Modeling the air change rate in a naturally ventilated historical church

*Multiple Linear Regression analysis*

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Preface

First of all we want to thank our supervisor Magnus Mattson for his support and dedication throughout the working period on the thesis. For providing a lot of interesting and useful information, sharing his acknowledgment and helping us with all the difficulties encountered especially in the calculation part of the report.

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Abstract

In this thesis the air infiltration through the envelope of a naturally ventilated stone church located in Bergby (Gävle, Sweden) is studied. The project is focused on Multiple Linear Regression (MLR) modeling the air change rate (ACH) inside the church hall and studying the factors (stack effect and wind effect) that influence the air infiltration. The weather parameters outside the building were recorded in a weather station and the properties of the air inside the church was analyzed with different methods. Infrared thermography techniques and thermistors were used to measure the temperature inside, the tracer gas method to measure the ACH and the blower door technique to measure the tightness of the building envelope. In order to know the pressure coefficients on the church envelope a physical model of the building was studied in a wind tunnel.

Firstly, only the values obtained from the weather station were used to calculate the predictors of ACH and see which parameter influence more on its variation: temperature difference ($\Delta T$) indicating the stack effect; and wind speed (WS), the component of wind speed perpendicular to the long-side facades of the church (WS90) and their square values ($WS^2$ and $WS90^2$) indicating the wind effect. The data obtained in the wind tunnel were later used to do the MLR study with new predictors for indicating wind effect ($\Delta C_p\cdot WS$, $\Delta C_p\cdot WS^2$, $\Delta C_{pout-in}\cdot A\cdot WS$, $\Delta C_{pout-in}\cdot A\cdot WS^2$, $\Delta C_{p-C}\cdot WS$, $\Delta C_{p-C}\cdot WS^2$).

Better prediction of ACH was obtained with the square of the wind speed ($WS^2$) instead of the magnitude itself (WS). However, the latter (WS) provided better results than the regression with the magnitude of the perpendicular component of the wind (WS90). Although wind speed influences in ACH, it alone seems to be a very poor predictor of ACH since has a negative correlation with $\Delta T$ when the data under study include both day and night. However when high wind speed are detected it has quite strong influence. The most significant predictions of ACR were attained with the combined predictors $\Delta T$ & WS and $\Delta T$ & $\Delta C_{pout-in}\cdot A\cdot WS^2$. The main conclusion taken from the MLR analysis is that the stack effect is the most significant factor influencing the ACH inside the church hall. This leads to suggest that an effective way of reducing ACH could be sealing the floor and ceiling of the church because from those areas the air infiltration has big influence on the ACH inside the church hall, and more in this case that have been noted that the floor is very leaky.

Although different assumptions have been done during the analyses that contribute to make the predictions deviate from reality, at the end it would be possible to asses that MLR can be a useful tool for analyzing the relative importance of the driving forces for ACR in churches and similar buildings, as long as the included predictors not are too mutually correlated, and that attained models that are statistically significant also are physically realistic.
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1 Introduction

Energy consumption has always been an important issue in the society. When speaking about industry, construction or other daily aspect, it is thought to be done in the most effective way. From the point of view of economy and environment energy is a very valuable thing that has to be considered.

This thesis work is part of an important project develop by a group of researchers from the Academy of Technology and Environment at the University of Gävle, Sweden. The project is called Energy Savings And Preservation In Historic Monumental Buildings and it is supported by the Swedish Energy Agency [1].

The investment done in this project is used in studying the possible methods to save energy and preserve the structure of monumental buildings, as churches, that are important for the Swedish cultural heritage.

The main points of the larger project are [1]:

- Search and find good methods to measure the ventilation rate and the effective leakage area of the buildings.
- Identification of different methods for air leakage in the building envelope.
- Study the effects of air movements and air cleaning referring to particle deposition and soiling surfaces.
- Study the possibility of using fan convectors and airborne heating.
- Study the main variation in air and surface temperatures and the appearance of air currents over the year.
- Study the possibilities to reduce the downdraughts.

However this thesis is going to focus on studying the air infiltration through the envelope of a church. Swedish churches are normally heated by direct electricity radiators and/or bench heaters (see figures 1 and 2). These devices produce different convective air currents and downdraughts along walls and windows. These air movements affect both, heat distribution and thermal comfort.
Air infiltration and air movement also contributes to the deposition of airborne pollutants, which causes the soiling of indoor surfaces where there are cold bridges in the building construction.

The air filtered through the walls causes flows inside the building that affect the energetic performance and the heating consumption and humidity presence rise.

This thesis focuses on churches, but the conclusions are applicable to other similar historical, monumental buildings that are large, leaky and naturally ventilated regarding heat loss and air infiltration. Normally they are subject to restrictions such as to insulation and tightening methods due to historical and aesthetical values of the building envelope.
1.1. Scope

The aim of this project is to investigate the applicability of the statistical function Multiple Linear Regression in modeling how the air change rate in a naturally ventilated church depends on the two main driving forces: wind and stack effect. Of particular interest was the relative importance of these forces, since this helps identifying the location of the main leakage points on the building envelope and, subsequently, pointing at actions that are likely to be effective in reducing air infiltration. These actions might include planting of wind-reducing vegetation or sealing of the building envelope. In the latter case the method might help suggesting where the sealing would be most valuable.

Once the objective is achieved, economical profits would be obtained since the heat losses are decreased and energy is saved as well. It also involves social profits as the church is considered an important cultural heritage. Moreover this purpose helps in the improvement of thermal comfort inside the church. However this project is focused in studying the factors that leads to the air infiltration through the building façade (wind speed and direction; and the suction effect created by the difference in temperatures between the inside and the outside part of the church).

Parameters which describe weather conditions outside the building (humidity, temperature, pressure, wind velocity, wind speed and precipitation) are recorded in a weather station located 1km to the Norwest of the church. In order to know the properties of the air inside the church, infrared thermography techniques are used to measure the temperature inside, and the decay tracer gas method to measure the air change rate.

With all these data it is possible to analyze the correlation between wind speed, temperature difference and air change rate in order to know which one influence more. This is done by using Multiple Regression function in Excel.

Finally local pressure coefficients obtained from a model of the church in a wind tunnel are analyzed as well. This is another way of studying the wind effect in the infiltration.
1.2. Outline of the thesis

Once the purpose of this project has been exposed and after explaining how important the energy is nowadays and the aim of constructing energy efficiency buildings, in the first section all the theoretical concepts related with the indoor environment are described. Moreover a depth explanation about air ventilation and infiltration is given. All these concepts are specially referred to the church. In this chapter, the fact of considering both effects (wind speed and temperature difference) in the variation of the air change rate is explained as well.

The second section consists of explaining the process done and results obtained with the data analysis. Referring to the method part, first how the measurements were taken is explained and secondly how the data of these measurements are analyzed.

In the third section the project is discussed. The data quality, the different methods that have been used, the coherence of the results and the processes done are analyzed and explained as well as criticized if they are not the same as it was expected. Moreover the limitations and possible error sources are going to be exposed.

Finally, the conclusions done after analyzing the results are exposed and some suggestions are presented to continue with the study of this church.

1.3. Description of the church

The present thesis relates to practical measurements done in Hamrånge Church, located on a hill in Bergby, in the surroundings of the town Gävle (Sweden).
The following figures 5 and 6 shows its internal dimensions: length 40.2 m and width 16.6m, with a total volume of 7800 m³. The height of the nave of the church is 13.7 m. It is common a void space under the floor in elderly Swedish churches. Hamränge church is provided with a crawlspace ventilated by opening of 30·30 cm² [2], i.e. a bit bigger than usual ones.

![Figure 5: Size of the church in relation to the height (H) of the roof [2].](image)

![Figure 6: Size of the church in relation to the height (H) of the tower (plan view). [2]](image)

The church is naturally ventilated and it is provided with no intentional vents for supply or extract air. During the winter it is heated intermittently, with a base temperature of about 11 °C.


2 Theory

In this part of the report some important concepts about Indoor Environment are described in order to understand better the studies done.

Three main topics in this section are: important characteristics about indoor environment in buildings, the concepts of Air Quality and Thermal Comfort and some specific items in churches.

2.1. Characteristics about indoor environment in buildings

The quality of Indoor and Built Environment influence the health, performance, efficiency and comfort of the people living or working inside a building. Because of that, having good conditions is something to take care about when a building is designed.

Different emissions from building materials, humidity and contaminants coming from outside and from people are the principal sources of health problems inside buildings [3]. Therefore, some measures should be taken to avoid them. Safe building materials have to be used instead of other producing contaminants and CO₂ emissions. Ventilation, air change rate and infiltration should be controlled. Some characteristics from the outside as the weather (sun, wind, rain, temperature, humidity) and its effects or the ground conditions influence and are also important in the indoor evaluation.

Indoor Environmental Quality (IEQ) is a term directly related to health and comfort of building occupants that refers to all the factors involved. Normally, IEQ depends on these factors: indoor air quality, thermal comfort, relative humidity, air change rate and acoustic and lighting quality [4].

The most important factors relevant to this thesis are elaborated below.

2.1.1. Indoor Air Quality

Indoor Air Quality is used as a denomination for the cleanliness of indoor air. The more pollutants present in the air the worse is the indoor air quality.
The different pollutants that can be found in air can cause health problems or discomfort. Some of them come from the supply air by ventilation so they are outdoor pollutants and others are generated indoors.

All the pollutants can be classified by various criteria. A common way to do it is by the different effects on human comfort and health. Another indicator is soiling of building surfaces, valuable indoor artifacts, etc [5].

Different examples of pollutants generated indoors:

- The ones produced by building components as: Volatile Compounds from building products.
- The ones created by human activity.

Different examples of pollutants generated outdoors:

- Compounds generated by combustion.
- Pollen and micro-organism coming from the plants.

The most useful method to improve the quality of indoor air is the ventilation. The people inside the building can decide when to ventilate or not in order to filter the contaminants and have a control of the air inside.

### 2.1.2. Thermal Comfort

Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment [6]. Humidity and temperature are two factors that play an important role in analyzing it but they are not the only ones:

Environmental factors:

- temperature
- humidity
- air speed
- thermal radiation
Personal factors:

- Personal activity and conditions
- Clothing

Referring to this thesis, air infiltration and indoor movements are two factors that can cause thermal discomfort in the church.

### 2.1.3. Air Change Rate (ACH)

When a ventilated space has been supplied with a volume of outdoor air that corresponds to the volume of the space, there is still pretty much old air in the space. The new air is mixed with the old one and some of this new air escapes with the old one through the exhaust. The Air Change Rate is defined:

\[
ACH (1/h) = \frac{q_v}{V}
\]

(Eq.1)

Where:

- \( q_v \) = air flow rate through a space [m³/h]
- \( V \) = the volume of the space [m³]

Definitely, Air Change Rate measures how quickly the air in an interior space is replaced by air coming from outside. Both ventilation and infiltration are taking into account [7].

The air change rate describes the tightness of a building. The larger the air leakage the larger its infiltration rate and also the ACH. However, no simple relationship exists between a building’s air tightness and its ACH, although some empirical methods have been developed to estimate the values.

The air leakage in buildings may be determined by pressurization testing or tracer gas measurement. Sometimes the predicted air flow rate is converted to an equivalent or effective air leakage area by using the following equation derived from Bernoulli equation for incompressible fluids [8]:
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\[ A_L = 1000 \cdot Q_r \cdot \sqrt{\frac{\rho}{2 \cdot \Delta P_r}} \]

(Eq. 2)

Where,

- \( A_L \) = the effective air leakage area \([\text{cm}^2]\)
- \( \Delta P_r \) = the reference pressure difference \([\text{Pa}]\)
- \( Q_r \) = the predicted air flow rate at \( \Delta P_r \) \([\text{m}^3/\text{s}]\)
- \( \rho \) = the density of the air \([\text{kg/m}^3]\)
- \( C_D \) = the discharge coefficient.

Air leakage area is determined by the building’s design, construction, seasonal effects, and deterioration over time.

For an entire building, all the openings in its envelope are combined into an overall opening area and discharge coefficient when the effective air leakage area is calculated. Therefore, the air leakage area of a building is the area of one orifice (with an assumed \( C_D \) value of 1 or 0.6 [8]) that would produce the same amount of leakage as the building envelope at the reference pressure.

### 2.2. Indoor Environment in a church

Old monumental buildings as churches are not like the contemporary buildings. They are not constructed with the same materials so its conservation is not the same. Normally, the materials used for its construction are wood, bricks and stone. They usually have a lot of columns to achieve the height desired [9].

At the beginning there were no heating inside these kind of buildings so the climate inside depended a lot on the outdoor one. The climate inside was much more stable than the outside one due to the construction. In the summer, it was cooler inside and in the winter it was warmer.
According to literature [9], some studies were done and some evidence was found that severe winters caused substantial damage to some precious church interior elements. The appearance of long periods of low relative humidity affected these interior parts of churches.

In order to prevent this damage and to avoid uncomfortable interior conditions for people, heating systems were installed. A lot of heating alternatives have been used: warm air heating, floor heating, radiator panel, local heating, convector heating, etc. All of these devices are used to compensate the lack of thermal comfort.

In addition, in some churches as it occurs in the Western Europe, other kinds of events as concerts or exhibitions are organized. Because of that, a heating system is needed inside.

It is not really easy to design a heating system for a church. At the same time, the thermal comfort and preservation of the esthetic have to be considered. Not only these characteristics are important but also the energy needed has to be a considerable value.

**2.3. Air infiltration and Natural ventilation**

Air infiltration and natural ventilation are two phenomena that have to be considered when speaking about a building, especially in old ones.

