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ANALYSIS OF HISTORICAL INTERIOR BY BUILDING PERFORMANCE SIMULATION

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Framework content:

State of a fresco into a modern building which it has not the best enviromental conditions for its preservation.

Data analysis of the previous year-round monitoring to understand the real climate behivour it has in terms of the interior of the building and also the external climate.

Understaning the relation in between the external climate conditions with the internal ones. The situation and location of the fresco and the conditions which need to be solved.

Calibration a previous numerical model in terms of temperature and humidity.

Proposal for a next steps.

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The student takes notice of the obligation of working out the Master's thesis on their own, without any outside help, except for consultation. The list of references, other sources and names of consultants must be included in the Master's thesis.

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Master's thesis supervisor Head of department

Date of Master's thesis proposal take over: July 2018

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To Jinu Kim, because the simplicity it is always the way.

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ABSTRACT

The historical fresco of the Assumption of the Virgin Mary by V. V. Reiner was removed and deposited, after the demolition of the chapel, in the castle park in Duchcov in Czech Republic in 1959 Kabele, Karel 2018. The newly constructed pavilion, however, is designed as semi-open space with extensive exposure to exterior climatic condition. The fresco is directly affected by significant air temperature and relative humidity fluctuations leading to its destruction. In response to the deterioration state of fresco the visitors limit (producing air moisture) and closing the ventilation holes have been proposed as immediate solutions. However, there is a request for better measure, which would open the space for visitors again. For this reason, the monitoring of the air temperature a humidity has been carried out during the whole last year.

First part of the project will be focus on analyzing measures data obtained by monitoring. Based on these results to assess the indoor environment situation in the pavilion in terms of preservation risk for the frescoes.

Second part is concerned with building performance simulation. Main task of this part represents the calibration of existing numerical model created in the software Design Builder by measures data. This step includes the creation the new EPW (energy plus weather data) file and applied it to the numerical model.

The aim of the project is to provide an overall picture of thermal performance in the pavilion based on measures data obtained by measuring the object and numerical model.

Based on the results of the analyses suggest the measures that would have open the area for visitors again and will not pose a risk for the fresco at the same time.

Po demolici barokního kostela v Duchově byla historická freska Nanebevzetí Panny Marie od V. V. Reinera sejmuta a deponována až do roku 1959, kdy byl v zámeckém parku postaven nový pavilon.

Nicméně, tento nový objekt, kde byla freska znovu vystavena, je navržen jako částečně otevřený prostor s velmi významným působením klimatických podmínek, které vedou ke značným výkyvům teploty vzduchu a relativní vlhkosti a tím tak destrukci fresky. Za účelem záchrany fresky byl stanoven limit pro počet návštěvníků, kteří svojí produkcí vlhkosti celou situaci ještě více zhoršují. Zároveň došlo k částečnému zakrytí některých ventilačních otvorů. Vzhledem k logickému požadavku správce objektu o znovu zpřístupnění fresky veřejnosti, je zde apel na nové řešení, které by vedlo ke zlepšení podmínek vnitřního prostředí v kapli. Za účel celkového pochopení tepelně – vlhkostnímu proudění byl v pavilonu proveden monitoring teploty vzduchu a relativní vlhkosti během jednoho roku.

První část práce se zaměřuje na analýzu dat v jednotlivých částech objektu získaných v monitoringu. Na základě naměřených hodnot je zhodnocena celková situace během různých období z hlediska konzervačního rizika pro fresku.

Druhá část práce souvisí s modelováním energetického chování budov. Hlavním cílem je kalibrace a následná verifikace numerického modelu, který byl vytvořen v software Design Builder, pomocí naměřených dat.

Hlavním cílem prezentované práce je celkového zhodnocení a analyzování vnitřního mikroklima v pavilonu pomocí naměřených hodnot v objektu a vypočtených numerickým modelem. Na základě výsledků analýzy může být navrženo opatření, které by bylo vedlo k přijatelným podmínkám z hlediska konzervačního rizika fresky a znovu otevření objektu návštěvníkům.

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1. INTRODUCTION

1.1. Context

This thesis content will talk about the indoor environment of the historical buildings and heritages and the air conditioning system of them focused on the frescoes preservation.

The typical air conditioning systems nowadays they use the classic thermodynamic cycles which, usually, they tend to use harmful substances to the ozone layer. The vast majority of these substances have been forgiven by the Montreal protocol. The reason of this rule or directive it is that the amount of energy used by the air conditioning it can reach a 40 % of the energy used for industrial matters Camufflo, D. 2014. Obviously, from the energy efficiency point of view, these numbers are too big to just avoid them, so the society, nowadays, it is working carefully in this field. The energy, needs production, and the production of this energy, plus the use of some substances, are polluting the air and because of it, a drastic reduction of it, is needed. It is impossible to forget, in any case, that the indoor air quality need to be preserved or improved. So, the matter to deal with, in this case study, it is the matching of the indoor quality of the air of a modern (1959) building with the needs of an old building (baroque church) by using an old techniques of air conditioning able to deal with a singular scenario, in order to be able to maintain the fresco environment in acceptable conditions.

Fresco is a method of painting on freshly plastered walls or ceilings with powdered pigments mixed with water. The late medieval period and the Renaissance saw the most prominent use of this technique, particularly in Italy, where most churches and many government buildings still feature fresco decoration.

Temperature and humidity changes can affect the conservation of frescoes. Ideally, the wall temperature should be at any point the same as the air temperature on the wall surface and in the immediate proximity. If it is different, it generates an air flow along the wall surface that increases the aerodynamic deposition of airborne particles and wall soiling. The natural ventilation and turbulence indoors also affect the transport and diffusion of airborne pollutants. Different works have characterized the distribution of thermal and hygrometric parameters, as well as the turbulence indoors, in order to study the interactions between the indoor atmosphere and walls supporting frescoes or mural paintings. The impact of other adverse factors such as heating, lighting, solar radiation, or people were also discussed.

Vertical gradients of temperature (*i.e.*, variations with height) generate air flows along the surface of frescoes that increase the aerodynamic deposition of airborne particles and soiling. Thus, weak gradients of temperature and *RH* are desirable for conservation purposes given that these conditions lead to little deposition of pollutants on the frescoes.

In conservation it is useful to use clear terms derived from the science, as for example, "regional climate" for the main characteristics of the geographic area where the monument it is found; "urban", "rural", "mountain", "coastal", "valley" and so on for the next dimensional step and "microclimate" relating to the small location where a monument or an object it is located. In practice, it refers to the whole ambience which is necessary to study in order to know the factors which have a direct influence on the physical state of the monument and the interactions with the air and the surrounding objects. This could be the perfect definition for the prefix: "micro ".

To define climate, can be done from the most purist definition, as: "climate is the fluctuating aggregate of atmospheric conditions characterized by the states and developments of weather of a given area Camufflo, D. 2014. It is evident that in this case study, the word "weather" it is inappropriate. To adapt the before definitions to this case study, the following interpretation can be given: "microclimate is the synthesis of the ambient physical conditions (e.g. time and space distributions, fluctuating values and trends, average and extreme values, space gradients and frequency of oscillations) due to either atmospheric variables (temperature, humidity, sunshine airspeed) or exchanges with other bodies (e.g. infrared emission, heating, cooling, lighting, ventilating) over a period of time representative of all the conditions, it should at least document one or a few examples of key different conditions just to understand the problem it is been dealing with.

Another key question is the weather meteorological data, taken from a standard weather station not too far from the monument, can be used for the estimation or interpretation of microclimatic situations, or is it always necessary to carry out a specific and expensive field tests. In any case, the weather meteorological data used for the modeling and study of this thesis will be accurately explained later on.

It is absolutely restrictive to consider the individual parameters separately (e.g. temperature, humidity, sunshine, wind, precipitation) omitting interactions and feedbacks between them and the surfaces. The microclimate is determined by the complex interaction of several factors. The microclimate is not only an accurate description of what is happening but also a good base to forecast what might happen in the future. The microclimate for conservation purpose is not just a mere collection of atmospheric variables but a description of the complex interactions between air, building and objects, an unicum that includes air and collections and all their mutual relationships.

Air and precious surfaces to be studied and preserved can be found everywhere, either indoors or outdoors. Although the indoor and the outdoor environments are traditionally considered very distinct, in practice they present similar problems: both undergo daily cycles of temperature and humidity, forced by either the solar cycle or by heating, ventilating and air-conditioning (HVAC) systems; both are exposed to intense shortwave radiation, which may be the direct solar irradiation on the open sky or through window or artificial light; both are affected by advective air movements that is wind or air currents or air leakage through cracks and openings or turbulences generated by sources of momentum, for example people movements, heat sources, surface roughness in the presence of advective movements. Rainfall and dew are considered typical of outdoor environment, but often rainfall penetrates inside through disconnections, or condensation forms on the window panes, on the surface of cold objects or inside pores.

The most important distinction is that the indoor environment can be controlled and the most important is to know how to do it properly.

In the past, local climate was carefully observed and exploited to adapt buildings and activities to the external ambient and benefit of a "natural microclimate". Some ancient building or architectural literature talks about how a building was built with respect to exposure to sun, wind and precipitation. Rooms were exploited according to the temperature and type of light that could enter through the windows.

Nowadays, the modern technology, often induces to believe that the climate outside can be ignored and that a new independent artificial microclimate can be developed inside the building, controlling temperature and humidity with advanced sensors and microprocessors.

By maintaining air intake higher than air exhaust, commercial buildings and museums are kept with indoor pressure higher than the outdoor level. This practice reduces infiltrations of external air and pollutants, but creates an internal atmosphere, with its artificial microclimate, which is usually not in equilibrium with walls, floors, ceilings, and exhibits, and needs many frequent heat and moisture transfers to balance the influence of people, the air leakage and the exchanges between air and surfaces. It has been calculated that about 30% of the moisture supplied to a room is absorbed by the room surface with the consequence that the benefit is mitigating air dryness is negatively compensated by moistening surfaces.

The excessive confidence on HVCA and their use has caused several problems. The indoor temperature is mainly regulated taking into consideration the people thermal comfort, sometimes irrespective of the regional climate (except for calculating the HVCA power), the outdoor moisture content and the internal vapor sources. The desired temperature level is assumed as a primary need, and the indoor concentration of water vapor is controlled to create an acceptable relative humidity (RH) level or range in this artificial microclimate. Several systems that control the humidity in historic buildings or museums have been analyzed with field tests; however, although these systems may be good in theory, and the machines may operate correctly, their long-term impact has been often found to be deleterious, especially if the main control unit goes out of order. Dry or moist air is blown near walls where paintings are located. Clouds of moist/dry, cool/warm air are generated, and the internal air motions will move them. The consequence is that objects and collections will suffer for repeated humidity and temperature fluctuations.

