor corresponds to a decrease in the output.

We wrote parameter selection code in Python that generates 200 trajectories consisting of 19 points (the number of input factors plus one), draws 10 trajectories from the 200 available 500 times and selects the 10 that are farthest among each other. This procedure guarantees a good exploration of the whole design space. Then, the algorithm computes 10 EEs for each input parameters. Finally, the sensitivity statistics are calculated. We run simulations with the selected parameter combinations by means of jEPlus (Dr Yi Zhang, 2011), an EnergyPlus shell for parametric studies.

The first elementary effects analysis involved 1440 simulations and showed that the solar and internal gains are the most influential parameters.

Therefore, we performed a second elementary effects analysis (840 simulations) fixing internal and solar gains to the lowest reasonable amount to better determine the influence of the other parameters. Table 3 lists the values that have been fixed for this second round of parametric analysis.

Table 3

Input parameter values that have been fixed for the second analysis

	DESCRIPTION	VALUE
F4	Exterior Window Solar Heat Gain Coefficient	0.6
F7	Overhang depth [m]	0.5
F15	Number of people per Zone	10
F16	Lighting Watts per Zone Floor Area [W/m ²]	5
F17	Electric equipment Watts per Zone Floor Area [W/m ²]	5

RESULTS AND DISCUSSION

The graphs in Figure 7 to Figure 10 compare the statistical indicators computed by the first Elementary Effect analysis. The influence percentages are based on the μ^* results. The graphs show similar tendencies in all the considered climate conditions and ventilation strategies. The parameters affecting solar and internal gains (F4, F15-F17) have a dominant influence on natural ventilation performance. In Figure 8 and Figure 10, the high σ values for parameters F15-F17 for the San Francisco weather suggests that the impact the internal loads have on comfort is strongly influenced by the selected values of the other (non-load) parameters. The positive μ means that an increase of internal gains improves comfort conditions for our Strategy B scenario because of the lower outdoor temperatures in San Francisco. On the contrary, in Palermo comfort can be improved by decreasing both internal and solar gains.

From Figure 9 we see that the window discharge coefficient (F13) for Palermo has a notably higher relative impact on the number of comfort hours, compared to the other two climates. We theorize that this is because the forces that drive natural ventilation (wind speed, indoor/outdoor temperature difference) are smaller in Palermo with moderate weather and low average wind speeds.

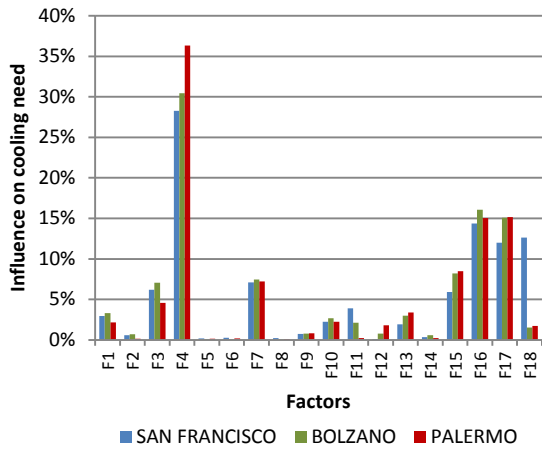


Figure 7 | Elementary Effect analysis results: influence on cooling need for Strategy A.

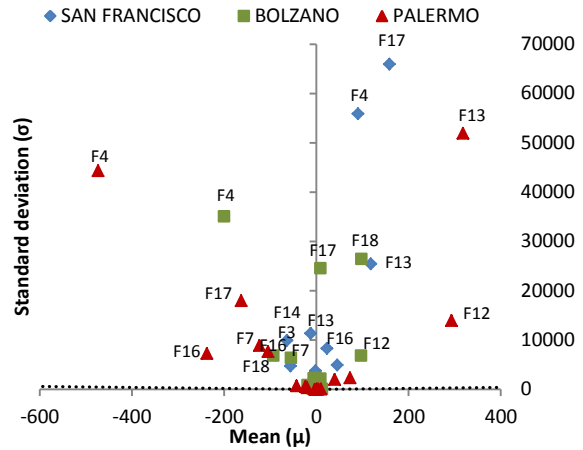


Figure 10 | Elementary Effect analysis results: mean and standard deviation of comfort hours number for Strategy B.