Swedish churches are normally naturally ventilated with different leaky areas around the building envelope. In order to save energy, there is a wish to reduce the air inlets and outlets. Air infiltration causes airborne particles to enter inside the church and accelerate soiling of artifacts and indoor building surfaces. Air inside the church and its movement influence thermal comfort and candle flickering.

Both natural ventilation and air infiltration are discussed in detail in the next sections, since they are important aspects to consider when studying air change rate.
2.3.1. Air infiltration

Building air infiltration is defined as the air entering a building by an unplanned or unmanaged way, commonly by holes in the building envelope [11]. These holes can be caused by the deterioration of the building in time or by changes and remodeling in the building. In addition, some of them can be there since the construction of the building due to poor construction joints. As an example, the interface between building facade materials is a common location of poorly executed joints.

Not only is the air entering by the holes but also pollutants, noise, insects, dust or moisture. Air entering in a building means a loss in energy, thermal comfort and efficiency of mechanical systems.

According to the study “The Affects of Air Infiltration in Commercial Buildings” [11], the 30 percent or more of the energy wasted in heating and cooling is attributable to air infiltration and moisture.

Managing air infiltration is something important to improve quality and save money. Therefore, a lot of effort and money is put into achieving comfortable buildings. Clean air and well controlled temperature are two of the main objectives to achieve inside a building.

Unmanaged air can cause a need in additional load on HVAC systems, bring moisture and cause mold, reduce the comfort in the interior space, create condensation or cause additional resources to be needed for maintenance and cleaning. Some money is expended in building cleaning, HVAC maintenance or larger HVAC equipment. The costs also depend on the weather. There will be fewer costs in mind climates than in extreme cold or hot weather.
When new buildings are constructed, they are done in the most efficient manner. However, if the efficiency of an old building is improved, generally a huge renovation is needed and this implies a high investment of money.

In a building facade a lot of different sources can produce air leaks. Some of these leaks are placed between facade elements or between facade and foundation and roof, around envelope penetrations or in windows and doors joints.

The movement of air through buildings is based on pressure differences between the indoor and outdoor environment.

Air pressure (or weight per unit area) varies with height above ground. Sea level is the reference altitude, at which the air pressure is about 101300 Pa [12]. Atmospheric pressure decreases as height above sea level increases. Air pressure difference results from variations in absolute pressure between one area and another. The variations can be the result of the following factors: stack effect, wind effect, ventilation equipment and appliances. These factors are combined to create a constantly changing pattern of air leakage in a typical house.

2.3.1.1. Stack effect

Stack effect occurs due to differences in air density with temperature between indoor and outdoor air. It is stronger in cold weather, when temperature difference between both sides is bigger. Warmer indoor air tends to rise in the building because it is less dense than outside air. This causes the interior air to push out through openings in the upper parts of the building envelope (at the roof and upper exterior walls), this is called exfiltration. At the same time, there is a reverse air-pressure difference at the lower parts of the building, which induces air inward, and it is known as infiltration. The location on the envelope where the air pressure difference reverses from infiltration to exfiltration, is known as the neutral pressure plane (NPP), and at this horizontal plane there is no pressure difference between the space and its surroundings, so there is no horizontal air flow at this plane (See Figure 8).
The density of air not only depends on temperature of air, but also on its humidity. Therefore, indoor humidity also causes air to rise inside the building because humid air is lighter than dry air (the hydrologic cycle). This is called cool tower effect, which together with stack effect contributes to buoyancy, but this parameter has normally much less influence than temperature difference.

The location of the neutral pressure plane depends on the characteristics of the building envelope (when the wind speed is zero), that is to say, on the number and distribution of openings in the envelope, the resistance of the openings to airflow and the resistance to vertical airflow within the building. If the openings in the building envelope are uniformly distributed, of equal airflow resistance and there is no indoor resistance to airflow between floors, the neutral plane will be at the mid-height of the building. However, the location of the neutral pressure plane is not static. It is displaced up or down by the action of wind and by the design and operation of the ventilation systems.

For the good understanding of the following lines it is necessary to know how pressure varies with height, that is to say, the Hydrostatic Pressure distribution. This is the pressure of a point inside a fluid due to the weight of an air column. It can be deduced from a control volume analysis of an infinitesimally small cube of fluid, since the only force acting on the infinitesimal cube of fluid is the weight of the fluid column above it [13].
\[ P(z) = \int_{z_0}^{z} \rho(z) \cdot g \cdot dz \]

(Eq. 3)

Where,
- \( P \) = pressure [Pa]
- \( \rho \) = density \([\text{kg/m}^3]\)
- \( g \) = gravity \([\text{m/s}^2]\)
- \( z \) = height [m]

The height \( h \) of the fluid column between \( z \) and \( z_0 \) is often reasonably small compared to the radius of the Earth, so the variation of \( g \) can be neglected. Under these circumstances, and for incompressible fluids, the integral boils down to the following equations, known as the fundamental equation of fluid statics [13]:

\[ P = \rho \cdot g \cdot h \]

(Eq. 4)

Where \( h \) is the height \( z-z_0 \) of the liquid column between the tested volume and the zero reference point of the pressure.

Since \( g \) is negative, an increase in elevation will correspond to a decrease in pressure, and vice versa. However air is not an incompressible fluid, since its density can vary with height, \( z \), therefore [13]:

\[ \Delta P = \Delta \rho \cdot g \cdot z \]

(Eq. 5)

\[ P_{\text{indoor}}(z) = P_o - g(\rho - \Delta \rho) \cdot z \]

(Eq. 6)

\[ P_{\text{outdoor}}(z) = P_o - g \cdot \rho \cdot z \]

(Eq. 7)

\[ \Delta P = P_{\text{in}} - P_{\text{out}} = g \cdot \Delta \rho \cdot z \]

(Eq. 8)
This equation shows a linear increment of the pressure with height, $z$, where the slope is $\frac{1}{\Delta \rho \cdot g}$.

![Figure 9: The variation of pressure with height.](image)

However, the line is shifted sideways depending on the location of the opening where air leaves and enters the building.

For a large opening at the bottom and a small opening at the top:

![Figure 10: Variation of pressure difference with height for a large opening at the bottom and a small opening at the top.](image)
For a small opening at the bottom and at the top:

![Diagram of pressure difference variation with height for a small opening at the bottom and at the top.]

Figure 11: Variation of pressure difference with height for a small opening at the bottom and at the top.

For a uniformly leaky façade:

![Diagram of pressure difference variation with height for uniformly leaky façade.]

Figure 12: Variation of pressure difference with height for uniformly leaky façade.
For an opening away from the neutral pressure plane but taking into account the temperature outside and inside the space:

Figure 13: Flow directions for vertical openings [14]
Where,
\[ T_\infty \] = outside temperature
\[ T_c \] = temperature in the space.

“For any orientation and location, the mass flow rate from the space through opening (i) can be expressed as a function of the height of the neutral plane” [14].

\[ m_i = f_i(H_n) \]  

(Eq. 9)

In the next figure it can be seen an example of the variation of the neutral pressure plane with height.
At all other levels, the pressure difference between the interior and exterior depends on the distance from the neutral pressure level and the difference between the densities of inside and outside air [13].

$$\Delta P_s = (\rho_o - \rho_i) \cdot g \cdot (h - h_{\text{npp}}) = \rho_i \cdot g \cdot (h - h_{\text{npp}}) \cdot \frac{T_i - T_o}{T_o}$$

(Eq. 10)

Where

- $\Delta P_s$: pressure difference due to stack effect [Pa]
- $\rho_i$: density of indoor air [kg/m$^3$]
- $g$: gravitational acceleration constant [9.81 m/s$^2$]
- $h$: height of plane above (or below) npp, [ m]
- $h_{\text{npp}}$: height of neutral pressure plane [m]
- $T$: absolute temperature [K]
- $i$: indoor
- $o$: outdoor.
2.3.1.2. Wind Effect

Wind can also have influence in the infiltration and so in the results of the church analysis. The wind is created by the difference in temperature in different areas of the earth.

As wind hits the facade of buildings, its velocity is abruptly exchanged for an increase in pressure, or push on the building facade, following Bernoulli’s principle [16]:

\[
\text{Dynamic pressure } \left( \frac{1}{2} \rho U^2 \right) + \text{Static pressure } (P) = \text{constant [Pa]}
\]

\[
\text{Kinetic energy density} + \text{Potential energy density} = \text{constant [J/m}^3\text{]}
\]

Bernoulli’s principle is derived from the principle of conservation of energy, which says that the total amount of energy in a system remains constant over time [17]. Its equation means that the sum of all forms of mechanical energy (kinetic and potential) remains constant. If an increase in the speed of the fluid occurs, this is proportional with the increase in both dynamic pressure and kinetic energy, and with the decrease in its static pressure and potential energy.

The maximum increase in pressure on the facade where the wind is stopped is called the stagnation pressure, and this point where the fluid meets the plate is known as stagnation point (Figure 16). There the local velocity of the fluid is zero, which means that the fluid stagnates.

![Figure 16: Stagnation point flow [18]](image)

When there is a streamline coming perpendicular to the surface, this streamline divides the flow in half: the flow that is above this streamline which goes upward the wall and the flow that is below this streamline which goes downward it.
The pressure measured at the stagnation point \( P_0 \) is a function of its speed and the density of the air, and it can be calculated as [18]:

\[
\rho_e + \frac{1}{2} \rho U_e^2 = \rho_0 + \frac{1}{2} \rho U_0^2
\]

(Eq. 13)

Where, point 0 is the stagnation point and the point \( e \) is far upstream. \( V_0 = 0 \) [m/s] (at stagnation point), therefore [18]:

\[
P_e + \frac{1}{2} \rho U_e^2 = P_0
\]

(Eq. 14)

\[
\text{static pressure} + \text{dynamic pressure} = \text{stagnation pressure}
\]

Where,

\( P_0 = \) the stagnation pressure of wind [Pa]

\( P = \) density of air [about 1.2kg/m]

\( U = \) velocity of the air [m/s]

The pressure anywhere in the flow can be expressed in the form of a non-dimensional pressure coefficient \( C_p \) [18]:

\[
C_p = \frac{P - P_e}{\frac{1}{2} \rho U_e^2}
\]

(Eq. 15)

\( C_p \) is always a value between -1 and 1 [18]. It takes both positive values when the pressure is higher than the reference pressure and negative values when the pressure is lower than the reference pressure. At the stagnation point \( C_p = 1 \) (the maximum value) [18].

\[
C_p = \frac{P - P_\infty}{q_\infty}
\]

(Eq. 16)
Where,

- \( C_p \) = the pressure coefficient
- \( P \) = the static pressure at the point at which pressure coefficient is being evaluated
- \( P_\infty \) = the static pressure at points remote from the body, or free stream static pressure
- \( q_\infty \) = the dynamic pressure at points remote from the body, or free stream dynamic pressure.

At the stagnation point the \( C_p \) is +1 since the subtraction of free stream static pressure to the stagnation pressure is equal to free stream dynamic pressure.

While the wind may stagnate on the windward side of the building, it will most likely increase in velocity along the sides and top of the building. In these areas, the pressure will be reduced, thereby causing suction on the building facade (see Figure 17).

As it can be noticed in the figure above, generally the wind driven air leakage is inward on the windward side of the building and outward on all other sides when there is no stack effect or fan pressurization at work and if the openings are uniformly distributed on the building envelope. In fact, normally the resultant indoor pressure is slightly lower than the ambient barometric pressure, so the result is a slightly increased pressure difference at the windward side and a slight decreased pressure difference on all other sides, including the roof. However, the indoor air pressure of a building can increase or decrease with wind speed depending on the number and location of openings.

In short, wind pressures are generally high/positive on the windward side of a building and low/negative on the leeward side. The occurrence and change of wind pressures on building surfaces depend on [8]:

![Figure 17: Wind effect](image_url)
• Wind speed and wind direction relative to the building
• The location and surrounding environment of the building
• Shape of the building.

2.3.2. Natural Ventilation

According to the ASHRAE Standard [19], ventilation is that air used for providing acceptable indoor quality. It is the intentional movement of the air from outside coming to the inside.

With careful design, natural ventilation can be a good method to reduce energy use and cost and also to achieve acceptable indoor air quality for health and thermal comfort. Having good natural ventilation can reduce the use of mechanical ventilation. By reducing the use of air-conditioning plants, a save about 10%-30% [20] of total energy consumption can be reached. High efficiency heat exchanger can however not be used.

The difference between infiltration and natural ventilation is that the last one is a desired and controlled movement of air through the building envelope, while the infiltration is not. Therefore, the driving forces for both are the same, that is to say, the pressure differences created by wind and
buoyancy effect. However, the openings in the case of natural ventilation are known, both its size and placement; in fact, they are located so that the required air flow is obtained. The specific approach and design of natural ventilation systems will vary based on building type and local climate.

2.3.2.1 Wind driven natural ventilation

As it has been explained in the section of infiltration, the wind causes a positive pressure on the windward side of the building and a negative one in the leeward one. In order to have the same pressure in both sides, fresh air is introduced inside the building by any windward opening and exhausted by any leeward one. Depending on the season, more or less wind is introduced. In the summer, wind is used to provide as much fresh air as possible but in the winter the opposite occurs, ventilation is used only to avoid high levels of moisture and pollutants.

The volume of airflow induced by the wind through a relatively large opening in the building envelope can be expressed as it follows [20]:

\[ Q_{\text{wind}} = K \cdot A \cdot U \]  
(Eq. 17)

Where,

- \( Q_{\text{wind}} \) = volume of airflow [m³/h]
- \( A \) = area of the opening [m²]
- \( U \) = outdoor wind speed [m/h]
- \( K \) = coefficient effectiveness.

Sometimes the wind comes parallel to a building instead of perpendicular. In this case it is still possible to induce wind ventilation by a casement window opens or by the different architectural features.