Water vapor is a variable constituent of the atmosphere, whose concentration depends on weather and other local factors, and generally ranges between 0.5% and 4%. This variability is a consequence of the fact that water vapor may change state, becoming liquid or solid, for example it may precipitate or be in different ways transferred from the atmosphere to the earth's surface or vice versa. The water molecule itself it is far from being a "perfect gas". It is composed of one oxygen and two hydrogen atoms that are 0.95 Aº distant from the oxygen nucleus. Atoms are disposed forming an H-O-H angle equal to 105º. This asymmetrical configuration generates a spatial imbalance between positive and negative charges, so that the water molecule is an electric dipole that can be oriented in an electric field (exerting a strong dielectric action) or may interact with other molecules or bodies exerting van der walls and electric forces.

However, in a crude approximation, when the water vapor does not undergo change of state, for several purpose, it may be treated taking advantage of our knowledge and formulas for perfect gases, although some departures may occur and should be considered as it will be seen later. Major problems arise when the water vapor approaches saturation. Or when water vapor molecules impact on a surface whose temperature is bellow to the dew point, or which is contaminated with hydrophilic salts. Under these conditions, instead of existing elastic impacts, the water molecules will stick on the cold surface, or on the salts (the same holds for condensation nuclei), and the effective number of "free" gaseous molecules will decrease.

Temperature, on the other hand, is the condition that determines the direction of the net flow of heat between two bodies, that is from the warmer to the colder one. For this property a thermometer can be put into equilibrium with a body, to read the temperature of the body on the thermometer, if the thermometer does not perturb the original temperature of the body and is not influenced by other factors.

Temperature is an important factor in the conservation of works of art for a number of mechanical, chemical, mineralogical or biological mechanisms. Change in temperature induces to differential expansions in materials and tensile strengths between surface and the subsurface layers.

Thermal expansion may be relevant for not only objects but also structural stability of monuments or buildings.

Temperature cycles. Another dangerous fact. The most popular example of dangerous daily cycles are the freezing-thawing cycles or the temperature cycles of objects directly exposed to sunshine. Temperature cycles induce internal stress and accelerate fatigue failure in vulnerable materials. Materials act as a low-pass filter that attenuates the penetration of fast fluctuations: the shorter of the duration of the fluctuation, the thinner the layer affected by it. However, it should be remembered that the key part of the artistic value of monuments lies in the surface layer. For these reason, daily (or shorter) temperature cycles might be much more important than the seasonal ones.

Air movements: Temperature variations over space affect the temperature (and density) of the air coming into contact with the colder or warmer surfaces. The air looses or gains buoyancy and convective cells develop. The air movements will be responsible for the transport and deposition of gaseous pollutants and airborne particulate matter and soiling of paintings and monuments surfaces.

Changes in relative humidity and moister content: It is to be noted, however, that the pure thermal effect is an academic abstraction, as various water activities, are always synergistically linked with temperature, and several deterioration mechanisms are caused by water, but triggered, by temperature, for example surface heating, moister evaporation, internal salt migration and efflorescence formation.

The most popular effect is that when the temperature increases, the relative humidity decreases and vice versa. Relative humidity is a key parameter in conservation and it is governed by temperature in addition to the moister content to the air, as we will see later. Temperature variations cause changes in the degree of saturation of water vapor, as well as moister content in bodies. Several materials, for example wood, parchment, ivory, plaster, change their dimension with the water content, swelling or shrinking, with deformations, micro or macro fissuring and so on. The effects of temperature forcing are in general very complex. For instance, wood is characterized by low thermal conductivity, but the propagation of heat is faster than the propagation of moister, and this cause a redistribution of moister absorbed into the grains. As a consequence, delayed differential stresses and shrinkage are induced. Again, temperature changes inside porous stones cause changes in RH within pores, which in turn is related to the evaporation of water, the concentration of dissolved salts and their participation in crystalline form when the solution becomes supersaturated.

1.2. Combination of people comfort, conservation and sustainability

When the natural microclimate of a building is not comfortable for a people (less frequently the problem is posed whether it is suitable for conservation too), HVAC systems are installed to obtain the desired comfort. Traditional systems are used, for example hot water radiators, fan coils convectors, radiant panels, humidifiers, following the everyday practice of keeping a temperature fluctuating around the selected lever or switching on/off the system according to the activity periods with sudden peaks or drops in temperature (and, consequently, in relative humidity). All these systems are characterized by intermittent use and are located in spot areas, so that they continually generate microclimate perturbations. Fans tend to destroy thermal layering but generally worsen the situation forcing air currents in the rooms.

The worst situation is reached in winter in buildings used only at times, as in the case of churches attended weekly for the Saturday and Sunday liturgy. The first need for conservation is a constant climate, people need a mild climate, and a constant mild microclimate seems the most obvious conclusions, but it is expensive and it is very difficult to keep RH unchanged. As it is not easy to combine man comfort, conservation needs and low costs, various solution have been attempted often, disregarding conservation.

It is evident that it is not easy to combine human comfort, conservation needs and low costs and that a compromise is required, where the conservation needs should dominate in proportion with the cultural heritage value and the building use. For instance, it could be said that the choice of microclimate in a museum, which should be aimed at conservation, and where many important items are concentrated, should be more rigorous than in a church which is more oriented to people use.

It is also clear that every system presents a number of negative aspects, some of which may have a major impact in certain circumstances or minor one in others. Therefore, it is important to carry out a careful analysis if pros and cons and choose, time by time, the system that causes the minimum damage. Sometimes, a combination of different systems might be considered to avoid the excessive impact of specific adverse factors; for example, in particularly severe climates, the combination of the floor radiation from the floor or other external emitters with an electrical pew heating might reach an acceptable comfort with a modest ambient perturbation and might be better than the more common solution of a radiant floor heating associated with warm in airflows.

As a general comment, it might be preferable to reduce interventions to a minimum level, to reduce negative impact to a minimum sustainable level. It can be argued that many objects have survived until today just because the modern heating was not yet invented and now it constitutes a new challenge. This is true in several cases, nevertheless it is also possible to use a modern technology to improve natural negative situations, as for example when a room temperature is bellow the dew point and condensation forms everywhere. The conclusion is that the heating systems should be installed by experienced engineers, but under the strict control of experts in conservation science. The real problem is that the conservation problems are many, complex and often disregarded.

1.3. Water vapor and dry air principle

The mixing ratio W of the moist air (i.e. dry air and water vapor) is the ratio of the mass of water vapor to the mass of dry air and this ratio represents the ponderal mixture of these two gaseous substances.

This parameter is dimensionless because the unit g g^{-1}, i.e. a pure number that represents the fraction of grams of vapour mixed with 1g of dry air. It might be expressed in percentage too. However, as the numerical value of W is very small, it is common to multiply it by 1000 and use the practical unit MR = 1000w, expressed in g kg^{-1}, which represents the number of grams of vapor mixed with 1kg of dry air. A plot of this parameter is shown in the figure bellow:

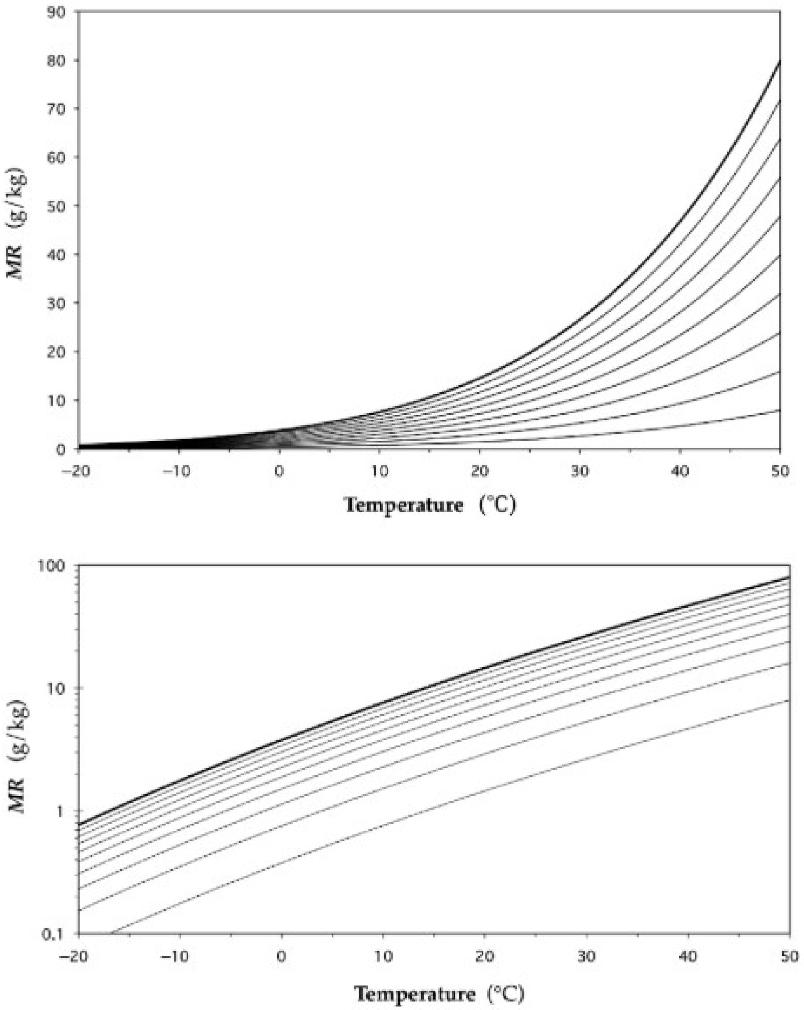

Figure 1 - Saturation mixing ratio of the vapor in ai rand actual MRat different values of RH = 90%, 80%, 70%... 10%. Of course, the RH = 100%

Specific humidity: The specific humidity **(S)** moist air is the ratio of the mass of water vapor to the mass of moist air and this ratio represents the ponderal dilution of the vapor in the atmosphere. It is also called mass concentration or moisture content of moist air.

Like the mixing ratio, this parameter is dimensionless, the natural unit being $g \cdot g^{-1}$. It might also be expressed in percentage; however, in order to avoid the use of small decimal umbers, the practical unit SH = (times) 1000 expressed in $g \cdot kg^{-1}$, has been introduced. This represents the number of grams of vapor dispersed in 1 kg of moist air.

Absolute humidity AH it represents the maximum quantity of vapor that the unit volume of atmosphere can carry under specified temperature conditions. For this reason, it is also called (moisture) capacity.

Relative humidity it is useful to state beforehand use of attributing all the properties of the atmosphere to only one fictitious gas, called "air", which behaves as the actual mixture of gases and vapours that form the atmosphere. In order to describe particular phenomena, a distinction is made between dry air and most air. The adjective dry may have two meanings, which are clarified by the context: the former is literal: without vapor, whereas the latter means without condensation. The mixture behaves as an ideal gas, with no changes or phase. Similarly, moist indicates the opposite of these two situations. From this point of view, the vapour component is formally ignored and it is improperly expressed in terms of relative humidity of the air or degree of saturation of the air instead of the correct form: relative humidity of the water vapor and degree of saturation of the vapor.