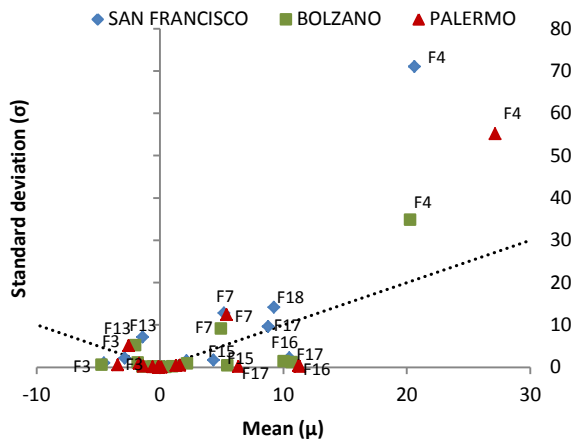


Figure 8 | Elementary Effect analysis results: mean and standard deviation of cooling need for Strategy A.

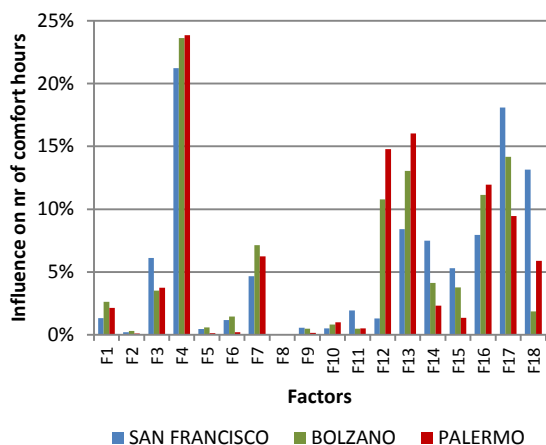


Figure 9 | Elementary Effect analysis results: influence on number of comfort hours for Strategy B.

The graphs in Figure 11 to Figure 14 compare the statistic indicators computed by the second round Elementary Effect analysis, where parameters affecting internal and solar gains are fixed. Results show more evident climate dependencies.

Wind velocity profile affects natural ventilation performance for 50% in San Francisco weather. This is because both wind speed and frequencies are higher in San Francisco rather than in Bolzano or Palermo. In windy locations wind velocity profiles parameters have to be carefully estimated depending also on building surrounding area.

Comparing Figure 11 to Figure 13, it is evident that in Palermo climate window discharge coefficient (F13) and opening factors (F12) have more effect on cross ventilation performance than on passive night cooling. In the Bolzano climate, night cooling performance is more dependent on envelope characteristics (F1 – F8) and on fraction radiant of internal gains (F9 - F10). An increase of the exterior wall density (F5) translates to an increase of the thermal mass of the building, which in turn improves night cooling performance because of Bolzano's large diurnal temperature swings. The effect of exterior roof density (F6) is not evident in the data, because it affects only zone temperatures in the upper floors of the building.

From Figure 11 and 12 we see that the Effective Leakage Area (F11) has more influence on night cooling performances in Bolzano and San Francisco than in Palermo. Both in Bolzano and San Francisco μ is equal to μ^* for F11, but they have opposite sign. This means that increasing the Effective Leakage Area will decrease the cooling needs in these two cities. In the Palermo climate, low values of μ are associated with high μ^* values. This means that there is not a direct correlation between ELA and the cooling need. Cooling need can either increase or decrease with ELA, depending on the values of our other input parameters.

The positive mean value of F3, F12 and F13 for Palermo in Figure 14 show how window U-value, opening factor and discharge coefficient has a greater effect on cross ventilation performance than on night cooling performance in that climate.

Figure 12 show that in all the analysed climates, an increase of wall insulation thickness (F1) would cause an increase of cooling need for Strategy A.

Figure 12 and 14 show that, in the San Francisco case, increasing window and vent discharge coefficient (F13 – F14) will decrease thermal comfort performances but reduce cooling need. We propose that is likely because of the lower outdoor temperatures and the high wind speed in the city. When windows are open during the day, the indoor temperature cools down quickly below the comfort temperature level. In the Bolzano climate, these parameters have less impact on cooling need and again whether they increase or decrease cooling need depends on the value of the other parameters. Figure 12 highlights the higher parameter interaction (higher standard deviations) in the Bolzano weather case compared to the other two climate types.