If improved ventilation is desired, it is important to avoid obstructions between the openings, between the opening in the windward facade and the opening in the leeward one.

2.3.2.2 Buoyancy ventilation

It is already known that buoyancy ventilation can be both temperature-induced (stack ventilation) and humidity induced (e.g. in cooling tower). Both can be combined to have a passive evaporative cool tower. Evaporative cooling principle is based on air passing through a media where the water content
evaporates taking energy from the air [21]. Therefore the warm air gets cold and humid after the evaporation process. The tower uses a column of this cool moist air, which is heavier than hot dry air from outside and heavier than hot moist air from inside. Thus the dropping of heavier air, forcing lighter air to exhaust, generates airflow inside the building. Within the room, heat and humidity given off by occupants and other internal sources both tend to make air rise. The heated air escapes from openings in the ceiling or roof and allows fresh air to enter lower openings to replace it.

Figure 19: Example of an evaporative cooling tower [20]

Stack effect ventilation is an especially effective strategy in winter, when the temperature difference is maximum, however it does not work in summer because it requires that the indoors be warmer than outdoors, and this is an undesirable situation in summer in most countries. However, a chimney heated by solar energy can be used to drive the stack effect without increasing room temperature.

The airflow induced by stack effect can be calculated as [20]:

\[ Q_{\text{stack}} = C_d \cdot A \cdot \left[ 2 \cdot g \cdot h \cdot \frac{(T_i - T_o)}{T_i} \right]^{1/6} \]  

(Eq. 18)
Where

\[ Q_{\text{stack}} = \text{ventilation rate [m}^3\text{/s]} \]

\[ C_d = 0.65, \text{a discharge coefficient} \]

\[ A = \text{free area of inlet opening [m}^2\text{], here assumed equal to outlet opening} \]

\[ g = \text{the acceleration due to gravity [9.8 m/s}^2\text{]} \]

\[ h = \text{vertical distance between inlet and outlet midpoints [m]} \]

\[ T_i = \text{average temperature of indoor air [K]} \]

\[ T_o = \text{average temperature of outdoor air [K]} \]

### 2.4. Combined effect of wind and temperature difference

In most cases, natural ventilation depends on a combined force of stack and wind effects. The pressure patterns for buildings continually change with the relative magnitude of wind and thermal forces.

Figure 20 shows the combined effect of thermal and wind forces. In order to determine the total pressure difference across the building envelope, the pressures due to each effect are added together.

The relative importance of the wind and stack pressures in a building depends on internal resistance to vertical air flow, building height, local terrain, location and flow resistance characteristics of envelope openings and the shielding of the building structure.

For the stack effect [22]:

\[ P_{\text{stack}} = \rho_{\text{out}} \cdot g \cdot h \frac{\Delta T}{T_{\text{in}}} \]

(Eq. 19)
Where,

\[ P_{\text{stack}} = \text{the characteristic pressure difference} \]
\[ \rho_{\text{out}} = \text{the density of the air outdoors [kg/m}^3] \]
\[ T_{\text{in}} = \text{the temperature inside [K]} \]
\[ g = \text{the gravitational acceleration [m/s}^2] \]
\[ \Delta T = \text{the temperature difference between indoors and outdoors [K]} \]

In the following figure it can be seen the linear change of stack pressure with height, given by the equation 19 above. The maximum stack pressure (\( P_{\text{stack}} \)) occurs when \( h=H \).

![Figure 21: Stack effect pressure and flow (when T_{in}>T_{out}) [22]](image)

Then, the pressure difference Across the building envelope due to stack effect is calculated as:

\[ \Delta P_s = f_s \cdot P_{\text{stack}} \]

(Eq. 20)

Where,

\( \Delta P_s \) = the pressure difference due to stack effect

\( f_s \) = the stack effect factor, dependent on leakage distribution, and inflow and outflow balance.

For the wind effect [22]:

\[ P_{\text{wind}} = \frac{\rho_{\text{out}} \cdot C_p \cdot W S^2}{2} \]

(Eq. 21)
Where,

\[ P_{\text{wind}} = \text{the characteristic pressure for the wind speed} \ [\text{Pa}] \]
\[ WS = \text{the wind speed} \ [\text{m/s}] \]
\[ \rho_{\text{out}} = \text{the density of the air outdoors} \ [\text{kg/m}^3] \]

Then, the pressure difference across the building envelope due to wind effect is calculated as:

\[
\Delta P_w = f_w \cdot P_{\text{wind}}
\]  
(Eq. 22)

Where,

\[ \Delta P_w = \text{the pressure difference due to wind effect} \]
\[ f_w = \text{the wind effect factor, dependent on leakage distribution, pressure coefficients (Cp) and inflow and outflow balance.} \]

Then, the air flow is function of those pressure differences [22]:

\[
Q = C \cdot \Delta P^n
\]  
(Eq. 23)
Where,

\[
Q = \text{the air flow [Volume/Time]}
\]
\[
C = \text{an empirical flow coefficient}
\]
\[
n = \text{an exponent with depends on the orifice-type.}
\]

The pressure differences created due to wind pressure and stack pressure are considered in combination by adding them together and then determining the airflow rate through each opening due to this total pressure difference. It is not possible to determine the airflow by adding first the airflow rates due to separate driving forces, because the airflow rate through the openings is not linearly related to pressure difference [8].

The resulting total airflow showed in Figure 23 is calculated taking both effects into account. Then, instead of neutral pressure plane been at \(h_{o,s}\), which corresponds only to stack effect, it is shifted to \(h_o\) due to wind effect. Depending on the contribution of the wind, the neutral pressure plane can be moved up or down.

![Figure 23: Total pressure difference and flow rate resulting from addition of wind and stack pressures [22]](image_url)

However, unfortunately the simple addition of pressure difference causing by each effect does not give the real total pressure difference Across the building envelope. This is because \(\Delta P_s\) and \(\Delta P_w\) normally have different internal pressures. Therefore another process is necessary since each physical process can affect the indoor and outdoor pressures, which can cause interactions between physical processes which are otherwise independent. The most simple physical models of infiltration consider the two driving forces (wind and stack) separately and then combine them in a superposition process. As normally detailed properties of building leaks are unknown and leakage is a non linear process, an exact solution for the superposition process is impossible. Sherman and Grismstrud, as well as Warren
[22] found that adding the stack and wind flow rates in quadrature to be a robust superposition technique:

\[ Q = \sqrt{Q_s^2 + Q_w^2} \]  

(Eq. 24)

Where,

- \( Q \) = total airflow [Volume/Time]
- \( Q_s \) = airflow due to stack effect [Volume/Time]
- \( Q_w \) = airflow due to wind effect [Volume/Time]
3 Process and results

In this section the different methods used to get all the data, inside the church and in the wind tunnel experiment, are explained. Later, some analyses were done in order to analyze the results and get different explanations and conclusions about them.

3.1 Methods of measurement

Normally it is difficult to determine exactly where the main leaks are. Several methods to identify building envelope leakages are exposed in the following lines.

The methods consist of measures of the temperature inside the church, air infiltration and air change rate. These data were used later in the study to know how the church is affected by them.

3.1.1 Methods to measure Air Change Rate

The air change rate is not easy to measure in large and naturally ventilated elderly churches, because the air inlets and outlets usually consist of a variety of unintentional leakage interstices in the church envelope. In this project a tracer gas techniques was used with the aim of calculating the air change rate inside the church.

3.1.1.1 Tracer Gas Technique

The properties of an ideal tracer gas are the following ones [24]:

- Safety: the presence of the gas should not involve any hazard to people, materials, or activities. Therefore, the tracer gas should not be flammable, toxic, allergic, etc.
- Non-reactivity: since the basic principle used in this technique is the mass conservation, the tracer gas can not react chemically or physically with any part of the system under study.
- Insensibility: neither the air flux nor the air density of the system should be affected by the tracer gas.
- Uniqueness: it should be possible to recognize tracer gas from all the other constitutes of air and substances presents in the system under study.
- Measurability: the tracer gas should be quantifiable.

In this case the trace gas used was SF6, which is considered to have close properties to ideal ones.
A perfect space to carry the tracer gas technique out should have the following properties [24]:

- Homogeneity: the fluid properties, such as density and tracer concentration, are the same at every point of this space.
- Isolated: there is not any area from which tracer gas can enter the space under study, and neither any buffer zone.
- Perfectly mixed: the outside air injected into the space under study becomes instantaneously and homogeneously dispersed. As long as the times of the analysis are significantly longer that the mixing time that exits in practice, the perfectly mixed assumption is valid.

In the real case it appears that the air inside the church is well mixed when the churches are heated, due to strong air currents occurring at heat sources and cooler outer building surfaces. However, during non-heating periods there are spatial differences in tracer gas concentration, what makes tracer gas measurements more difficult to perform.

Two tracer gas techniques were used in this project:

One of them is the decay method which consists of injecting tracer gas inside the zone under study till it reaches a known initial concentration and then stop the injection and leave its concentration decreases. There are several ways of analyzing the decrease of the concentration: decay regression, integral decay and two-point (average) decay. In this case decay regression was used to solve the mass balance equation. “Its principle is to mix and initial dose of tracer gas with the air of the space into a homogeneous concentration and then to determine the rate at which the gas mixture is replaced with fresh air. The faster the replacement takes place, the higher is the air change rate.” [23]. As no more tracer gas is injected, its initial concentration will decay exponentially as time goes on:

\[ C = C_0 \cdot e^{-ACR \cdot t} \]

(Eq.25)

Where,

- \( C_0 \) = initial concentration directly after injection and mixing of the tracer gas [M/V]
- \( ACH \) = air change rate [1/T]
- \( t \) = time [T].

“A gas analyzer (Brüel & Kjaer 1302) was used to measure the time variation in tracer gas concentration in, usually, six measuring points distributed both horizontally and vertically in the church space. The tracer gas SF6 was distributed manually directly from a gas cylinder; the discharged
gas jet was directed obliquely upwards in about 10-15 places in the church, taking about one minute in total.” [23].

Figure 24: Example of set-up for decay measurements [23]

Apart from the decay method, the **passive tracer gas method** was used as well. Some tracer gas sources (figure 25) were distributed in the church and the gas is mixed with the air by molecular diffusion. Its concentration was measured in different parts of the room, exactly in those points where the samplers (figure 25) were placed. Those samplers contain activated carbon, which adsorbs the tracer gas. The tracer gas content of the sampling tubes was analyzed by gas chromatography in a laboratory. The average gas concentration for the sampling time can be calculated as [23]:

\[
C_{average} = \frac{m_{average}}{(S \cdot t)}
\]

(Eq. 26)

Where

\[ m_{average} = \text{the average gas content over all samplers [M]} \]

\[ S = \text{equivalent sampling rate [V/T]} \]

\[ t = \text{sampling time [T]} \]
Therefore, the average air change rate is [23]:

$$\text{ACH}_{\text{average}} = \frac{E}{V \cdot C_{\text{average}}}$$

(Eq. 27)

Where,

ACH = average air change rate [1/T]  
E = total emission rate [M/T]  
V = the church volume [V].

Figure 25: Passive source (left) and sampler (right) of tracer gas [23].

With this method long-time average data are obtained because the adsorption process is very slow, in fact the equivalent sampling rate, S, was 16 ml/h [23], so the sampling time needed was about 3 or 4 weeks. As the emission rate of the sources, E, is normally very low (typically 5-20 µg/h [ref1]), several source units are needed (as it can be seen in the figure 26, and specifically for this project from 10 to 30 source tubes were used [23]).
The tracer gas collection can also be *active*, where samples of air are pumped into the sampling tubes, see figure 27. With this method hence fairly momentary values can be attained because the sampling time can be as small as ten minutes.
Figure 28 shows typical tracer gas concentration response during the measurements time when the decay method was used for a case of heated church. It can be seen that after one hour the tracer gas seemed to be uniformly mixed inside the church hall.

There was a point with quite big deviation from the main curve (after around 230 min). This happened because this point was located close to the floor (this line corresponds to 0.1m over the floor [23]), which it was noted to be very leaky. Thus the air comes from the crawlspace underneath, causing locally more diluted tracer gas.

Figure 28: Time history of tracer gas concentration in a heated church upon sudden gas release [23].

3.1.2 Methods to measure air infiltration through the church façade

The phenomenon known as infiltration happens due to different craks and openings over the building envelope. The different thechniques and models used to measure and quantify the quantitiy of air infiltrated are explained here.

3.1.2.1. Blower Door Technique

This method is used to measure the air infiltration through the leaky points of the church envelope.
Using the blower door the church is depressurized making the outdoor air enters through all holes of the envelope and allowing measuring the total infiltration of air. The blower door’s airflow rate is proportional to the surface area of holes through the air barrier.

In this case the blower door was installed in the vestry of the church, as it can be seen in the figure 30.

This method could not be possible to use if the leaky area of the building envelope was very big, but it is not the case of the church under study.
3.1.2.2 Pressure Pulse Technique

Another leak-measuring technique under development is the pulse technique, which gives leakage data for more realistic pressures than those of the blower-door method [25].

3.1.3 Methods to measure the temperature inside the church

3.1.3.1 Infrared (IR) Thermography

This technique consists of representing a visible infrared light emitted by objects in accordance with their thermal condition. The cameras used for this technique measures the temperature of the objects present in the room and they create an image with colors which represent the thermal design. Figure 31 shows two thermography pictures of Hamrânge church. The dark areas indicate that infiltration of cooler air was coming from the crawlspace, which supports the results obtained from tracer gas decay of air leaking in through the floor. Radiators appear bright. Unfortunately this technique can only detect infiltration leaks, but not exfiltration leaks.