The dew point temperature, commonly termed dew point, DP, is the temperature to which a parcel of moist air must be cooled at constant atmospheric pressure and constant water vapor content in order for saturation to occur. It can be alternatively defined as the temperature at which the actual pressure of the vapor contained in an air parcel equals the saturation pressure, under constant atmospheric pressure and MR.

The wet bulb temperature or isobaric wet bulb temperature, is the temperature an air parcel would have if adiabatically cooled to saturation at constant pressure by evaporation of water into it, all latent heat being supplied by the parcel. This temperature is directly measured by the wet bulb of a psychrometric or can be obtained indirectly by means of a psychrometric diagram or formula, after the dry bulb temperature and any one hygrometric value (MR, SH, AH, RH or DP) are known.

The psychrometric chart is the graph which can contain all of the terms mentioned above.

- The abscissa is the actual air temperature T
- Vertical lines are isotherms. Going upwards, the MR increases. Going downwards, it decreases.
- Horizontal lines are isohumes in terms of constant MR. A displacement to the right indicates warming of the system without change in MR; a displacement to the left, cooling, and according to the previous definition, the final point of this horizontal cooling is the DP.

- The nearly exponential curve on the left is the saturation curve and represents simultaneously the MR, the RH = 100% and the DP.
- The (vertical) distance between each point of the saturation curve RH = 100% and the abscissa (RH = 0%) is divided into 100 parts. Each of them, by definition shows a given percentage of SH or MR. Matched values of T and MR used as orthogonal Cartesian coordinates in a psychrometric diagram determine the actual value of the RH of the same air parcel. In the diagram, the nearly exponential curves with RH = 10%, 20%, 30%... 100% are evidenced. These lines are named isohumes in terms of RH.

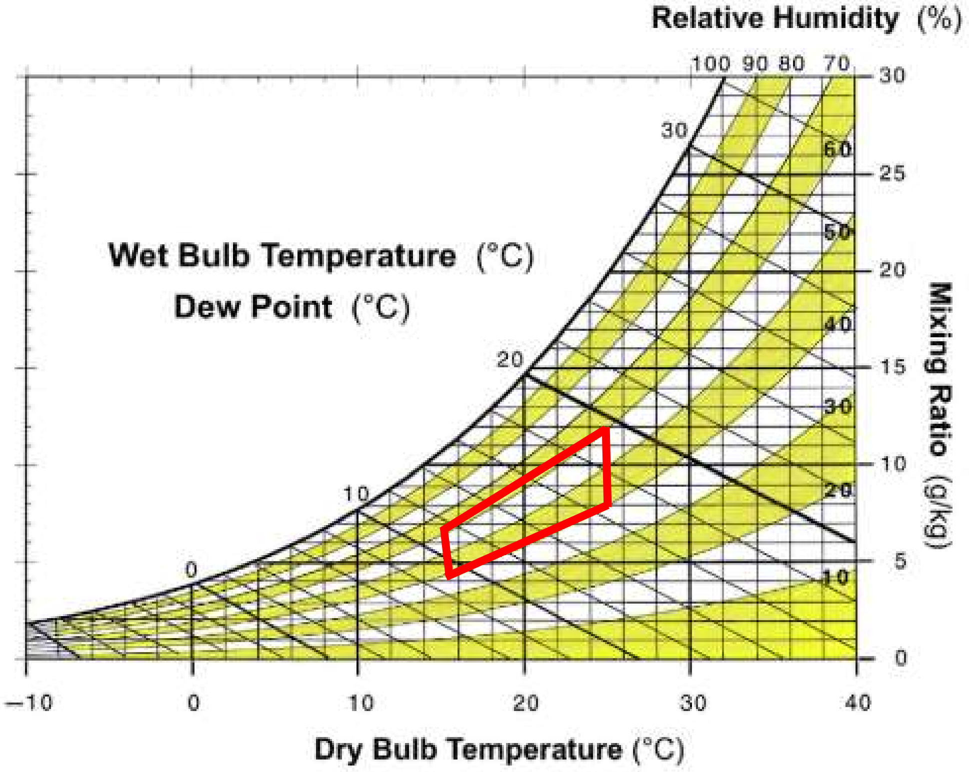

Figure 2 - The psychrometric chart with tolerated range highlighted Camufflo, D. (2014)

1.4. Humidity and conservation

The humidity mixing ratio (MR) is very useful for diagnostic purpose, to provide evidence of the action of heating, ventilating and air-conditioning (HVAC) systems or air-surface interactions. By measuring this parameter along a horizontal cross-section of a room, it is possible to see the advection of external air penetrating through open door or windows, the moisture released by visitors, or where the walls are evaporating or absorbing moisture. The effects of humidifiers are also pointed out, as they do not generate a homogeneous increase of vapor content, but a cloud of moisture air that might damage objects in proximity or moves into the room borne by the advective currents between adjacent rooms. A very common, but inappropriate, position for a humidifier is near the corners or walls where works of art are located.

Humidifiers generates clouds of moisture that grow in sheltered space. Then these clouds diffuse into the room, are displaced by local air currents, or are broken and transported in several directions by the turbulence generated by the motion of visitors- Works of art are alternatively immersed into, or emerge from, these clouds or portions of them.

The result is continuous stress and fatigue of objects that lead to weakening, micro fissuring and flaking of their outermost layer of their colour coating. A more appropriate position is far from the exhibits in the central part of the room, either on the floor or on the ceiling, although the later position presents a further problem: the suction outlets placed on the lower part of walls determine a preferential path of the moisture into the room and nonhomogeneous distribution.

2. EXISTING STATUS

2.1. Model

The pavilion is modelled using Design Builder Software Package. The software consists of a 3-D modeller and 10 modules that work in conjunction to thoroughly analyse any building. The software combines modelling technology with advanced energy simulation so that professionals can reduce a building’s impact on the environment. The software has a large database of numerous weather data. The software also has a massive materials database that contains the properties of countless building materials.

The 3D model was created as per the exact dimensions of the pavilion. The triangular extrusions roof was modelled as an outer dome to simplify the processing.

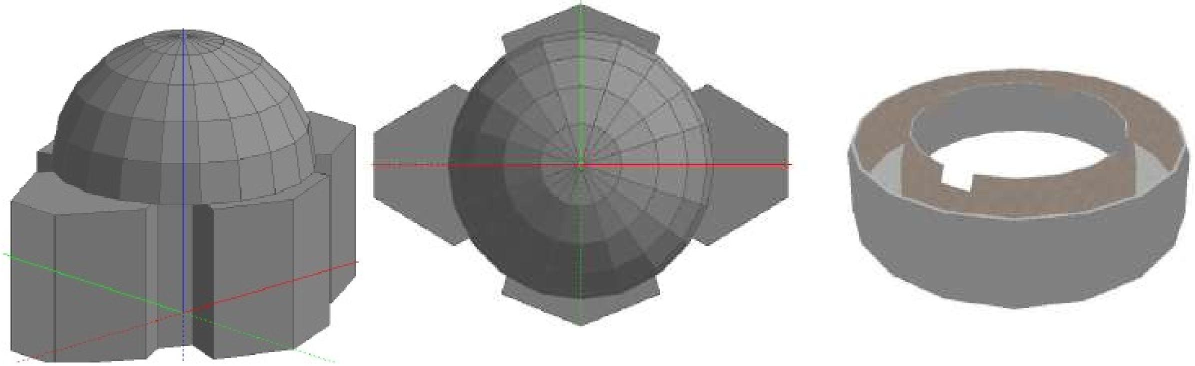

Figure 3 - different model views

The pavilion’s energy performance is strongly correlated to its occupancy. The latter determines the type of activities that are normally taking place during a day, an evening, and weekends. By knowing the type of activity, internal gains can be assessed and incorporated in modelling the precise energy performance of a structure. When accounting for internal heat gains generated by occupants, the density of occupants and their metabolic rate are two of the most important factors to take into account. Such information is usually available to change within the modelling software. Most packages offer an extensive list of occupancy usages to choose from. The density of people and their metabolic rate can also be changed within the software package. As it was explained in the introduction, the pavilion is currently not open to the public. However, it would be beneficial to model the building under different occupancy modes to better assess the energy performance in such conditions. Two main occupancy activities are created to predict the results of both an unoccupied and occupied functions.

Unoccupied is the current condition of the pavilion. It is assumed to be closed year-round. It must be noted that gains are close to null in such occupancy. In addition to no occupancy, there are no lightings in the pavilion. The translucent windows at the entrances keep the solar gains to the minimum, and lack of windows in the pavilion aids in that.

Occupied is to model the building in case it was decided to be opened to visitors interested in the fresco, and possibly other artworks by V.V. Reiner. The occupied activity would be similar to public circulation areas where people are walking around, and where display items are exhibited. Such categories are usually applied to libraries, museums, and galleries. The density of people is assumed 0.1497people/m2, which is roughly equivalent to 3.5W/m2 of energy generated. This occupancy is scheduled from 10:00AM until 4:00PM five days a week. Similar to the unoccupied activity, gains from other sources such as solar gains and lightings are limited. Yasser Sidaoui (2017).

The best method to control indoor micro-climates in any historical structures is to use an HVAC system; whether the system consists of simple heating apparatuses, or a more robust system that offers dehumidification capabilities. To try and mitigate the condensation issue, the structure was modelled with different scenarios for each occupancy type. The inside temperature of the structure was kept at 5°C, 10°C, and 15°C to test at which temperature the condensation would stop. In addition, dehumidification would be added when heating alone does not suffice to eliminate the condensation.

The external weather has been chosen from the weather library from the same software. Perhaps there is big number of locations, the exact location of the pavilion it has been impossible to update on the software. Instead of that, the climate used has been the Prague weather.

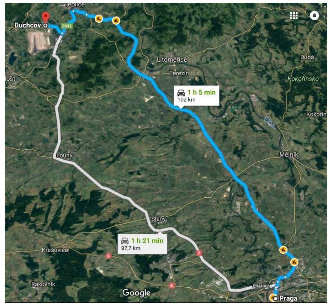

Figure 4 - Real distance from Prague to the pavilion location (Duchov)

The real distance from the real location of the fresco (the pavilion) and the city from the weather data has been collected is around 100 km. In terms of climate conditions, it can be avoided or can be assumed as equals. Duchov has, also, the same altitude (more or less) than Prague. The altitude is another factor which can affect substantially the weather data. In this case, but, as soon it is the same, the weather data will be not affected by these minimum changes.