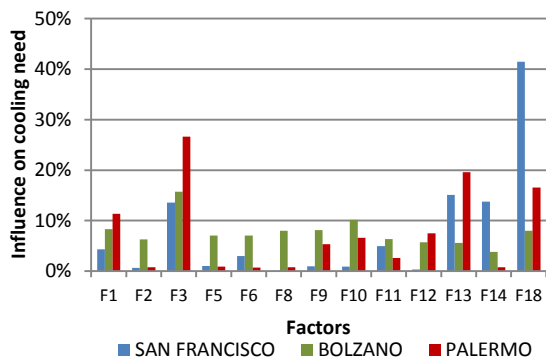


Figure 11 II Elementary Effect analysis results: influence on cooling need for Strategy A.

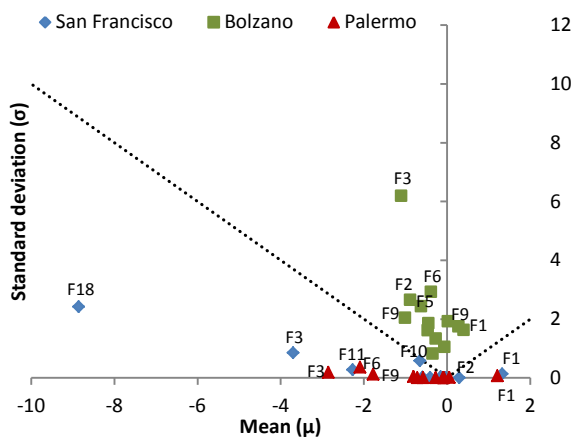


Figure 12 II Elementary Effect analysis results: mean and standard deviation of cooling need for Strategy A.

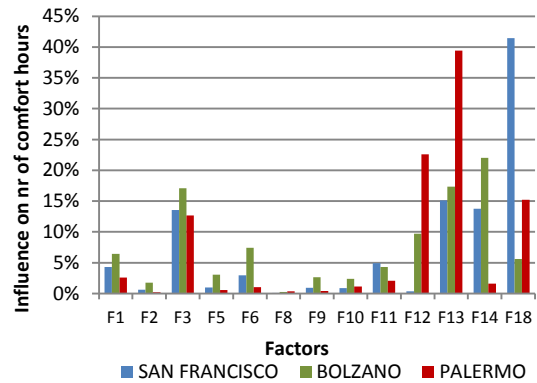


Figure 13 II Elementary Effect analysis results: influence on number of comfort hours for Strategy B.

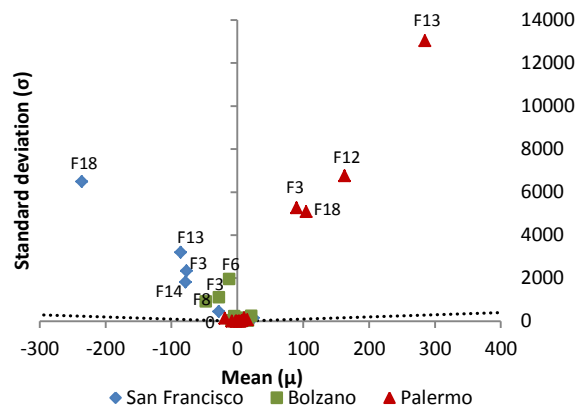


Figure 14 II Elementary Effect analysis results: mean and standard deviation of comfort hours number for Strategy B.

Wind velocity profile influence seems directly correlated to how windy the location is. The fact that these results were highly dependent on the weather data used highlights the importance of a reliable weather file even in early design stages.

CONCLUSION

The results presented in this paper underline the most important parameters and their effect on night cooling performances and natural ventilation strategies in three different climate types.

Our sensitivity analysis showed a dominant influence of parameters affecting solar and internal gains on natural ventilation performance in all the considered climates. An accurate assessment of those parameters could reduce significantly the results uncertainty.

Simulation results showed that airflow network parameters had the most significant impact on thermal comfort; these include the window opening factors and discharge coefficients. Airflow parameters influence ventilation flow rates which directly impact comfort due by lowering indoor air temperatures. In case of high wind speeds, window opening factors and discharge coefficients are less significant than wind pressure coefficients.

In climates with large diurnal swings in temperature, envelope characteristics have greater impact on both thermal comfort and cooling needs.

The graphs provide quantitative measures of the parameters effect on natural ventilation performances and can be used to support natural ventilation design using building simulation. Generalizing these results to other buildings should be limited to non-residential buildings with regular geometry in similar climate types and wind conditions.

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