![Infrared Thermography](image)

Figure 31.- IR Thermography inside the church hall [25].

This technique gives a rapid idea of the leakiest zones on the building envelope.

3.1.3.2 Thermistors

Thermistor is a word form by the combination of “resistor” and “thermal” [26]. It is a temperature sensor that has a resistance proportional to their temperature so it is used to measure temperature.

They are really useful in science and engineering studies because they are more temperature sensitive than usual.
There are two types of thermistors: PTC (Positive Temperature Coefficient of Resistance) and NTC (Negative Temperature Coefficient of Resistance). The PTC thermistors have a resistance that increases with the rising of temperature and vice versa. They can work as thermal switches and also as protector of circuits from overload. On the other hand the NTC thermistors have a resistance that varies inversely with the temperature. They are normally used for temperature control and indication.

They are usually accurate so the measures taken by them are really exact (within ±0.05% to ±0.2%) comparing with other devices used in temperature measure as thermocouples. However, they are non-linear as a typical semiconductor so they have to be compensated when circuits are built. They cannot be used at high temperatures [27].

15 different sensors were placed thorough the church and each one with a different height from the floor (from 0.1 to 9.8m). A sensor at 5.0 m height was used to collect all the data from the indoor air temperature. In general, the indoor air temperature did not differ so much. It was quite homogeneous above the height of 1.5 m. Below this point, temperatures were decreasing as it was closer to the floor. The thermistors used in this experiment had 0.47 mm in diameter and 4 mm of longitude [27].

3.1.4 Wind Tunnel

The wind tunnel is a tool used in order to study the effects that the air in movement can cause when it comes up against solid materials [28]. It is used to measure the air velocity and pressure affecting to a model.

It is normally used by scientist and engineers in order to study the air movements around a model of an airplane, automobile or a building. Looking to the behavior of the wind against the model, they can
realize how a real airplane will fly or a building will be affected. It is a safer and cheaper way to know if something will be wrong or not [29].

A model of the church analyzed in this report was studied in a wind tunnel. Its length was 10 m, its width 3 m and its height 1.5 m. In figure 33 the wind tunnel with the church model used for the measurements can be seen. The wind tunnel used for this thesis was a closed circuit wind tunnel at the University of Gävle.

The church model was placed on a plate and on it there are 400 pressure taps following a quadratic pattern with 37 mm of distance between them [2].

The forces acting on the model were measured with some cables or strings connected to it.

The pressure difference between the sides is measured by small holes placed in the model and using multi-tube manometers to measure each hole.

![Figure 33. Wind tunnel with church model on pressure plate [2].](image)

In the wind tunnel, the air was coming from the same place all the time. The church was rotated in a counter clockwise to know how this wind affects it.

The pressure was measured at different wind direction with a 15 degrees interval.
3.2 Analysis of the data

3.2.1 Theory needed for the analysis

3.2.1.1 Multiple linear regression

Microsoft office Excel is the program used to analyze all the data provided and to represent them graphically. Different functions as “average” or “multiple regression” are used to facilitate interpretations. In particular, multiple regression is really useful in analyzing the factors affecting air change rate and the differences between them.

The most important results of multiple linear regression (MLR) are R and R², which are measures of the strength of the relationship between the set of independent variables and the dependent variable.

The closest the coefficient of determination, R², is to one, the better the lineal correlation between them, that is to say, it indicates the percentage of variation of the dependent value which can be explained with the independent variables. The higher this percentage, the better the model is to predict the behavior of the dependent variable. The multiple correlation coefficient, R, is the correlation coefficient between the observed values of the independent variable and its predicted values; therefore it provides the same information about the relationship between dependent and independent variables.

Another MLR indicator of how well the air change rate can be explained by e.g. stack and wind effect, is the P-value, that is the possibility of the results occurring by chance. The lower this value is, the more certainty that the independent variable affects the dependent one. A common limit for assuming that the P-value is low enough for the independent variable to be considered having a significant effect is P< 0.05. This limit is called “level of significance”.

The predicted value of air change rate is a linear transformation of the independent variables such that the sum of squared deviations of the observed and predicted independent variable is a minimum. The regression equation that shows how the air change rate varies with each parameter is obtained using the coefficients calculated by MLR. An example of that is the equation:

\[
ACH = a + \Delta T \cdot b + WS \cdot c
\]

(Eq.27)

Where,

- \(ACH\) = Air Change Rate
- \(\Delta T\) = Temperature difference
- \(WS\) = Wind Speed
The coefficients depend on the quantities and units of the variable. One way to estimate how influential $\Delta T$ and $WS$ are is to estimate some kind of “normal” values to multiply with their coefficients for the location of the church under study. Annual average wind speed around Gävle is 2-3 m/s while average $\Delta T$ might be around 10 °C [30]. Now, the coefficient multiplied by the average (“Coefficient-Average”) has to be calculated: for the wind is “c·2.5” and for $\Delta T$ it is “b·10”.

Depending on the values of b and c, one of the values of “Coefficient-Average” will be larger than the other one. The higher value of them is the one with more influence in the Air Change Rate measured in the particular church that is studied.

All the coefficients obtained have to be carefully analyzed to know which effect, wind or stack, has more influence in the variations of air change rate. Although the expected results are to obtain all positive values of coefficients, sometimes unexpected values can appear that can be difficult to explain.

One important way of analyzing the results is to study the change in $R^2$ when adding an independent variable. For example, comparing the value of $R^2$ when both wind and temperature difference are taken into account, and the value of $R^2$ when only the temperature difference is considered, the increase in $R^2$ can be seen. If there is a negligible increase in the value of $R^2$, it indicates that the temperature difference has much more influence than the wind, i.e. the variations in air change rate tend not to be explained by wind.

3.2.1.2 Wind velocity rates

Making a comparison between the real wind speed ($WS_w$) and the wind speed calculated from the stack effect (buoyancy), ($WS_b$), an idea of whether wind effect or stack effect is more dominant can be obtained by looking at the velocity rate between those two speeds: $WS_w/WS_b$ [-].

The velocity due to the temperature difference can be physically calculated as:

$$WS_b = \sqrt{g \cdot \frac{\Delta T}{T} \cdot H}$$

(Eq.28)

Where,

$WS_b$ = the wind speed [m/s]
g = the gravitational force [9.81 m/s²]

H = the height of the building (14 m for the present church)

T = the mean temperature between indoor and outdoor [K]

ΔT = the temperature difference between indoor and outdoor [K].

If the velocity rate is more than 1 the wind speed tends to be more dominant, and vice versa. However, it should be kept in mind that in reality those velocity values differs from the theoretical value, which means that the unit is not an exact limit to determine which parameter dominates more, but a theoretical value.

In the case of the WS_W, this value is taken from the atmospheric profile of wind speed at the height of the roof of the church (WS_H). The figure 34 shows the usual wind speed profile, but it varies depending on the obstacles close to the building and on the structure of the building itself.

![Atmospheric wind speed profile](image)

**Figure 34: Atmospheric wind speed profile [30]**

In order to get WS_H values closest to the real ones (WS_H'), wind speed is estimated applying some corrections to the hourly wind speed measured from the weather station. The wind speed is usually measured in flat, open terrain and the anemometer which records it is located at 10 m above the ground level (WS_{10}). From the following formula the wind speed for the height of building under study can be obtained, which considers not only the real height of the building but also the corrections due to the terrain and obstacles around the building: [31]
\[ W_{S_H}' = WS \left( \frac{\delta_{10}}{H_{10}} \right)^{a_{10}} \left( \frac{H}{\delta} \right)^a \]  

(Eq. 29)

Where,
\[ \delta = \text{the wind boundary layer thickness [m]} \]
\[ H = \text{the height [m]} \]
\[ WS = \text{the wind speed [m/s]} \]

Values of \( \delta_{10} \) and \( a_{10} \) are available in tables (see appendix A). The wind driven ventilation force is considerably reduced also due to the fact that almost no building surface is perpendicularly exposed to \( WS_{10} \).

Obstacles in the surroundings and the structure of the building results instead in locally reduced wind pressures, represented by wind pressure coefficients (“Local Wind Pressure Coefficients” section).

The wind speed calculated from stack pressure difference (\( WS_B \)) differs as well as the real wind in its representation of an air infiltration force. The pressure difference represented by \( WS_B \) in equation 28 indicates the difference between minimum and maximum indoor-outdoor pressure difference occurring in the building; locally the indoor-outdoor pressure difference will vary between these limits. Hence, the average indoor-outdoor pressure difference will differ significantly from that represented by \( WS_B \). For instance, in the reference case of a uniformly leaky distribution on the building envelope (see figure 35), trigonometry tells that the average pressure difference will be reduced to one fourth; i.e. \( WS_B/4 \) would be more representative. The leakages distribution is usually unknown, but in case of the church under study it seems that neutral pressure plane usually is located at quite a low level (as in figure 23) because the floor is very leaky. This makes the reduction in average pressure difference smaller, around \( WS_B/2 \). But the high pressure differences then occur where the building envelope is relatively tight, in the upper part of the building. In conclusion, it would be needed to know the vertical air leakage distribution to properly assess the air infiltration force of \( WS_B \).
3.2.1.3 Local wind pressure coefficients

Values of the wind pressure coefficients depend on the shape of the building, the direction of the wind, the nearby buildings, vegetation, and terrain features.

First of all it is necessary to know the movement of the air flow around the building. When the wind hits the wall, airflow separates at the building edges, generating zones with air recirculation over the roof, sides and leeward walls, and it extends into the downwind wake (see figure 36). As it can be seen in the wind profile of the windward side, the mean speed of wind ($U_H$) that is approaching a building increase with height above the ground. The higher the wind speed at roof level, the larger the pressure on the upper part of the wall than near the ground. Once the airflow has beaten the building, part of it goes down one-half to two-thirds of the building and before reaching the ground level it separates from the building and moves upwind to form a vortex which can generate high velocities close to the ground. The other part of the total airflow goes up one-quarter to one third of the building and then crosses it over the roof. For a tall buildings an intermediate stagnation zone can exist where the wind hits the building. At that point the airflow changes the direction to pass horizontally around the building.

In the leeward side of the building a “Flow Recirculation Section” can be found, where the average speed is low (one-quarter of those at the windward) and where there is high turbulence. This region extends a distance $L_r$. As it can be seen in figure 37, the airflow moves upward over most of the leeward walls [31].
Airflow patterns depend mainly on building shape and upwind conditions (atmospheric wind profile) and they are more or less independent of wind speed.

However, if the angle of the wind is not perpendicular to the windward wall, the flow patterns are more complex (see figure 37, right). If the angle between the wind direction and the windward wall is less than 70°, the patterns on this wall are less pronounced and also are the vortex created close to the ground [31].

Next the distribution of pressure coefficients for walls of low-rise buildings is going to be explained. Generally, for tall buildings, height is more than three times the crosswind width; otherwise it is considered low-rise building, as it is the case of the church under study.
Figure 38: Local pressure coefficients (Cp·100) for low-rise building with varying wind direction. [31]

At wind angle perpendicular to the façade, $\theta = 0^\circ$, pressure coefficients are positive, and as flow velocities increase, their magnitudes decrease near the sides and the top.

Generally the pressure coefficient increases with height, because the wind speed increases with height, which results in increasing velocity pressure in the approach flow. As $\theta$ increases the region of maximum pressure occurs closer to the upwind edge (A or D in figure 38) of the building. When the wind angle is $\theta = 90^\circ$, pressures become negative at the parallel façade (AB or DA in figure 38). The
degree of this recovering depends on the length of the side in relation to the width of the building. The average pressure on a wall is positive for wind angles from $\theta = 0^\circ$ to $60^\circ$ and negative for $60^\circ$ to $180^\circ$ [31].

3.2.2 Results

The principal quantities used in the multiple regression were the Air Change Rate, Temperature difference (Indoor-Outdoor) and Wind speed. The Air Change Rate was defined as the dependent variable and its predictors as independent ones (see Appendix B).

To start with, the necessary data to calculate the values of the predictors were recorded in the weather station located 1 km from the church. The predictor which indicates the stack effect was the Temperature difference ($\Delta T$), and the others, such as the magnitude of the wind speed (WS), indicated the wind effect. The value of Wind Speed component in the direction perpendicular to the facades was analyzed as well because it was expected to influence more than the one coming from another directions. Wind Speed and Wind Speed component were studied to notice the different influence that Wind direction could have on ACH. The square values of both WS and WS90 were also considered as predictors since the dynamic pressure of the wind is related to $WS^2$ and $WS90^2$.

The measurement data used were attained at three different occasions at different times of the year, namely in the months of May, June and October in 2010. Each of the three data sets was first analyzed separately and later all the sets were analyzed together.

In the multiple regression analysis, only data that were fairly distant in time was used, typically with two hours or more in between. This selection was done in order for the data to represent more or less random samples, thus keeping the auto-correlation low. Further, in the selection of data, especially peak values of ACH were adopted, since with these biggest changes in the air change rate were represented, which could be expected to influence more in the results.

3.2.2.1 First data set- May

As mentioned, only the peak values were used for the analysis in the multiple regression. These values were taken from a graph that can be seen below (figure 39). The peak values used for the analysis of the first data set can be seen in Table D1 Appendix D.

The multiple regression results are discussed below.
Values of $R^2$ obtained:

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.8413</td>
<td></td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>0.0445</td>
<td></td>
</tr>
<tr>
<td>WIND SPEED 90</td>
<td>0.3701</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.8741</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$ 90</td>
<td>0.8425</td>
<td></td>
</tr>
</tbody>
</table>

Different interpretations of the results obtained were done to explain the behavior of wind speed and temperature difference and their influence in Air Change Rate.