2.2. Reality (Data collection)

he building has been monitored along an entire year (01/02/2017 – 31/01/2018) by using 10 sensors and their respective data logger. These sensors have been collecting the local temperature (ºC) and the relative humidity (%) from different points of the interior of the building and also from outside. The distribution of the sensors and the location into the building it is shown on the picture bellow:

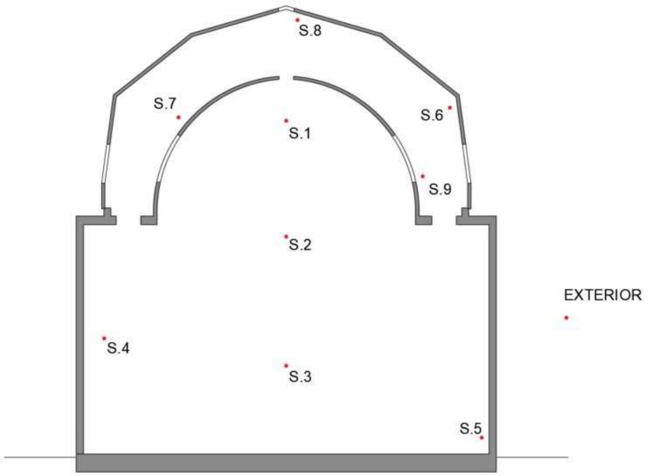

Figure 5 - Distribution of the different sensors. (Sensor 1: interior hanging on top; Sensor 2: interior hanging in the middle; Sensor 3: interior hanging down; Sensor 4: interior south door; Sensor 5: interior east side down; Sensor 6: space between the two vaults north; Sensor 7: space between the two vaults south; Sensor 8: space between the two vaults on top; Sensor 9: space between the two vaults next to the window).

The data has been collected every 15 minutes, which means 4 times per hour. It means, also, that there are 96 readings per day, per sensor. This interval of readings has been decided in order to find differences along the days. In that way, it will be possible on the next steps, to find the behaviour of the trends along the year (smoothing the data line for example to one reading per day, by using the average of all the data collected in one entire day), but also to find the behaviour of the trend along the day (by using the raw data and cutting it to study daily).

On the other hand, a numerical model has been carried out by applying possible scenarios or fictional scenarios. This numerical model has been developed in order to reproduce the interior environment of the building and analyse how it affects to the preservation risk for the frescoes and has been studied by performing a new building simulation by using the software: *Design Builder.*

Since the pavilion's energy performance is strongly correlated to its occupancy, two different scenarios will be developed: occupied and unoccupied.

The first one, the occupied scenario, pretend to reproduce the interior environment by closing the public entrance one year-round.

The second scenario reproduce the interior environment of the building by applying public concurrence (the same than in public buildings such libraries, museums, etc) in order to study how the energy generated by the people affects the frescoes.

The idea is calibrating the numerical model from the first scenario (no public concurrence) by using the data collected along the entire year.

The main goal of this point is find the dispersion with the reality by using the first scenario (unoccupied) and apply this dispersion for the second scenario (occupied) and try to study how it will affects the public concurrence or even if it is a possibility or not open to the public.

3. ANALYSIS OF THE MEASURED DATA

3.1. Temperature VS. Humidity

As has been commented above, this data has been taken every 15 minutes along a year-round. From February the 1st of 2017 until January the 31st of 2018. 365 days with 96 readings per day.

The parameters in this specific case are the temperature (ºC) and the relative humidity (%) and the boundary conditions, the tolerated conditions for the preservation of these lime paintings. ASHRAE standards dictate that the perfect condition for the room in class A range between 15ºC to 25ºC and from 40% to 60% in terms of RH. So, the boundary conditions will be these two ranges.

By using the data collected along the year, a graph for every single sensor has been plot in order to show the quantity of readings are in between the tolerated indoor environment conditions. And the location of all of them in general. To have an overview of the current situation.

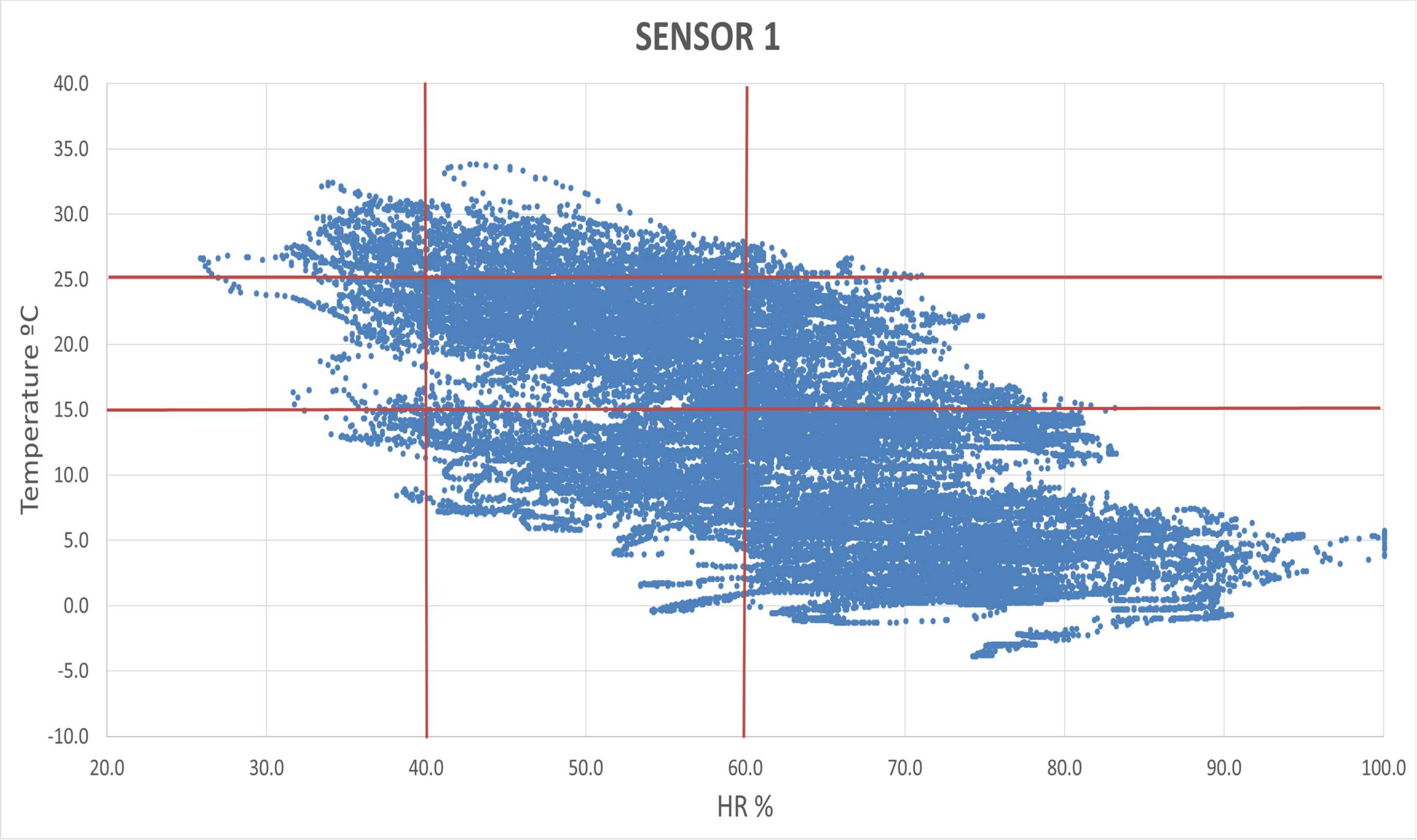

Figure 6 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 1

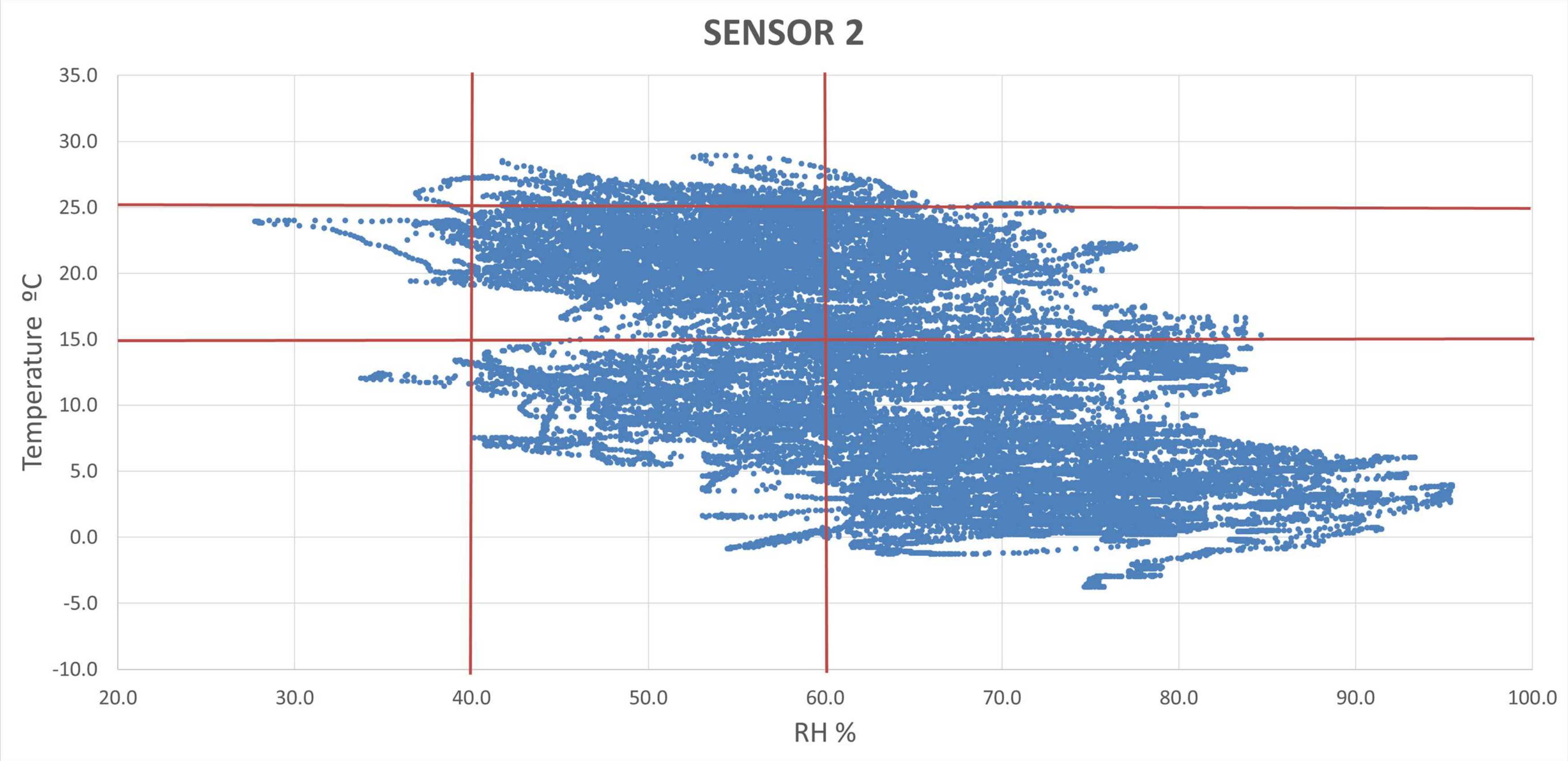

Figure 7 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 2.