- **Increasing $R^2$:**

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.8413</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.8741</td>
<td>0.0328</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WS</td>
<td>0.0445</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.8741</td>
<td>0.8291</td>
</tr>
</tbody>
</table>

As it can be seen in Table 2, the $R^2$ only taking into account the temperature difference was 0.841, that was the 84.13% of variations in air exchange rate can be explained by the stack effect. Considering both effects that value increased slightly, till 0.8741, what means that stack effect has much more influence in the air exchange rate than the effect of wind speed (WS). That can be also seen in Tables 2 and 3, looking at the increase of $R^2$: the increase was much bigger when the stack effect was considered.

It can be said that the wind speed alone is not a good predictor; only the 4.45% of variations in air change rate can be explained by it.

Making a comparison between wind speed and wind speed in the perpendicular direction:

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.8413</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$ 90</td>
<td>0.8425</td>
<td>0.0012</td>
</tr>
</tbody>
</table>
It can be noticed that WS90 does not correlate better with ACH. The increase of $R^2$ is bigger when the Wind Speed is considered and not the Wind speed in the perpendicular value. This was not the result expected.

- Coefficients:

Table 5. Coefficient obtained from multiple regression for the wind speed.

<table>
<thead>
<tr>
<th></th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interception</td>
<td>0.2529</td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>-0.0065</td>
</tr>
</tbody>
</table>

It is noteworthy (see Table 5) that when the multiple regression was made only taking into account the wind effect, a negative coefficient value was obtained and therefore a negative correlation. This means that the higher the wind velocity, the lower the air exchange rate, the opposite of what it is expected.

However, it is logic because as it can be seen in Figure 39, the wind was stronger during the day, when the temperature difference was smaller, and the influence of temperature difference on the air exchange rate was bigger.

![Figure 39. Wind speed, temperature difference and air exchange rate for the first data-set (May).](image)

Adding Temperature difference as a predictor the regression equation was the next one:
$ACH = 0.0186 + 0.0136 \cdot \Delta T + 0.0061 \cdot WS$  

(Eq. 30)

-Studying the P-values:

Table 6. P-value for each predictor when both are analyzed together with multiple regression

<table>
<thead>
<tr>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
</tr>
<tr>
<td>WIND SPEED</td>
</tr>
</tbody>
</table>

P-value for $\Delta T$ was lower than 0.05 so the Temperature difference has a significant effect.

The P-value for WS was about 0.05, on the limit for being considering significant.

The significance-value of the total regression was $F = 2.24E-08$, which is less than 0.05, as it was expected. It means that a highly significant prediction of ACH can be done with the independent variables $\Delta T$ and WS.

-Representation of coefficients:

Doing the multiple regression of only $\Delta T$, the next graphics were obtained:

![Figure 40: Representation of the predictor $\Delta T$ when Regression of $\Delta T$ was done](image)
In the figure above, it can be seen the representation of the coefficients of ∆T. It suggests that, when the temperature difference increases 10 degrees, the air change rate also increases, in 0.1 units.

Doing the multiple regression of ∆T&WS, the next graphics were obtained:

The linear correlation that exists between ∆T and ACH is depicted in Figure 40, showing both measured and predicted ACH when only ∆T is used as predictor. When the wind is added as a predictor (see Figure 41), the average discrepancy between measured and predicted ACH is somewhat reduced, illustrating the contribution of wind in the prediction.

3.2.2.2 Second data set-October

The peak values used for the analysis of the second data set can be seen in table D2 in Appendix D.

This table was formed by all selected peak values of the data set that are represented in Figure 42 where it can be seen that in the beginning there is a appreciable wind higher than 8 m/s on average.
The multiple regression was used and the results obtained are discussed in the lines below.

Values of $R^2$ obtained:

Table 7. Results of $R^2$ from the multiple regression (Second data set)

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.0051</td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>0.2712</td>
</tr>
<tr>
<td>WIND SPEED 90</td>
<td>0.3932</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$</td>
<td>0.6610</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$ 90</td>
<td>0.4835</td>
</tr>
</tbody>
</table>

Different interpretations of the results obtained were done to explain the behavior of wind speed and temperature difference and their influence in Air Change Rate.

- Increasing $R^2$:

Table 8. Increase in $R^2$ adding Wind Speed

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.0051</td>
<td></td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$</td>
<td>0.6610</td>
<td>0.6559</td>
</tr>
</tbody>
</table>
As it can be seen in Table 8, the $R^2$ only taking into account the temperature difference was 0.0051, that is to say, only the 0.51% of variations in air exchange rate can be explained by the stack effect.

When including both variables that value increased a lot, till 0.661, which indicates that the wind effect has more influence on the air exchange rate than the stack effect. That can be also seen in Tables 8 and 9, looking at the increase of $R^2$: the increase is much bigger when the wind effect is considered.

It can be said that now the wind speed alone is a better predictor than in the last data set.

These are indeed interesting data, where there was low correlation with only $\Delta T$ and WS separately, but quite good correlation when both were taken into account. Looking at Figure 42 where ACH, $\Delta T$ and WS are plotted together, it can be seen that this actually is explicable. These data include quite high WS, high enough to have a significant impact on ACH, as compared to the previous data set.

Next, a comparison between Wind speed and Wind speed in the perpendicular direction was done.

Again the Wind speed in the perpendicular direction does not have a better correlation with ACH.

-Coefficients:

Table 11. Coefficient obtained from multiple regression for the wind speed.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interception</td>
<td>0.1869</td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>0.01066</td>
</tr>
</tbody>
</table>

Table 12. Coefficient obtained from multiple regression for the temperature difference.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interception</td>
<td>0.2648</td>
</tr>
<tr>
<td>TEMP. DIFF.</td>
<td>-0.0017</td>
</tr>
</tbody>
</table>
In this case a positive coefficient value was obtained for wind speed when the multiple regression was made taking into account only the wind speed. The higher the wind velocity, the higher the air change rate.

In contrast, as can be seen in Table 12, it is the \( \Delta T \) which presents a negative correlation when the regression was done only taking into account the value of \( \Delta T \). This can be explained because at the beginning the \( \Delta T \) varies in a contrary manner to the ACH.

Adding Temperature difference as a predictor the regression equation was the next one:

\[
ACH = -0.1345 + 0.026 \cdot \Delta T + 0.029 \cdot WS
\]

(Eq. 31)

-Studying the P-values:

<table>
<thead>
<tr>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta T )</td>
</tr>
<tr>
<td>WIND SPEED</td>
</tr>
</tbody>
</table>

Both, \( \Delta T \) and WS, have a significant effect in ACH because the possibility of the results occurring by chance is really low (P-value of WS < 0.05 and P-value of \( \Delta T \) < 0.05).

The significance-value of the total regression was \( F=0.0227 \), which is less than 0.05 and it means that a highly significant prediction of ACH can be done with the independent variables \( \Delta T \) and WS.
- Representation of coefficients:

Figure 44. Representation of the predictor $\Delta T$ when Regression of $\Delta T$ was done

Figure 45. Representation of the predictor $\Delta T$ when Regression of $\Delta T$ & WS was done

The lineal correlation that exists in figure 44 in the Predicted ACH was lost when the wind was added as a predictor (see Figure 45).

The ratios between the values measured in the weather station, $W_{SW}$, and the wind speed calculated as $W_{Sb}$ (using the Eq.28) are represented in the next graphic:
The figure suggests that wind has a comparatively strong influence on air infiltration in the beginning, but that this influence gradually gets weaker, compared to the stack effect. All the values obtained in figure 43 are below the point of 1 but, as was discussed in the theory chapter, this does not mean that the wind speed does not affect the ACH.

### 3.2.2.3 Third data set-June

The selected values used for the analysis of the third data set can be seen in table D1 and D2 in the Appendix D.

The multiple regression was used and the results obtained are discussed below.

<table>
<thead>
<tr>
<th>Values of $R^2$ obtained:</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Table 14. Results of $R^2$ from the multiple regression (Third data set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
</tr>
<tr>
<td>WIND SPEED</td>
</tr>
<tr>
<td>WIND SPEED 90</td>
</tr>
<tr>
<td>$\Delta T$ &amp; WS</td>
</tr>
<tr>
<td>$\Delta T$ &amp; WS 90</td>
</tr>
</tbody>
</table>
Different interpretations of the results obtained were done to explain the behavior of wind speed and temperature difference and their influence in Air Change Rate.

-Increasing $R^2$:

Table 15. Increase in $R^2$ adding Wind Speed

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.8663</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.8663</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 16. Increase in $R^2$ adding Temperature difference

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WS$</td>
<td>0.6809</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.8663</td>
<td>0.1854</td>
</tr>
</tbody>
</table>

As it can be seen in Table 15, the $R^2$ only taking into account the temperature difference was 0.8663, that is to say, the 86.63% of variations in air exchange rate can be explained by the stack effect. Considering both effects that value increased slightly, till 0.8663, which means that stack effect has much more influence in the air exchange rate than the effect of wind speed. That can be also seen in Tables 15 and 16, looking at the increase of $R^2$: the increase is much bigger when the stack effect is considered.

It can be said that the wind speed alone is not at all a good predictor. There is not an increase in $R^2$ when wind speed was added as a predictor to $\Delta T$.

A comparison between wind speed and wind speed in the perpendicular direction was done:

Table 17. Increase in $R^2$ adding Wind speed in the perpendicular direction

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.8663</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS90$</td>
<td>0.8666</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

There is practically no difference between the value of $R^2$ of $\Delta T & WS$ and the one of $\Delta T & WS90$.

-Coefficients:

Table 18. Coefficient obtained from multiple regression for the wind speed.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0.2474</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>-0.0439</td>
</tr>
</tbody>
</table>
When the multiple regression was made only taking into account the wind effect, a negative correlation was obtained (see Table 18). This means that the higher the wind velocity, the lower the air exchange rate. As it can be seen in the Figure 44, the wind was faster during the day, when the temperature difference was smaller, and the influence of temperature difference in the air exchange rate was bigger.

Adding Temperature difference as a predictor the regression equation was the next one:

\[
ACH = 0.02069 + 0.015 \cdot \Delta T - 0.0006 \cdot WS
\]  
(Eq. 32)

-Studying the P-values:

Table 19. P-value for each predictor when both are analyzed together with multiple regression

<table>
<thead>
<tr>
<th>P-value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta T)</td>
<td>0.0064</td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>0.9665</td>
</tr>
</tbody>
</table>
The P-value of $\Delta T$ was lower than 0.05 so it can be considered having a significant effect but the one of WS was really high so there is a higher possibility of the result occurring by chance, it cannot be considered having a significant effect.

The significance-value of the total regression was $F= 0.0001$, which is less than 0.05 so a highly significant prediction of ACH can be done with the independent variables $\Delta T$ and WS.

- Representation of coefficients:

Doing the multiple regression of $\Delta T$-WS, the next graphics were obtained:

![Figure 45. Representation of the predictor $\Delta T$ when Regression of $\Delta T$-WS was done](image)
Figures 45 and 46 are really similar and this is because the addition of the wind speed as a predictor does not affect too much in the results. The $\Delta T$ is which clearly dominates in ACH. Looking at Fig. 44 it can be seen that there are relatively small values of wind speed and this is likely to be the cause of having a little influence of it in the ACH.

3.2.2.4 **ANALYSIS OF ALL THE DATA SET TOGETHER**

This is the most important part of all the analysis done with multiple regression in the present study. In this section all the data of the three data sets are going to be studied together.

The function multiple regression was used to analyze the peak values.
The values of $R^2$ obtained were the next ones:

Table 20. Results of $R^2$ from the multiple regression (all data)

<table>
<thead>
<tr>
<th>Variable</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
</tr>
<tr>
<td>WIND SPEED</td>
<td>0.0290</td>
</tr>
<tr>
<td>$WS^2$</td>
<td>0.0780</td>
</tr>
<tr>
<td>WIND SPEED 90</td>
<td>0.1549</td>
</tr>
<tr>
<td>$W90^2$</td>
<td>0.1003</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$</td>
<td>0.7481</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS^2$</td>
<td>0.8104</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$ 90</td>
<td>0.3672</td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$ 90$^2$</td>
<td>0.3667</td>
</tr>
</tbody>
</table>

Increasing $R^2$:

Table 21. Increase in $R^2$ adding Wind Speed

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
<td></td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$</td>
<td>0.7481</td>
<td>0.3832</td>
</tr>
</tbody>
</table>

Table 22. Increase in $R^2$ adding Temperature difference

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$WS$</td>
<td>0.0290</td>
<td></td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$</td>
<td>0.7481</td>
<td>0.7191</td>
</tr>
</tbody>
</table>

Comparing the increase in table 21 with the one in table 22, it can be concluded that the stack effect has more influence than wind effect in the variation of ACH. Referring to all data sets, the wind speed alone is a very bad predictor; the value of $R^2$ is really small.

A comparison between wind speed and wind speed in the perpendicular direction was done:

Table 23. Increase in $R^2$ adding Wind speed in the perpendicular direction

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
<td></td>
</tr>
<tr>
<td>$\Delta T$&amp;$WS$ 90</td>
<td>0.3672</td>
<td>0.0023</td>
</tr>
</tbody>
</table>

In addition the influence of $WS^2$ and $W90^2$ was also analyzed:
Table 24. Increase in $R^2$ adding the square value of Wind speed and the square value of wind speed in the perpendicular direction

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS^2$</td>
<td>0.8104</td>
<td>0.4455</td>
</tr>
</tbody>
</table>

Table 25. Increase in $R^2$ adding the square value of Wind speed and the square value of wind speed in the perpendicular direction

<table>
<thead>
<tr>
<th>Variables in Equation</th>
<th>$R^2$</th>
<th>Increase in $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
<td></td>
</tr>
<tr>
<td>$\Delta T &amp; WS90^2$</td>
<td>0.3667</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

There is not a bigger increase when $WS90^2$ is taking into account instead $WS^2$. However, comparing table 24 with table 21, a bigger increase is obtained when adding $WS^2$ as a predictor and not WS.

-Comparing coefficients:

$$ACH = -0.0141 + 0.0141 \cdot \Delta T + 0.0213 \cdot WS$$

(Eq.33)

The “Coefficient-Average” for each predictor was calculated:

$\Delta T \rightarrow 0.0141 \cdot 10 = 0.1410$

$WS \rightarrow 0.0213 \cdot 2.5 = 0.0533$

The “Coefficient-Average” for $\Delta T$ is bigger than the one for $WS$ which suggests that, in general, $\Delta T$ dominates in predicting the Air Change Rate.

-Studying the P-values:

When $\Delta T & WS$ were studied in the multiple regression the results for the P-values were the next ones:

P-value $WS = 2.38E-09 < 0.05$ so $WS$ it can be considered having a significant effect.

P-value $\Delta T = 5.49E-13 < 0.05$ so also $\Delta T$ has a significant effect.

The $\Delta T$ is dominating but also the $WS$ has influence on $ACH$.

The significance value of the total regression was $F= 2.115E-12$, which is less than 0.05 so a highly significant prediction of $ACH$ can be done with the independent variables $\Delta T$ and $WS$. 
- Representation of coefficients:
In the multiple regression of $\Delta T$&WS, the next graphics were obtained:

Figure 47. Representation of the predictor $\Delta T$ when Regression of $\Delta T$&WS was done

Figure 48. Representation of the predictor $\Delta T$ when Regression of $\Delta T$ was done
Figure 48 was obtained when only $\Delta T$ was used as predictor. The linear correlation that exists between $\Delta T$ and $\text{ACH}$ can be seen on it.

When the wind was added as a predictor (see Figure 47), the average discrepancy between the values of measured and predicted $\text{ACH}$ was reduced and the influence of wind can be seen in the prediction.

As a conclusion of the analysis of the three different data sets it can be said that they represent three different situations as regards stack vs. wind effect on ACR. In the first data-set, stack effects dominates and wind is just barely a significant predictor ($p=0.05$). In the second data-set, wind dominates, but also stack effect is a significant predictor. Finally, in the third data-set, only stack effect is a significant predictor – wind has practically no effect.

3.2.2.5 USING WIND TUNNEL DATA – FACADE $\Delta \text{C}_p$ VALUES:

Above are presented three ways to include the effect of wind on ACR in the multiple regression calculations: (1) the magnitude of the wind speed ($WS$), (2) component of the wind speed perpendicular to the church facades ($WS90$), and (3) square value of wind speed (for both $WS^2$ and $WS90^2$). The next step was to make use of data obtained in the wind tunnel: the $\text{C}_p$ values. At first, only $\text{C}_p$ values measured on the long side facades (at the windows) were studied because it was considered logical that wind effect is bigger on points of this row.

In this case air change rate is the dependent variable and the indoor-outdoor temperature difference and $\sum (\text{C}_p - \text{C}_p)_{\text{positive}} \cdot WS$ and $\sum (\text{C}_p - \text{C}_p)_{\text{positive}} \cdot WS^2$ (“the total $\text{C}_p$ factor”, see Appendix E) the independent ones, where the last variable represents the wind effect. In the Appendix D are the values corresponding to each peak.

After doing the multiple linear regression values of $R^2$ obtained are the followings:

<table>
<thead>
<tr>
<th>Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
</tr>
<tr>
<td>$\Delta T - \Delta \text{C}_p \cdot WS$</td>
<td>0.3649</td>
</tr>
<tr>
<td>$\Delta T - \Delta \text{C}_p \cdot WS^2$</td>
<td>0.5783</td>
</tr>
</tbody>
</table>

It can be noticed that a better regression is obtained when using $WS^2$ instead of $WS$ so in this case only the factors depending on $WS^2$ are going to be studied.
-Coefficients:

Table 27. Coefficient obtained from multiple regression with $\Delta T$ and $\Delta C_p U^2$.

<table>
<thead>
<tr>
<th></th>
<th>Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interception</td>
<td>0.0356</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>0.0127</td>
</tr>
<tr>
<td>$\Delta C_p WS^2$</td>
<td>0.0018</td>
</tr>
</tbody>
</table>

$ACH = 0.0356 + 0.0127 \cdot \Delta T + 0.0018 \cdot \Delta C_p WS^2$ (Eq. 34)

3.2.2.6 USING WIND TUNNEL DATA-TOTAL $\Delta C_p$ AREA VALUES

As the total $C_p$ factor at the long side facades did not seem to provide very good prediction of air change rate, the next step was to include all the measured points in the wind tunnel and also the building area that they can be supposed to represent (see appendix F).

It is interesting to make a sign-analysis of the $\Delta C_p$ between the church hall and each sub-volume. After making all calculations the results obtained for the four main wind directions (N,S,E and W) were the following for $\Delta C_{p\text{OUT-IN}}$.

**Long side facades of the hall**

<table>
<thead>
<tr>
<th></th>
<th>Western facade</th>
</tr>
</thead>
<tbody>
<tr>
<td>(North ) point</td>
<td></td>
</tr>
<tr>
<td>122</td>
<td>(South ) point</td>
</tr>
<tr>
<td></td>
<td>128</td>
</tr>
<tr>
<td>340° (from N)</td>
<td>-0.3015</td>
</tr>
<tr>
<td>250° (from W)</td>
<td>0.4486</td>
</tr>
<tr>
<td>160° (from S)</td>
<td>-0.0168</td>
</tr>
<tr>
<td>70° (from E)</td>
<td>-0.2661</td>
</tr>
<tr>
<td></td>
<td>0.0270</td>
</tr>
<tr>
<td></td>
<td>0.0654</td>
</tr>
<tr>
<td></td>
<td>0.0123</td>
</tr>
<tr>
<td></td>
<td>0.0830</td>
</tr>
<tr>
<td></td>
<td>0.0972</td>
</tr>
<tr>
<td></td>
<td>0.0832</td>
</tr>
<tr>
<td></td>
<td>0.4726</td>
</tr>
<tr>
<td></td>
<td>0.4652</td>
</tr>
<tr>
<td></td>
<td>0.4407</td>
</tr>
<tr>
<td></td>
<td>0.4704</td>
</tr>
<tr>
<td></td>
<td>0.4439</td>
</tr>
<tr>
<td></td>
<td>0.3943</td>
</tr>
<tr>
<td></td>
<td>0.0415</td>
</tr>
<tr>
<td></td>
<td>0.0496</td>
</tr>
<tr>
<td></td>
<td>0.0058</td>
</tr>
<tr>
<td></td>
<td>-0.0388</td>
</tr>
<tr>
<td></td>
<td>-0.1820</td>
</tr>
<tr>
<td></td>
<td>-0.2884</td>
</tr>
<tr>
<td></td>
<td>-0.2168</td>
</tr>
<tr>
<td></td>
<td>-0.2005</td>
</tr>
<tr>
<td></td>
<td>-0.2120</td>
</tr>
<tr>
<td></td>
<td>-0.2145</td>
</tr>
<tr>
<td></td>
<td>-0.2579</td>
</tr>
<tr>
<td></td>
<td>-0.2636</td>
</tr>
</tbody>
</table>
Saioa Goicoechea & Patricia López

Modeling the air change rate in a naturally ventilated historical church

<table>
<thead>
<tr>
<th>(North) point 328</th>
<th>Eastern facade</th>
<th>(South) point 322</th>
</tr>
</thead>
<tbody>
<tr>
<td>340° (from N)</td>
<td>-0,3172</td>
<td>0,0331</td>
</tr>
<tr>
<td>250° (from W)</td>
<td>-0,2377</td>
<td>-0,1944</td>
</tr>
<tr>
<td>160° (from S)</td>
<td>0,0007</td>
<td>0,0597</td>
</tr>
<tr>
<td>70° (from E)</td>
<td>0,4688</td>
<td>0,4808</td>
</tr>
</tbody>
</table>

Figure 49: \( \Delta C_{P_{OUT-IN}} \) for the facades.

Crawlspace

<table>
<thead>
<tr>
<th>340° (from N)</th>
<th>0,0090</th>
</tr>
</thead>
<tbody>
<tr>
<td>250° (from W)</td>
<td>0,0860</td>
</tr>
<tr>
<td>160° (from S)</td>
<td>-0,0360</td>
</tr>
<tr>
<td>70° (from E)</td>
<td>0,0783</td>
</tr>
</tbody>
</table>

Figure 50: \( \Delta C_{P_{OUT-IN}} \) between the church hall and the crawlspace
Looking at figure 49 the following deductions can be made:

Logically on the facade where the wind hits all $\Delta C_p$ values are positives and on the opposite facade all values are negatives. Moreover the maximum magnitudes are found in the facade where the wind is perpendicularly hitting, that is to say, western facade when the wind direction is 250° and eastern facade when the wind direction is 70° [30].
As it is explained in the literature [30] when the wind is blowing from a wind direction close to 340° (North) the ΔCp magnitude is higher in the side of the facade closer to the north (point 122, west; or point 328, east), and when it hits from a direction close to 160° (South), the absolute values are higher next to this side (point 128, west; or 322, east). In those cases variations of ΔCp on the façade are big.

According to figure 49, when the wind comes from the parallel direction to those facades, the ΔCp are negatives closer to the side where the wind is coming from, which agrees with the diagrams in the literature [30]. This happens due to air recirculation in this outside area.

Looking at the figure 50 it can be noticed that all values are positives except when the wind is coming from South, this might be due to some flow phenomena, but it is a low value anyway.

However, in the figure 51 all ΔCp values are negatives except when the wind is coming from South, the opposite than in the crawlspace, so it seems that when the wind is blowing from the south the airflow is going down inside the church, weakening the stack effect. This could be explained taking considering the position of the tower: when wind is from South the roof is upstream of the tower, which causes an overpressure there, when wind is coming from North instead the tower causes a wake with negative pressure over the roof, which helps the stack effect.

Figure 52 shows that when the wind is coming from North the ΔCp is positive, which is logical since the tower is facing towards the north. Likewise, in figure 53 all ΔCp values are negatives except when wind hits from the South.

Next step was to make a multiple linear regression to see if the difference of pressure coefficients with its related area is a good predictor of air change rate. Therefore, in this case air change rate is the dependent variable and the indoor-outdoor temperature difference and $\sum(\Delta C_{p_{\text{OUT,IN}}} \cdot A_i) \cdot WS$ and $\sum(\Delta C_{p_{\text{OUT,IN}}} \cdot A_i) \cdot WS^2$ (see Appendix F ) the independent ones, where the last variable represents the wind effect.
After doing the multiple linear regression values of $R^2$ obtained are the followings:

<table>
<thead>
<tr>
<th>$\Delta T$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$ &amp; $\Delta C_{p_{\text{OUT-IN} \cdot A \cdot WS}}$</td>
<td>0.4072</td>
</tr>
<tr>
<td>$\Delta T$ &amp; $\Delta C_{p_{\text{OUT-IN} \cdot A \cdot WS^2}}$</td>
<td>0.6597</td>
</tr>
</tbody>
</table>

\[
\text{Table 28. Results of } R^2 \text{ from the multiple regression with } \Delta C_p / \text{Area}
\]

-Coefficients:

\[
\text{Table 29. Coefficient obtained from multiple regression with } \Delta T \& \Delta C_{p_{\text{OUT-IN} \cdot A \cdot WS^2}}.
\]

\[
\begin{array}{l|c}
\hline
\text{Coefficients} & \\
\hline
\text{Interception} & 0.02763 \\
\text{\quad } \Delta T & 0.0132 \\
\text{\quad } \Delta C_{p_{\text{OUT-IN} \cdot A \cdot WS^2}} & 1.32E-05 \\
\hline
\end{array}
\]

\[
\text{ACH}=0.02763+0.0132 \cdot \Delta T+1.32E-05 \cdot \Delta C_{p_{\text{OUT-IN} \cdot A \cdot WS^2}}
\]

\[
\text{Eq.35}
\]

3.2.2.7 - USING WIND TUNNEL DATA - CRAWLSPACE $\Delta C_{p_{\text{CH}}}$ VALUES

Finally, it was considered worth to pay extra attention to the crawlspace because the floor seems to be the much dominating leaking point, at the same time as its low position suggests great influence on the stack effect. In fact the floor is at the lowest level, where the stack induced negative indoor pressure should be greatest. Moreover, after carrying out some indoor-outdoor pressure measurements [32] it was possible to deduce that the neutral pressure plane of the church is located quite close to the floor, making that greatest negative indoor pressure relatively small. Therefore, a fairly low pressure difference is required to make the air rise from the crawlspace to the hall. From this measurement it was also possible to deduce that the church floor is very leaky. As it was indicated in the figure 54 from those pressure measurements which have been taken at midnight (when there is no wind) and when temperature difference was about 15 °C, the $\Delta P_{\text{stack}} = 7 \text{ Pa}$ and 1.5 Pa was the difference corresponding to the lower height.
Since the pressure inside the crawlspace (relative to the hall), can be expected to strongly influence the stack effect, it was decided to try multiple linear regression but now considering the difference of pressure coefficients between the crawlspace and the hall ($\Delta C_{C-H}$) instead of $\Delta C_{OUT-IN} \cdot A_t$ as before (see table G1 appendix G).