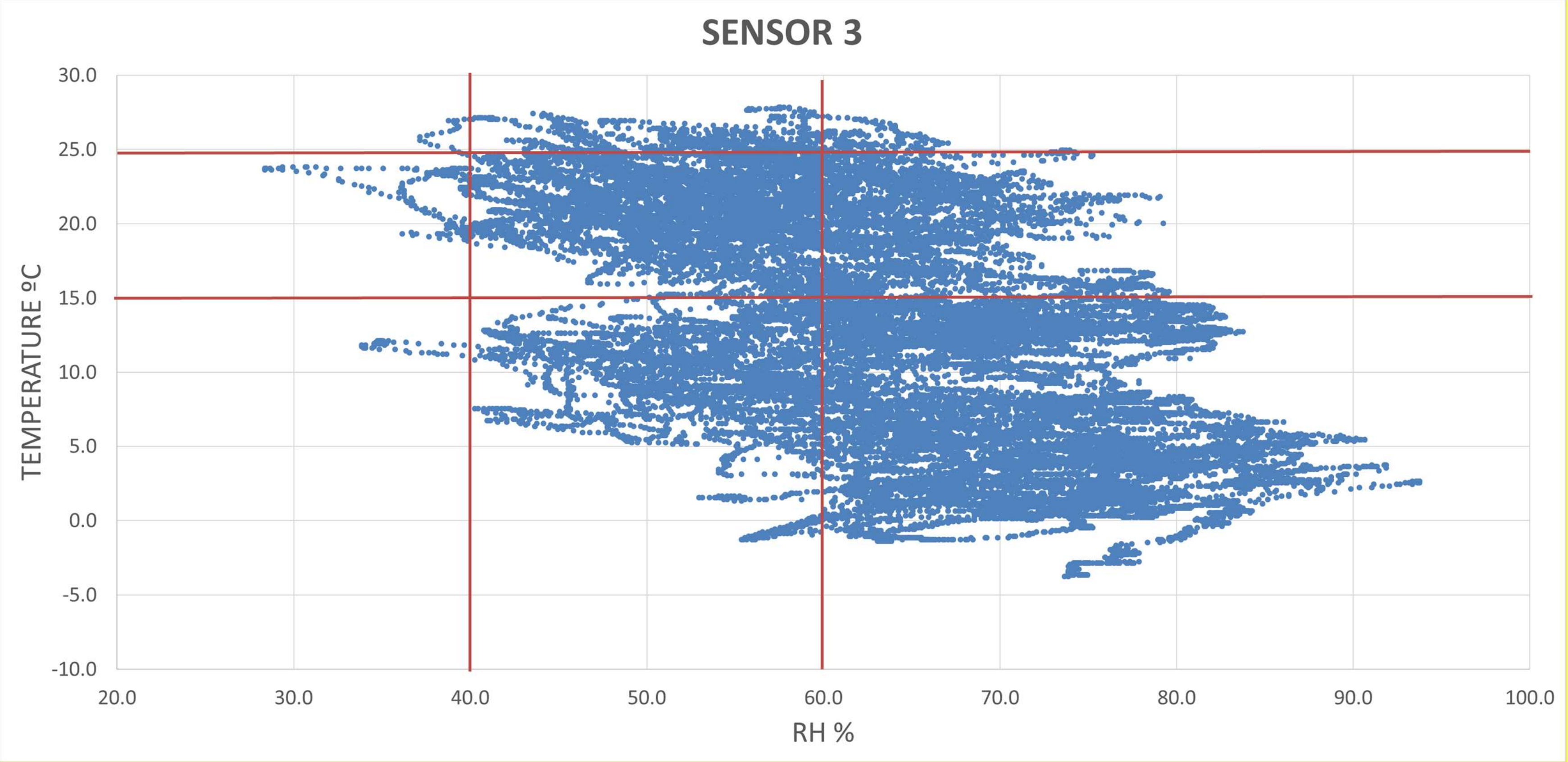

Figure 8 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 3.

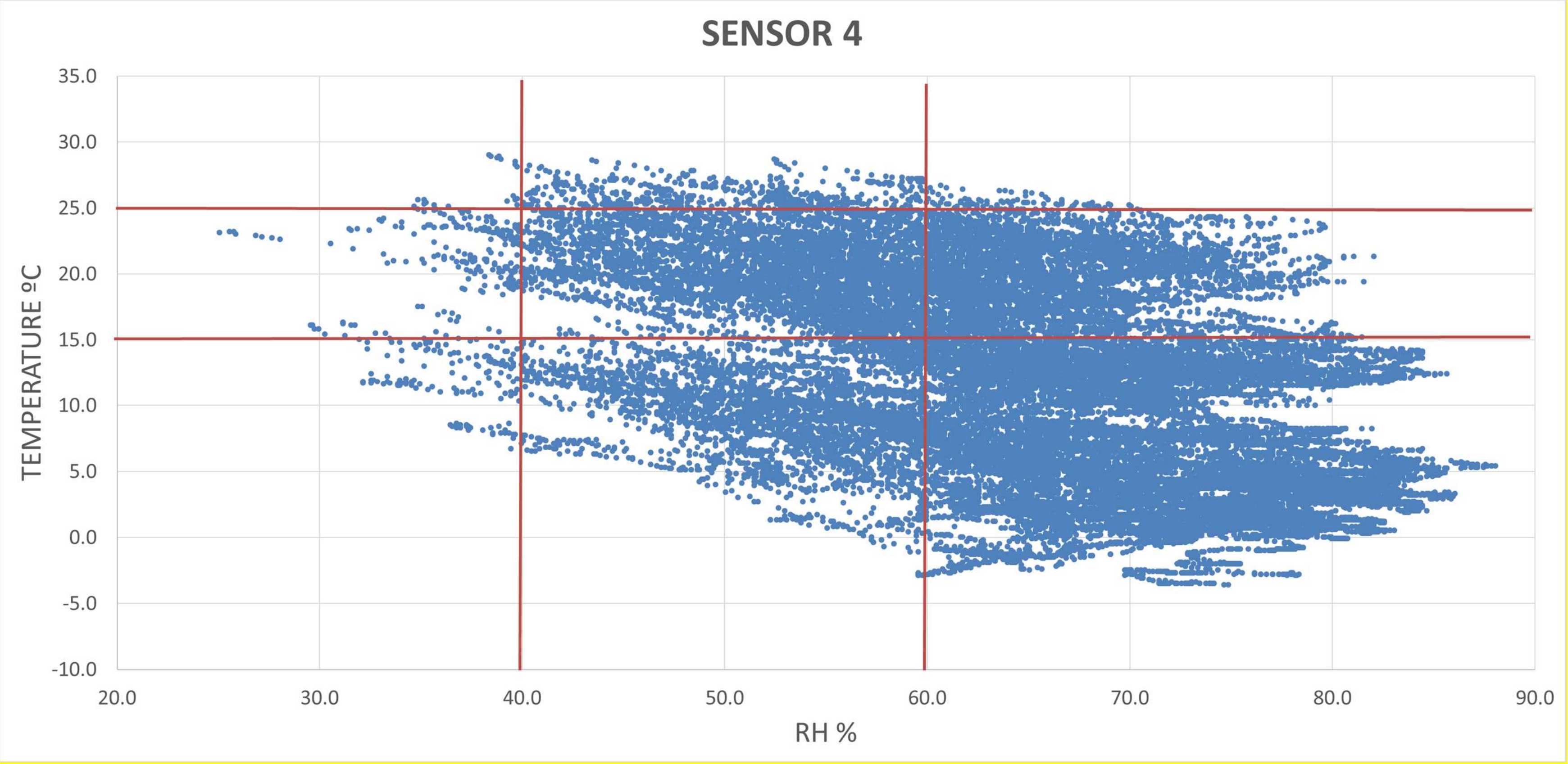

Figure 9 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 4.