After doing the multiple linear regression values of $R^2$ obtained are the followings:

Table 30. Results of $R^2$ from the multiple regression with $\Delta C_{C-H}$

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
</tr>
<tr>
<td>$\Delta T &amp; \Delta C_{C-H} \cdot WS$</td>
<td>0.3682</td>
</tr>
<tr>
<td>$\Delta T &amp; \Delta C_{C-H} \cdot WS^2$</td>
<td>0.5732</td>
</tr>
</tbody>
</table>
-Coefficients:

Table 31. Coefficient obtained from multiple regression with $\Delta T$&$\Delta C_{p,H} \cdot WS^2$.

<table>
<thead>
<tr>
<th>Coefficients</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Interception</td>
<td>0.0456</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>0.0122</td>
</tr>
<tr>
<td>$\Delta C_{p,H} \cdot WS^2$</td>
<td>0.0455</td>
</tr>
</tbody>
</table>

$ACH=0.0456+0.0122 \cdot \Delta T+0.0455 \cdot \Delta C_{p,H} \cdot WS^2$

(Eq. 36)

Finally, it looked reasonable to make a multiple regression with the three predictors temperature difference, $\Delta C_{p,H} \cdot WS^2$ and $\Delta C_{p_{OUT-IN} \cdot A} \cdot WS^2$ as independent variables. These three predictors are significant parameters on $ACH$ variations: the temperature difference represents the stack effect; the $\Delta C_{p_{OUT-IN} \cdot A} \cdot WS^2$ indicates the total wind force on the whole building envelope; and the $\Delta C_{p_{C-H}} \cdot WS^2$ indicates the wind force only at crawlspace vents. The latest was constituted as a significant additional predictor to $\Delta C_{p_{OUT-IN} \cdot A} \cdot WS^2$ in order to see the influence of the assumed leaky floor.

However, this idea of making the triple correlation had to be rejected since, as it can be seen in the table G1 of the appendix G, two of those three independent variables ( $\Delta C_{p_{OUT-IN} \cdot A} \cdot WS^2$ and $\Delta C_{p_{C-H}} \cdot WS^2$) are mutually highly correlated, its correlation coefficient is too high (0.986). It is common not to use them as predictors because once one of them is included, the other has very little own information to contribute with on the variation of dependent variable. Therefore, in case the regression for this three-variable model would be good, it would probably be due to a deceitful mathematical logic, so obtained results would be unreliable [33].

The correlation coefficients (first column) in the Correlation table are more or less the same as the correlation coefficient (R-value) of MLR.

Finally a graphic is presented with the theoretical curve of the perpendicular component of the wind (appendix C) and the perpendicular component obtained from measured data (appendix D), both represented as WS90/WS. Also in that diagram are added the other two most important predictors: wind speed magnitude ($WS^2$ divided by 75 for axis-fitting) and $\Delta C_{p_{OUT-IN}}$ between the hall and surroundings for each direction ($\Delta C_{p_{OUT-IN} \cdot A} \cdot WS^2$).
The figure 55 shows one apparent shortcoming of the model involving wind speed perpendicular component (WS90). The dips that occur at wind flow parallel to the church are unrealistic; actually the wind tunnel data and cp-diagrams from the literature have shown that also at this flow direction there is pressure variation over the building envelope, which will induce air infiltration. Thus, at those angles (160° and 340°) WS90 cannot be expected to be good predictor.

From this figure 55 it can be extracted that \( \Delta C_p W S^2 \) is not very dependent on wind direction, but also that it tends to yield higher values than \( W S^2 \) at wind angles more perpendicular to the facades. This results in higher cp-values.
4 Discussion

As it has been already said the results obtained from the analysis are not always the expected ones.

Referring to the calculations done in Excel, in the majority of the steps some simplifications were used.

In the first step when the data were organized some averages were needed to refer all the values to the same moment in time. The air change rate was measured each minute but the wind speed and temperature difference measurements followed a different schedule. The time used as reference was the time when air change rate was measured.

In later calculations, when calculating the perpendicular component of the wind speed or the pressure coefficient multiplied by the wind, averages of two hours needed to be calculated for obtaining the values for the air change rate peaks. The amount of data after all was limited, representing only a limited amount of combinations, because only the peak values of the air change rate were studied and not all the real data obtained by the tracer gas technique. This leads to a lost in accuracy too.

The following figure 56, shows the deviation of the present data (appendix D) from the theoretical variation of $\Delta C_{pC,H}$ with the wind direction (appendix G). The variation of the wind speed with its direction is also represented in this figure.
As it is shown in figure 56, and looking to the theoretical curve, this model suggests that wind alone causes an overpressure in the crawlspace (related to the hall), except when the wind direction is 145°, 160° and 175° ($\Delta C_{p C-H} < 0$). However, for the present data $\Delta C_{p C-H}$ is always positive. This is because average values were used (see appendix B) for calculating the value for each considered peak. Therefore, in the analysis done $\Delta C_{p C-H}$ was always positive, increasing the stack effect.

The data analyzed in this thesis were from a specific period of time, of May, June and October. However, the weather conditions vary depending on the season and during a day, so assuming the present data as general results means one more time a lost in precision.

The shape of the church taken to do the study was not the real one. Some changes were again assumed here to facilitate the calculations. The height of the tower was not always taken into account and the southern sub-volume was considered plane and not round as it is in reality.

Furthermore, a uniform distribution of the leaky points over the church envelope was considered since the real one is unknown.
The surroundings (objects, trees or other buildings) of the church were not considered in the study and depending on them the air infiltration and the wind influence can be higher or not through the openings and cracks of the church envelope.

Analyzing a church model in a wind tunnel to obtain the coefficient pressures of the different points of the church envelope was not very accurate. Firstly, because the study was done on a model of the church and secondly, because in this case the measuring points on the model envelope were evenly distributed, so not all the real points causing infiltration were included in the study. Furthermore, for calculating the value of the predictors that indicate wind effect from wind tunnel data it was supposed that each point represented one certain area, which is an approximation. In addition, the values for those wind direction for which Cp-value was not available were obtained by interpolation.
5 Conclusions

It seems that MLR can be a useful tool to assess the relative importance of the driving forces for ACH in churches and similar buildings. Careful checking is however needed to be sure that the included predictors are not too mutually correlated, and that attained models are statistically significant and also physically realistic.

The main conclusion from multiple linear regressions is that the stack effect is the most influential factor on the air change rate in the studied church. The multiple linear regressions performed and discussed indicate that the wind effect have also to be considered to explain the ACH variations, but always together with the temperature difference. Adding the wind as a predictor reduced the average discrepancy between the values of measured and predicted ACH. Wind speed alone seems however to be a very poor predictor of ACH, since, like in this study, it will tend to be negatively correlated with stack effect (ΔT). This occurs when the data include both days and nights, since nights tend to be cool and calm and night the opposite. In this study ΔT seems to be the prime predictor also because of its high and physically logical correlation (R) with ACH. In the second data set (data from October) it has been especially useful to notice that when the wind is strong (high speeds) its correlation with the ACH is quite big, so the air leakage from wind can be the dominant factor on a windy day.

An unexpected result has been not to obtain better correlation when considering the perpendicular component of the wind speed (WS90) instead of the wind speed magnitude. From the multiple linear regressions it has been also possible to deduce that using WS\(^2\) instead of WS gives better correlations. This is logical since the blower door tests indicated that the infiltration air flow was approximately proportional to the pressure difference (exponent=0.86), and the dynamic pressure of wind is in turn related to the square of the wind speed (WS\(^2\)).

In the following table the main results of the regression for all data sets are presented. The results of the MLR from wind tunnel data with WS do not appear because, as it has been explained, they are not good predictors for air change rate variations.
Table 32: results for the MLR from all data sets together (from May to October of 2010)

<table>
<thead>
<tr>
<th></th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta T$</td>
<td>0.3649</td>
</tr>
<tr>
<td>$\Delta T &amp; WS$</td>
<td>0.7481</td>
</tr>
<tr>
<td>$\Delta T &amp; WS^2$</td>
<td>0.8104</td>
</tr>
<tr>
<td>$\Delta T &amp; WS_{90}$</td>
<td>0.3672</td>
</tr>
<tr>
<td>$\Delta T &amp; WS_{90}^2$</td>
<td>0.3667</td>
</tr>
<tr>
<td>$\Delta T &amp; \Delta C_p \cdot WS^2$</td>
<td>0.5783</td>
</tr>
<tr>
<td>$\Delta T &amp; \Delta C_p \cdot C_{H} \cdot WS^2$</td>
<td>0.5732</td>
</tr>
<tr>
<td>$\Delta T &amp; \Delta C_p \cdot A \cdot WS^2$</td>
<td>0.6597</td>
</tr>
</tbody>
</table>

A substantial fraction of the variation ($R^2$) in ACH could be explained by the tested independent variables (predictors). The table above shows the most significant models that had been analyzed in the multiple regressions. They are supposed to indicate the influence of stack and wind effect in ACR. For that the five first took data recorded in the weather station, while the others used data from wind tunnel. Specifically the factor $\Delta C_p \cdot WS^2$ represents the difference between pressure coefficients at both sides of the long-side facades of the church; the factor $\Delta C_p \cdot C_{H} \cdot WS^2$ represents driving force through the crawlspace and the church hall; and the factor $\Delta C_p \cdot A \cdot WS^2$ takes into account all the sub-volumes surrounding the church hall, such as, tower, southern volume, attic and crawlspace. The most significant predictions of ACH were attained with the combined predictors $\Delta T \& WS^2$, $\Delta T \& WS$ and $\Delta T \& \Delta C_{OUT-IN} \cdot A \cdot WS^2$, yielding $R^2 = 0.8104$, 0.7481 and 0.6597, respectively, with very high statistical significance (P-value < 0.001 both for full models and for the individual predictors).

General trend is that the more sophisticated model that is use, the better is the prediction of the air change rate, except for the simple $\Delta T \& WS^2$ and $\Delta T \& WS$ model, which gives the best regression. However, the latter might have occurred by chance, since the amount of data after all is limited, representing only a limited amount of combinations of temperature difference ($\Delta T$) and square value of wind speed ($WS^2$).

After all the studies it can be concluded that the parameters deduced from the wind tunnel data are better predictors of the variation of air change rate than the façade-perpendicular parameter ($WS90$). One convincing reason for expecting better regressions with the wind tunnel models is that at angles parallel to the facades (160˚ and 340˚) the perpendicular component of the wind certainly must underestimate the infiltration driving force.
It can also be concluded that one of the leakiest areas of the Hamrånge church is the floor of the hall. This idea was firstly got from the methods used for measuring pressure and temperature inside the church hall.

On one hand the images obtained with IR thermography technique showed the airflow coming through the church hall.

On the other hand, the fact of the pressure difference being 1.5 Pa at a low level (close to the floor) comparing with the total stack pressure difference (ΔPstack=7 Pa) suggests a small lower section of overpressure on the building envelope (see figure 57). Therefore, at any leakages in this section there will be infiltration of air and in the upper section there will be exfiltration of air since the pressure difference is opposite. Infiltration and exfiltration flow rates should be equal, so the leakage area must be substantially larger in the lower section since the infiltration occurs through a smaller area.

Moreover, the air change rate measured using tracer gas decay method was around 0.25 h⁻¹, which is relatively high for being an old stone church. This indicates a fairly leaky church.

Further, the fact of needing high wind speed for it to be influential on the ACH leads to think that the main leaks are not on the façade of the church since air infiltration and so ACH then would be more dependent on wind. Therefore, the idea of major leaks at the floor is strengthened.
Taking into consideration that the prevailing wind directions among the analyzed data mainly are within the ranges from 70° to 110° (SE) and from 300° to 360° (N) (see figure 55), it is possible to corroborate that the presence of the wind contributes to stack effect, and so to the air change rate. In fact, as it has been possible to deduce after analyzing the difference between pressure coefficients ($\Delta C_p$) between the crawlspace and the church hall, when the wind is coming from the north it contributes to the stack effect because of the underpressure created inside the attic and the above all because of the overpressure created inside the crawlspace (comparing with the hall).

**Suggestions for future studies**

The next step for finding the leakiest point on the church façade would be to analyze the blower door technique data to assess the airflow through the envelope.

Another useful suggestion is to study deeply the tower of the church, since several assumptions were made for simplifying the case in this thesis.

It would be also interesting to determine the neutral pressure plane over the church façade since it would provide more detailed information about the pressure distribution over the envelope.

Other output statics like Tolerance or Variance inflation factor (VIF) would help in indicating the amount of individual contribution that each predictor of ACH has.

For future analysis it would be interesting going through superposition methods to study the effect of both stack and wind effect.

Finally, as regards improvements in the modeling, one reasonable next step might be to use all present knowledge to assume another, more likely distribution of the leaks, rather than the uniform distribution at the building envelope which has been assumed in this study. And also, of course, to try to get more statistics of the kind used in the study. After all it is a rather limited amount of combinations of weather and indoor temperature data that is included in the study.

**Possible solutions for decreasing air infiltration through the church envelope**

Once the significant factors affecting the air change rate inside the church hall are known, then an effective solutions should be found in order to decrease it and so the air infiltration through the church
envelope. Control of infiltration is needed to assure indoor thermal comfort, minimize building energy use and to reduce infiltration of soiling airborne particles.

The finding that the stack effect usually has higher influence than wind on the ACH in the church suggests that the most effective action for reducing ACH would be sealing of the upper and lower parts (floor and ceiling level) since the stack pressures are greatest there. This is a promising idea only if it does not modify the esthetic and so the value of a historical building. The sealing could be made with e.g. a wall-to-wall carpet, although it is a bit difficult to perform, and in this case the nice old wooden floor would be hidden. An experiment was carried out, where the vents located on the crawlspace envelope were blocked with wooden plates and hard foam plastic. This result in reducing crawlspace pressure significantly, (relative to indoors), reducing the airflow through the floor, so that it was achieved a 35-50% of reduction of the air change rate [32].