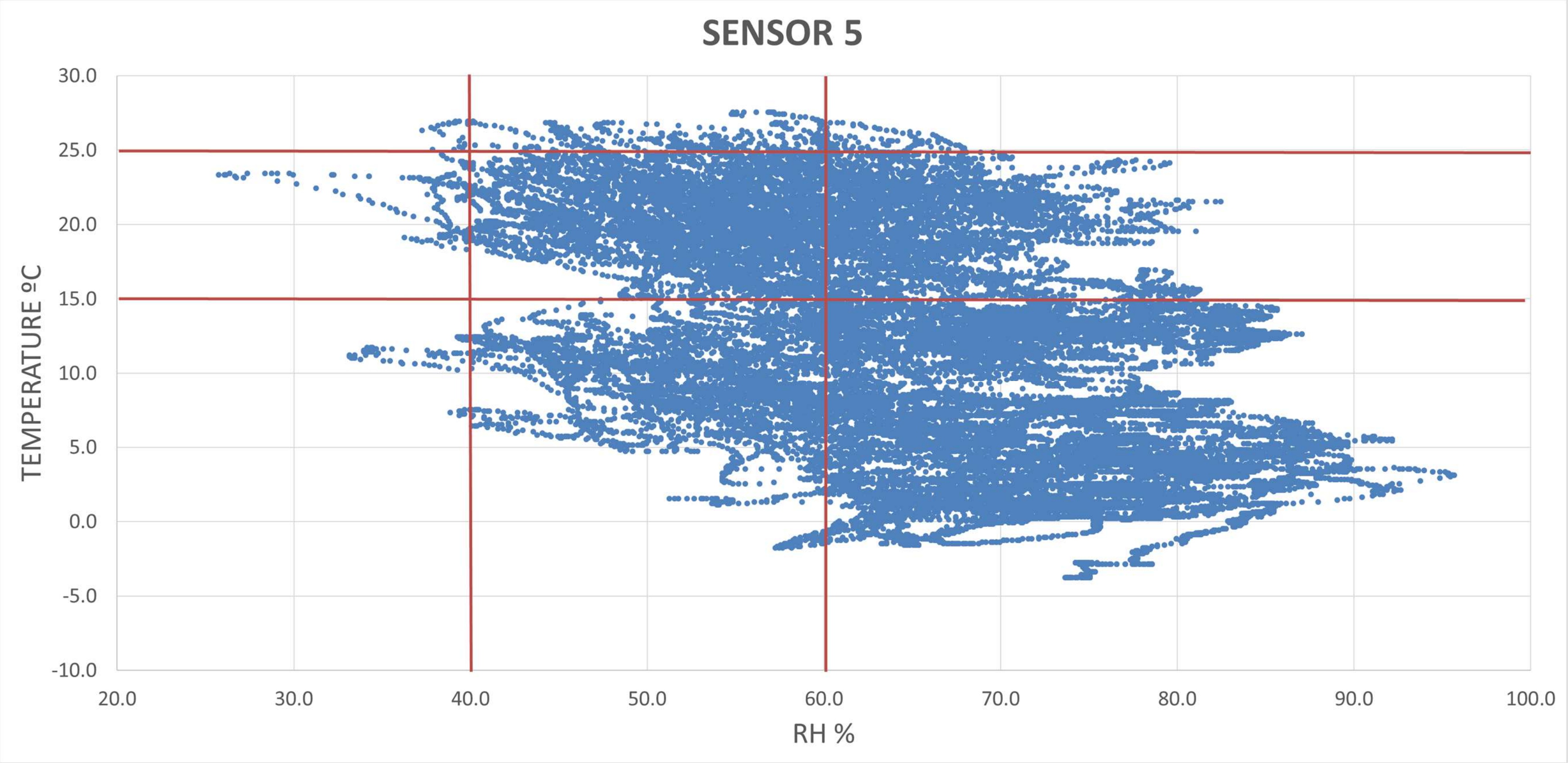

Figure 10 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 5

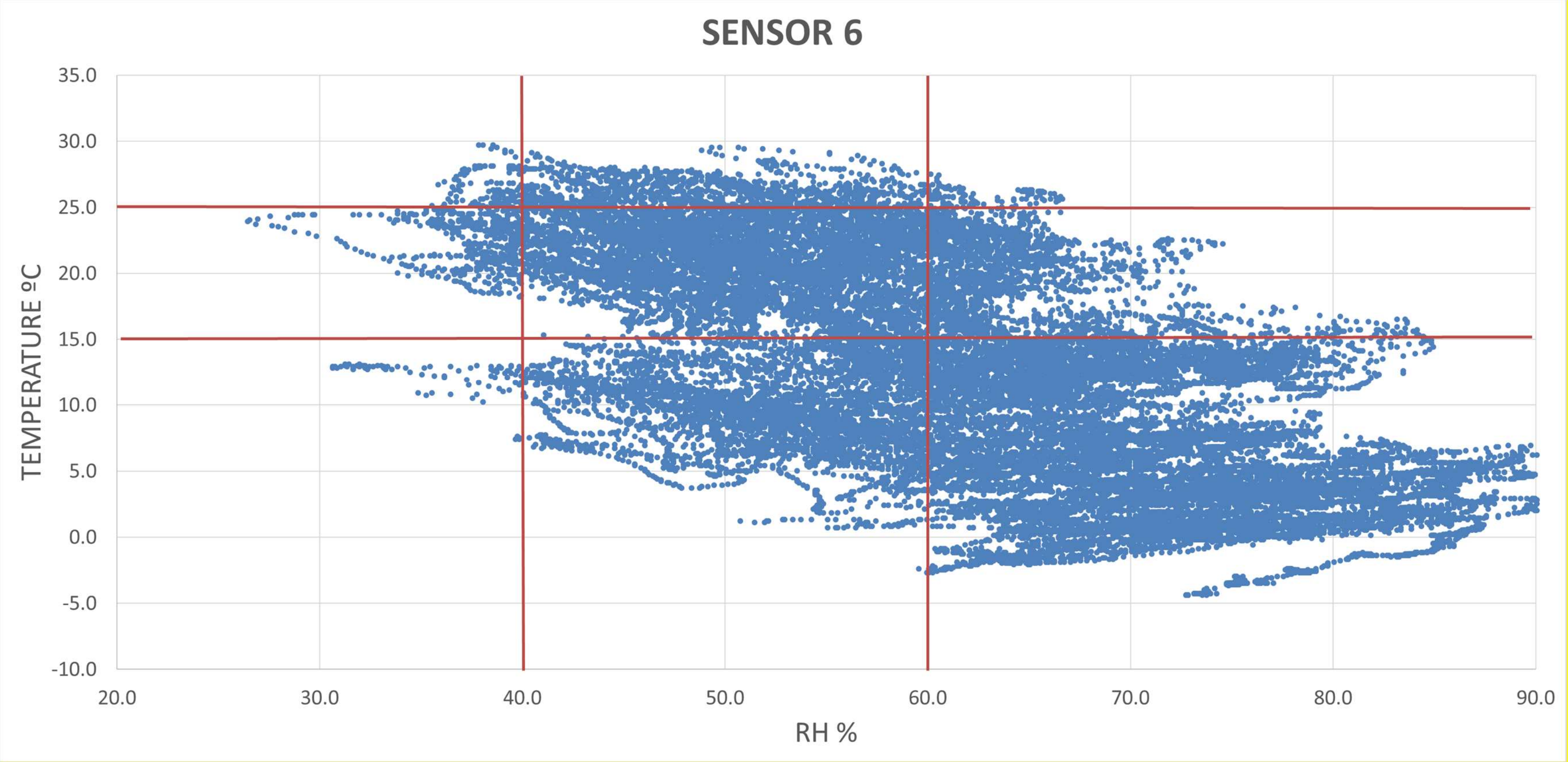

Figure 11 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 6

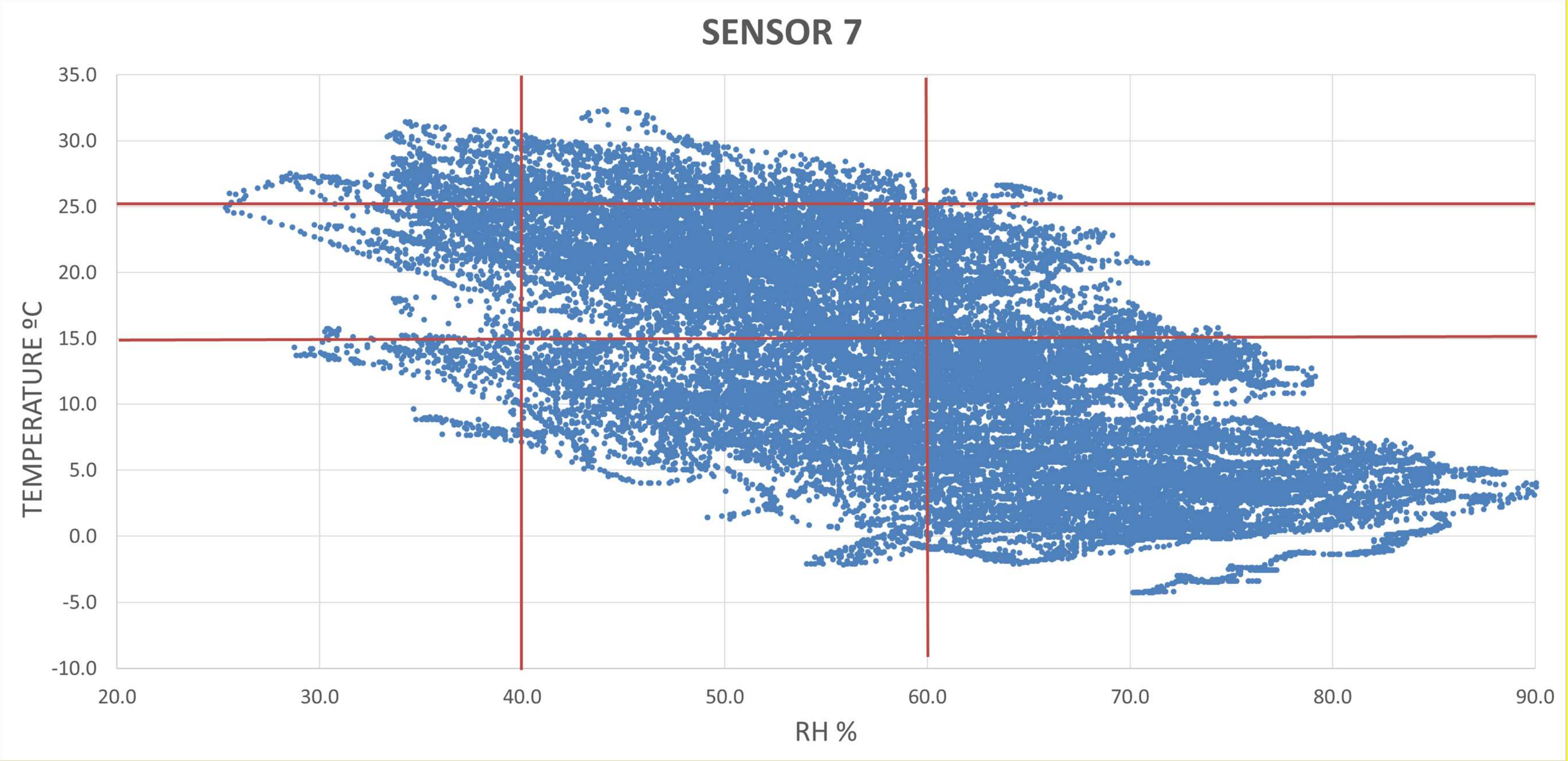

Figure 12 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 7

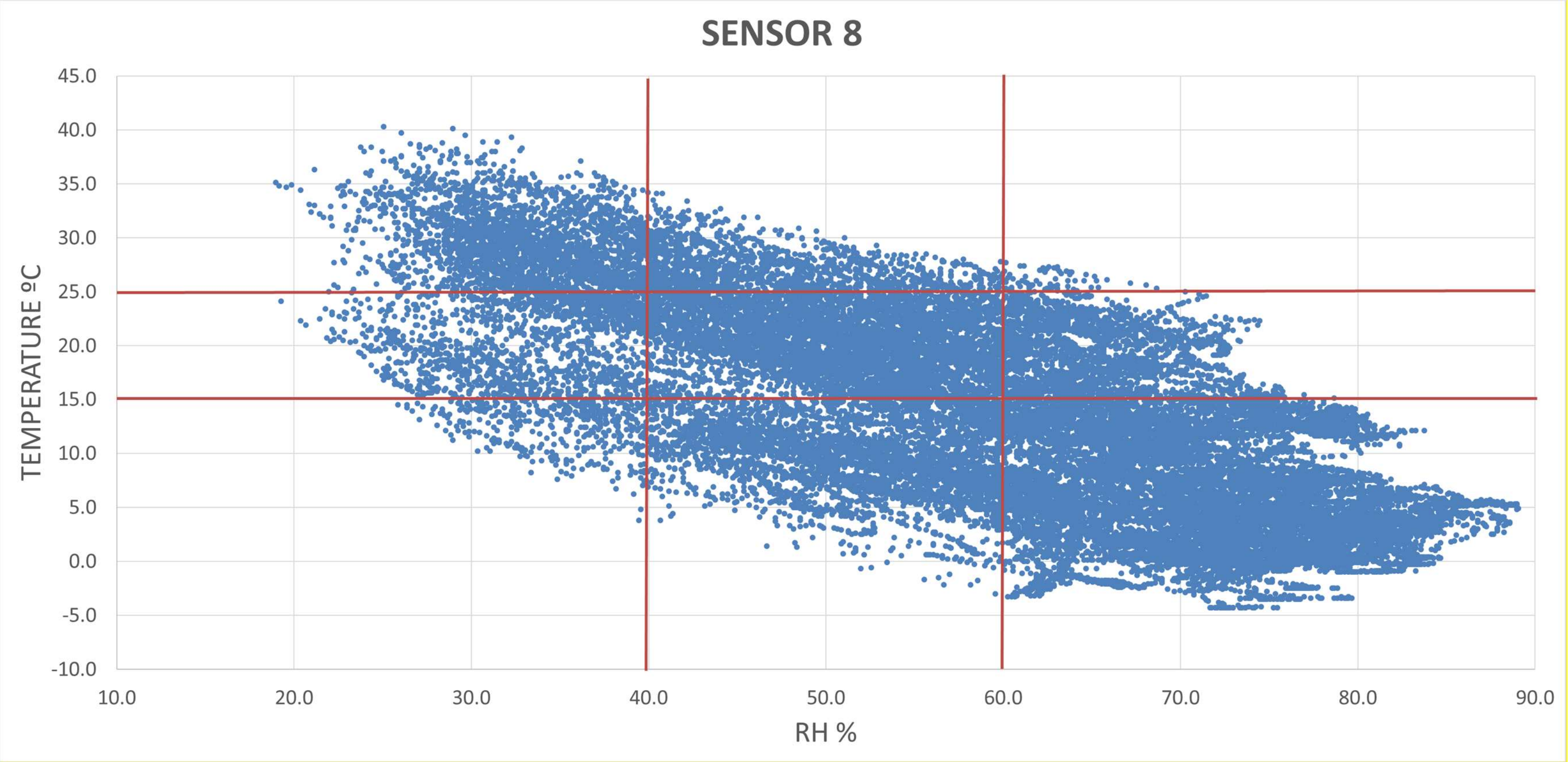

Figure 13 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 8

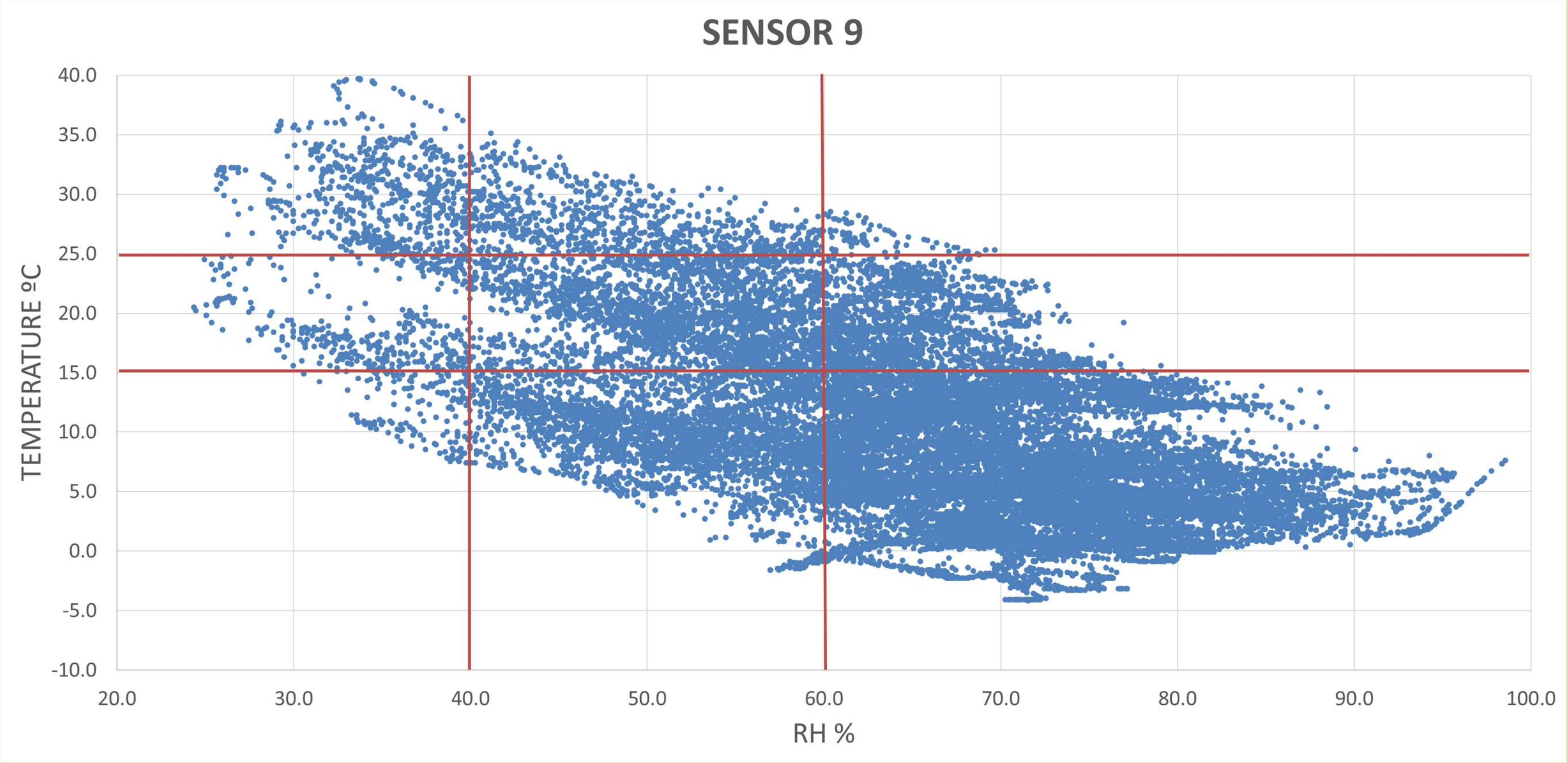

Figure 14 - Location of all of the readings along the year-round in terms of temperature and humidity, plus the tolerated range and the gross vision of the amount of them are inside of it. Plot for sensor number 9

The conclusion from this first overview is that perhaps every sensor could record some readings into the tolerated range, the vast majority of the recordings are out of range. So, the major part of the year, the fresco is not surrounded for the best environmental conditions for its preservation. On the table bellow it is shown, in percentage, the amount of readings into this range and outside. This table it is developed per sensor and total.

Table 1 - Amount of readings into and out of the tolerated range (15ºC - 25ºC and 40% - 60% RH)

SENSOR	Reading out of range (%)	Reading into the range (%)
S1	80.01	19.99
S2	79.82	20.18
S3	79.96	20.04
S4	83.92	16.08
S5	81.14	18.86
S6	78.62	21.48
S7	72.30	27.7
S8	83.11	16.89

Talking about the readings into the tolerated range it is good to mention that, perhaps there are some readings into this range, there is an important part (geography talking) without almost any reading. The south-western part of every single graph of every sensor it is almost empty. Without any reading. The part ranging from 15ºC to 20ºC and from 40% and 50%. Most of the readings in this tolerated range are concentrated on the upper and right part. The north-eastern part. The part ranging from 20ºC to 25ºC and from 50% and 60%. This is repeating it as a pattern. It means that the interior of the pavilion it is a perfect place to have a dry environment when the temperatures are high, although when the temperatures decrease, the humidity increase. This is the reason there is a blank on the south-western part of the ideal range.