Fan pressurization combined with filtered supply air can reduce the latter problem: incoming airborne particles, since it means pressurizing slightly the inside volume of the church, resulting in a downward displacement of the neutral pressure plane, thus reducing air infiltration.

Another measure could be planting vegetation outside the church in order to reduce the wind hitting the façade.
References


[28] Farnborough Air Sciences Trust, "A Tale of Three Historic Buildings and Five Windtunnels"


[31] ASHRAE Fundamentals Chapter 16, “Airflow around buildings”


Appendix A: parameters for the terrain

In the Table A1, values for the parameter $a$ and $\delta$ used in the calculation of wind speed ($U_w$) are provided. There are four different categories, depending on the terrain description.

<table>
<thead>
<tr>
<th>Terrain Category</th>
<th>Description</th>
<th>Exponent $a$</th>
<th>Layer Thickness $\delta$, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Large city centers, in which at least 50% of buildings are higher than 21.3 m, over a distance of at least 0.8 km or 10 times the height of the structure upwind, whichever is greater</td>
<td>0.33</td>
<td>460</td>
</tr>
<tr>
<td>2</td>
<td>Urban and suburban areas, wooded areas, or other terrain with numerous closely spaced obstructions having the size of single-family dwellings or larger, over a distance of at least 460 m or 10 times the height of the structure upwind, whichever is greater</td>
<td>0.22</td>
<td>370</td>
</tr>
<tr>
<td>3</td>
<td>Open terrain with scattered obstructions having heights generally less than 9.1 m, including flat open country typical of meteorological station surroundings</td>
<td>0.14</td>
<td>270</td>
</tr>
<tr>
<td>4</td>
<td>Flat, unobstructed areas exposed to wind flowing over water for at least 1.6 km, over a distance of 460 m or 10 times the height of the structure inland, whichever is greater</td>
<td>0.10</td>
<td>210</td>
</tr>
</tbody>
</table>

Table A1. Atmospheric Boundary Layer Parameters [30]
Appendix B: average values for data sets

All the data provided in the data files were not taken in the same period of time so some averages were done to have all the data in order and take the exact number needed. In this appendix the way used is going to be explained.

The time used as reference was the time when Air Change Rate was measured. The method used to obtain the data of Air Change Rate was the tracer gas decay where each value represents an average decay during 2 hours.

The Temperature difference was measured each minute. To obtain the values of Temperature difference at Air Change Rate time, an average between the values between one hour before that time and one hour later was done in order to consider the measuring period of tracer gas decay.

About Wind Speed, the values were taken each one minute but also the same average as in the case of Temperature difference was done to refer them to Air Change Rate time.

To calculate the values of perpendicular component of the wind firstly the perpendicular component for each value of wind speed was calculated and later an average of all these values was done for obtaining the value for each peak.

The method followed to calculate $\Delta C_p \cdot WS$ differs a little from the last one. In this case, the average of all the values of $\Delta C_p$ was done at the beginning and later this value was multiplied by the wind speed of each peak.
Appendix C: calculations for obtaining the perpendicular component of the wind speed (WS90)

This appendix clarifies how to calculate the speed of the perpendicular component of the wind. This component direction is the perpendicular one to the church façade (long side wall), which was used in the horizontal axis and applied in the median point of the facade.

The tower of the church under study is pointing to the North but diverted 20 degrees to the west; see Figure C1 where the church is represented in a circumference where different degrees are written as reference:

![Figure C1](image)

*Figure C1. Degree difference between wind direction and perpendicular direction.*

Therefore, the degrees between the wind direction and the wind perpendicular component were calculated using a simple equation (*equation C1*) obtained from a graphical explanation of trigonometry.

\[
70^\circ - \text{Wind direction} = \text{Degrees between wind direction and the perpendicular direction} \ [D]
\]

*(Equation C1)*
The value of $[D]$ was calculated in radians:

$$[D] \cdot \left(\frac{3.1416}{180}\right) = \text{Degrees between wind direction and the perpendicular direction in radians} \ [R]$$

$$\text{Perpendicular component magnitude} = (\text{wind speed} \mid \cos [R] \mid$$

(Equation C2)

The following table shows the theoretical values for the perpendicular component of the wind, calculated as:

$$\frac{WS_{90}}{WS} = |\cos (R)|$$
Table C1: perpendicular component of wind speed.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Theoretical WS90/WS</th>
</tr>
</thead>
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</tr>
<tr>
<td>10</td>
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Appendix D: data provided from the measurements

All the measured values were organized in three different data sets. The peak values of all these data sets can be seen in tables D1 and D2.

For the first data set there were 4 different time periods when the ACH was measured:

- From 18:28:37 of 2010-05-05 to 05:14:27 of 2010-05-06
- From 23:35:01 of 2010-05-06 to 09:28:14 of 2010-05-07

The reason for the time gaps between these data periods is that the tracer gas concentration in the church eventually got too low to yield reliable ACH data. Then more tracer gas was added, but it took some additional time before good mixing of the tracer gas with the room air was attained, and useful data could be recorded. In the calculations, the three first time periods were studied because for the time of the forth one the measures of wind speed and temperature difference were missing.
### Table D1. Peak values from the 3 data sets together

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<th>Time ACH(YYYY-MM-DD hh:mm:ss)</th>
<th>ACH(1/h)</th>
<th>AT[°C]</th>
<th>WS (m/s)</th>
<th>WS 90 (m/s)</th>
<th>ΔCp·WS (m²/s²)</th>
<th>ΔCp·A·WS² (m²/s³)</th>
<th>ΔCp·WS (m/s)</th>
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D2
Table D2. Peak values from the 3 data set together (continuation)

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<th>WS 90 (m/s)</th>
<th>ΔCp·WS(m/s)</th>
<th>ΔCp·WS²(m²/s²)</th>
<th>ΔCp·A·WS²(m²/s²)</th>
<th>ΔCp·A·WS³(m³/s²)</th>
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Appendix E: using wind tunnel data, façade $\Delta C_p$ values

Some calculations were done with the $C_p$ values provided from the wind tunnel measurements in order to analyze them later in the multiple regression, which are going to be exposed in this appendix.

It was assumed that air leakages were evenly distributed over building envelope of the church, so it can be said that the pressure inside the church ($P_i$) is the same as the average of the pressure generated or loosed when the air is coming in or out through the church envelope ($P_j$):

$$P_i \approx \frac{1}{N} \sum_{j=1}^{N} C_p_j \cdot \rho \frac{u^2}{2}$$

(Equation E1)

Where, $N$ is the amount of holes in the facade where the $C_p$ values have been measured in the wind tunnel.

The air flow going through the walls can be calculated as:

$$Q_j = C_D \cdot A \cdot (P_j - P_i)^n$$

(Equation E2)

Where $n$ typically is a value between 0.5 and 1. The smaller the cracks, the closer this value is to 1. In this case, after making the blower door test, it has been noticed that this $n$ value is 0.86, which means that the cracks are quite small:

$$Q_{tot}[L/s] = 250 \cdot \Delta P^{0.86}$$

(Equation E3)

Therefore, it can be considered that the air flow is roughly proportional to the pressure difference between indoor and outdoor, and so also is to $C_p$ difference:

$$Q_j \propto P_j - P_i \propto C_p_j - C_p_i$$

(Equation E4)

As it is indicated above, the inside $C_p$ value can be estimated from average value of the $C_p$'s on the envelope:

$$C_p_i = \frac{1}{N} \sum_{j=1}^{N} C_p_j$$

(Equation E5)
The mass balance forces to:

\[ \sum Q_j \big|_{IN} = \sum Q_j \big|_{OUT} \Rightarrow \sum \left(Cp_j - Cp_i\right)_{positive} = \sum \left(Cp_j - Cp_i\right)_{negative} \]

(Equation E6)

In order to make the correlation with total Cp factor it is enough with checking only one of those sums of Cp-differences. In this case it was decided to do it with positive ones.
Appendix F: using wind tunnel data, total \( \Delta C_p \cdot \text{Area} \) values

From the analysis of the data from the wind tunnel the difference between the pressure coefficient on the church envelope and inside the church hall was obtained for each zone. In fact the church was divided into five different zones: Hall, crawlspace, attic, tower and southern sub-volume (S).

The zone of interest where good indoor thermal environment is desired is the church hall. The tower is located in the north (with 20° of deviation toward the west, as it has been already explained). The wind induced an air flow through the church façade which probably has a significant influence on the air change rate; but it might be important to study the other zones, since these constitute sub-volumes which have their own indoor pressure and this affects the indoor pressure and flow rate to the main church hall. For example in the case of the crawlspace, even if it is not the zone under study, the fact of wind blowing against it makes an air flow go into this zone, and part of this flow goes straight to
come out through the opposite facade, but some of this air flow rises through the floor of the church hall are due to the stack effect and so affecting the air change rate there. The same phenomenon happens when the wind hits the attic of the church, the tower or the southern wall of the church.

For the crawlspace, attic and tower, the indoor pressure coefficient was considered to be the average of all the Cp-s of these sub-volumes measured in the wind tunnel. That is, the average of points from 101 to 121 (western side) and from 301 to 321 (eastern side) in the case of the attic (see figure F2) and the average of points 129 to 134 (western side) and 329 to 334 (eastern side) for the crawlspace (see figure F3 and F4). For the tower only the points of mid-height were considered (136, 139 and 401, see figures F3, F4 and F5), because these probably were the ones which have greatest influence on the air infiltration into the church hall. In fact the tower is not heated which means that there is not big temperature difference between outdoors and the tower to drive the stack effect and moreover inside the tower there are some doors and above the mid-height point some walls (compartmentalization) which stops vertical air flow through the tower. In order to analyze the wind effect in the southern side of the church, a mid-height point was considered, the opposite one to 139 located in the tower.

The points facing east and west were not taken because this wall is curved, and thought in reality this wall is not straight, this simplification was made since it represents quite well the reality.
Figure F3. Measuring points in the wind tunnel on the western side of the church.

Figure F4. Measuring points in the wind tunnel on the eastern side of the church.
Then, in order to calculate the influence of those pressure coefficients inside these three zones in the hall, those average values had to be multiplied by the area through which the air goes inside the hall because each point is representing one area. In the case of the attic and the crawlspace this area is the same but located above and under (respectively) of the zone under study ($A_{\text{attic}}$ and $A_{\text{chaw}} = 680 \text{m}^2$).

However, to calculate the pressure coefficient inside the church hall, not only those averages calculated in all sub-volumes had to be taken into account, but also the $C_p$ originates when the wind hit the west and east facades directly. In this case, it was decided to study each measured point separately since they seems to be the points where the wind was most effective. Therefore, the contribution to the pressure coefficient inside of those points was the measured $C_p$ multiplied by the associated area to each point ($83 \text{m}^2$ for the façade points). After, it was possible to calculate an estimated total $C_p$ inside the church hall by adding all $C_p \cdot A$ and dividing them by the total enclosing area ($2937 \text{m}^2$) (see Table F1).
Table F1. Local pressure coefficients

<table>
<thead>
<tr>
<th>Area (m²)</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long side facades of the hall (w)</td>
<td>A_w = 83</td>
</tr>
<tr>
<td>Crawlspace (c)</td>
<td>A_c = 680</td>
</tr>
<tr>
<td>Attic (a)</td>
<td>A_s = 680</td>
</tr>
<tr>
<td>Tower (t)</td>
<td>A_t = 190.9</td>
</tr>
<tr>
<td>Southern zone (s)</td>
<td>A_s = 190.9</td>
</tr>
<tr>
<td>Hall</td>
<td>A_{tot} = 2937</td>
</tr>
</tbody>
</table>

Where:

C_p_j = Local pressure coefficient measured on the church envelope in the wind tunnel

j = Measuring point on the church envelope

C_p_{in,i} = Average of all the values of C_p_j

i = each sub-volume

C_p_w = Local pressure coefficient on each point over the long side façade of the hall

C_p_{IN} = Local pressure coefficient inside the church hall

So once the Cp inside (C_p_{IN}) the hall has been obtained, all ΔC_p-s between outside and inside the church hall envelope can be estimated. More exactly, the wind-induced pressure difference between outdoor and indoor for each individual enclosing sub-area around the church hall is estimated as:

For the long side façade: \[ ΔC_p_{OUT-IN} = C_p_w - C_p_{IN} \] (Equation F1)

For the sub-volumes: \[ ΔC_p_{OUT-IN} = C_p_{in,i} - C_p_{IN} \] (Equation F2)

Once all ΔC_p_{OUT-IN} through each area were calculated and multiplied by the area that each of them represents; then, from all obtained values, positive ones were summed. It can be considered either the sum of all positive ΔC_p_{OUT-IN} · A or all the negatives; actually the absolute value is the same, corroborating the mass balance.
Appendix G: correlation coefficients

The following table shows the correlation between the different parameters taken as predictors of the air change rate. It was the results of using the function Correlation in excel, useful to know which predictors were good to include in regressions models and which not.

Notice that the correlation coefficients (first column) in the Correlation table are more or less the same as the correlation coefficient (R-value) of MLR.
### Table G1: Correlation table

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<th>ACH (1/h)</th>
<th>ΔT (°C)</th>
<th>WS (m/s)</th>
<th>WS^2 (m^2/s)</th>
<th>WS90 (m/s)</th>
<th>WS90^2 (m^2/s)</th>
<th>Wind direction (°)</th>
<th>ΔCp∙U (m/s)</th>
<th>ΔCp∙U^2 (m^2/s)</th>
<th>ΔCp∙OUT-IN·A·U (m/s)</th>
<th>ΔCp∙OUT-IN·A·U^2 (m^2/s)</th>
<th>ΔCp∙C-H·U (m/s)</th>
<th>ΔCp∙C-H·U^2 (m^2/s)</th>
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