The other fact extracted from the graphs is that most of the readings, in general, are over 60% of relative humidity and in cold temperatures. No more than 15ºC.

The exterior sensor, also has been studied and what can be extracted from it, is that the temperature ranges from -10 ºC to 35 ºC with a relative humidity from 20 % to 100 % with a thick lineal decreasing trend. From the cloud of points can be seen a trend almost lineal going from the north-western part to the south-eastern part of the graph. It indicates that, at the exterior, the lower relative humidity values match with the higher temperatures and vice versa, with higher values of relative humidity, the temperature values are lowers. It is due to the H-X diagram theory. The cold air it is not able to absorb as much water as the hot air, this is the reason that with the same amount of water (specific humidity), depending of the temperature, the relative humidity will increase or decrease oppositely to the temperature.

In this points cloud, it can be seen two big mass of points. Two regions where the vast majority of the points are concentrated. The first one, and the most important in terms of density, is located in the south-eastern part of the point cloud. More or less on the range in between 0ºC to 10ºC and between 70% to 90% of relative humidity. The second big region in terms of population of points is located on the upper part of the point cloud on the western part. On the range between 20ºC to 30ºC and 30% to 50% of relative humidity. It is shown on the graph bellow, where the two-arrow head line represents the trend and the squares, the two big regions in terms of readings:

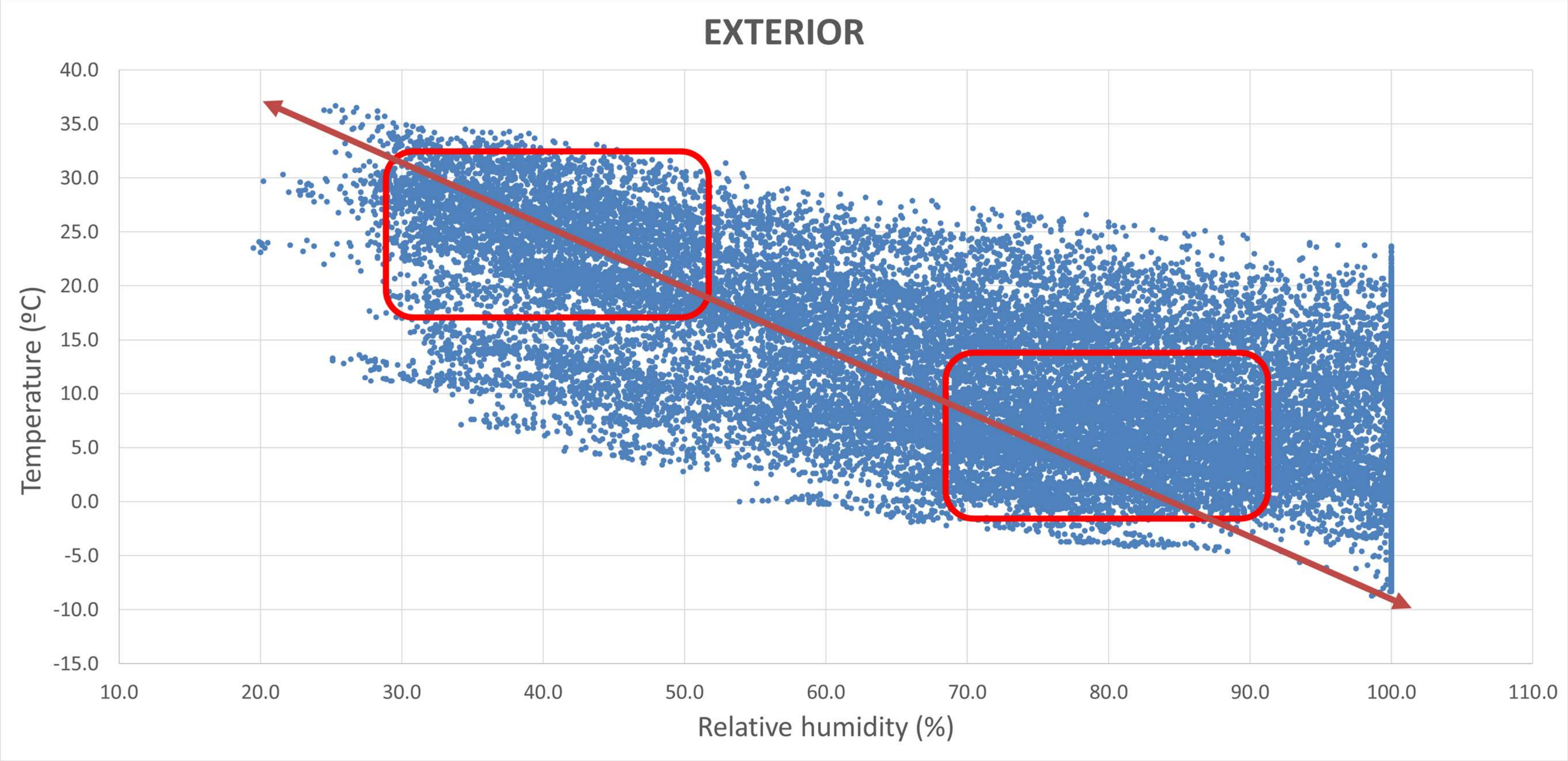

Figure 15 - Point cloud. Exterior sensor plot as Temperature against relative humidity along one year (01/02/2017 - 31/01/2018)

From the graph above and in comparison, with the rest of the graphs of the interior sensors, can be concluded that the point cloud has the same shape in all the sensors. It means that the exterior climate affects directly to the interior environment of the building. Can be noticed the same shape, but also, the same trend and the same location of the most populated regions. It ensures the theory of the direct correlation of the exterior and interior climate.

To support the text above, the graphs of Temperature (ºC) against Relative Humidity (RH) trend of two different sensors have been compared with the external climate conditions to try to find how directly affects to the interior conditions and, in affirmative case, if there is some difference in between the sensors. It is supposed, due to the humidity and temperature behaviour, that the upper sensors must be more affected by the external conditions than the lower ones. Thus, the two sensors chosen to compare their results with the external results are the sensor number 8 and 3. Both of them in the interior of the pavilion, but one located in the lower part (S3) and the other on the upper part (S8).

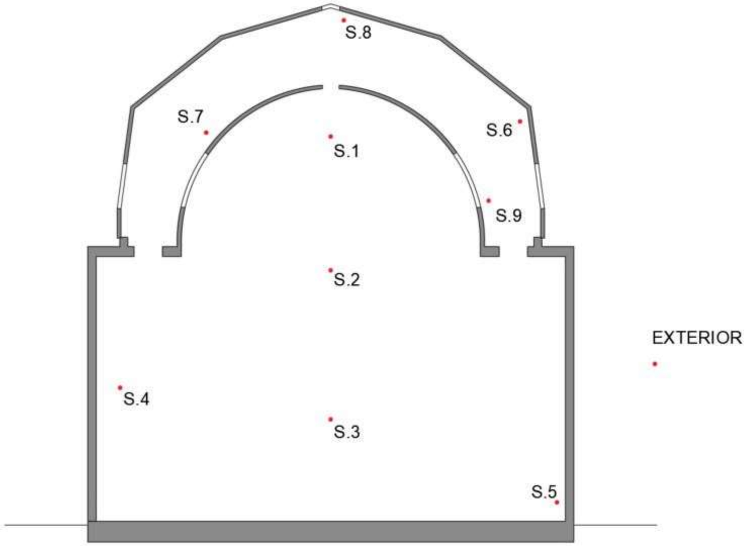

Figure 16 - Distribution of the different sensors. (Sensor 1: interior hanging on top; Sensor 2: interior hanging in the middle; Sensor 3: interior hanging down; Sensor 4: interior south door; Sensor 5: interior east side down; Sensor 6: space between the two vaults north; Sensor 7: space between the two vaults south; Sensor 8: space between the two vaults on top; Sensor 9: space between the two vaults next to the window)

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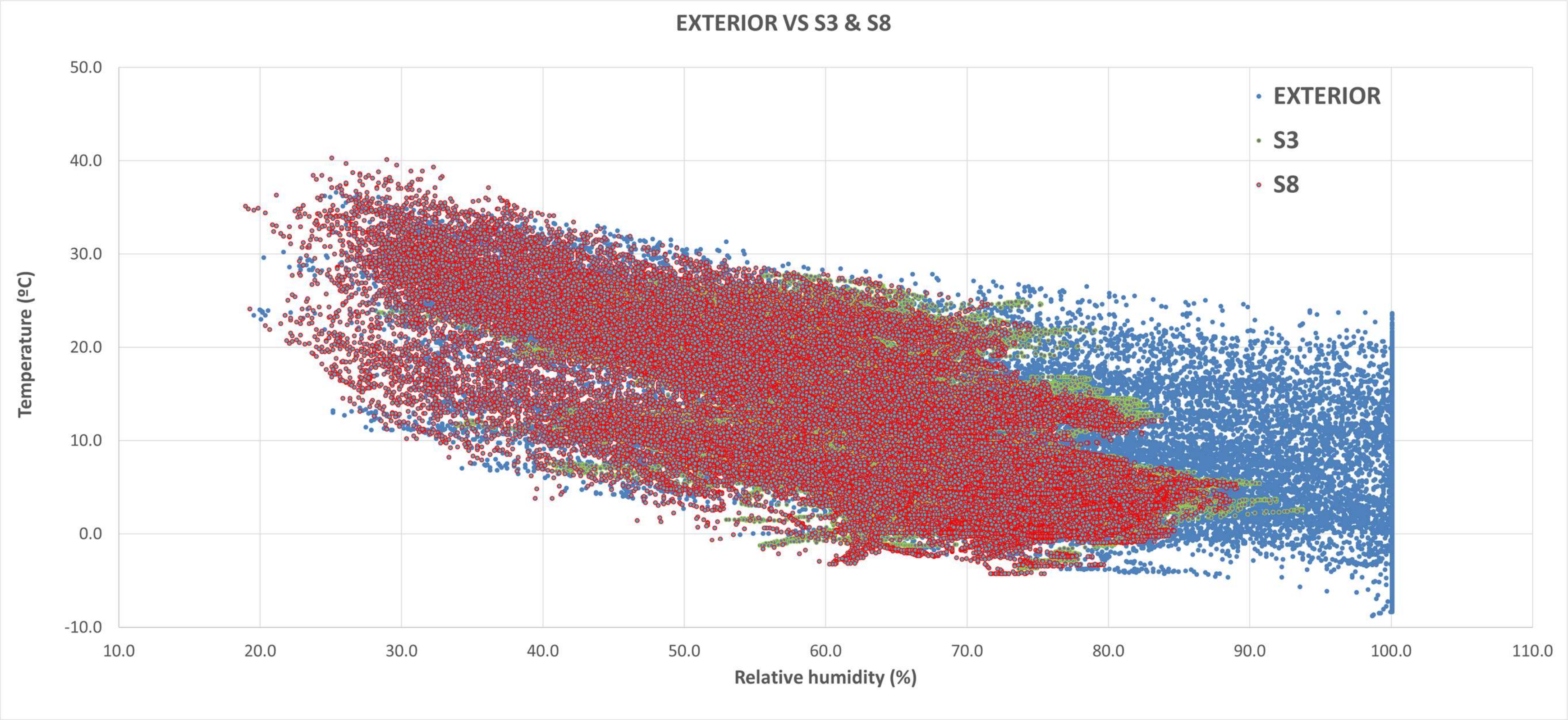


Figure 17 - Comparison graph between the climate conditions (Temperature against Relative humidity) recorded at the exterior and sensor 3 and sensor 8

Taking into account that the red point cloud it references the sensor number 8 readings and the green one it does it for the sensor number 3, it is clearly seen that in comparison with the blue one, which it is the cloud point referencing to the exterior readings, as it was expected the upper sensor (sensor number 8) it is much more influenced by the external climate conditions (Temperature and Relative Humidity) than the lower one (sensor number 3).

At the exterior, it reaches high relative humidity values. More than 80%, values unreachable for any sensor (even the number 8 which it is located closer to the exterior than the number 3 and upper), but either in small values of relative humidity and in high temperature values, the trend of the sensor number 8 it is really equal to the external conditions or, at least, much more similar than the sensor number 3 values. It can be seen that the sensor number 3 has a small amount of values bellow to 40% of relative humidity, meanwhile at the exterior it is easy reached much smaller values and it is followed by the sensor number 8 readings. Even, one of the biggest point concentrations it can be found (at the north-western part of the graph), it is equally built by both recordings (sensor number 8 and exterior).

The conclusion can be extracted from this graph; thus, it is that the sensors closer to the exterior, are much more sensitives to the external variations in terms of climate parameters. It is because of the proximity, but also due to the location of them into the building. The upper part, it is more sensitive to host bigger amounts of specific humidity.

This first brief overview of the data has been useful in order to understand the gross location of the climatic conditions in one year.

Independently of the sensor studied and also of the season or period of the year, from this first overview can be concluded that in every sensor (1 to 9), the vast majority of the readings are out of the tolerated range (15ºC-25ºC and 40%-60%). One of the most interesting way to show this statement is dividing the entire year into cold and warm period and analyse, in this way, when (what period) has more readings inside the tolerated range. Three reference graphs have been chosen in order to show the difference in between the cold and the hot months (cold months = October to April; hot months = May to September) The graphs chosen, have been the sensor number 1, 3 and 8. In order to show how varies the location of the dots depending the location of the sensor. One of them on the bottom, the other on the upper part of the vault and the last one, located on the upper part of the second vault. On the graphs bellow can be seen the three representative graphs dividing the year in between cold months and hot months:

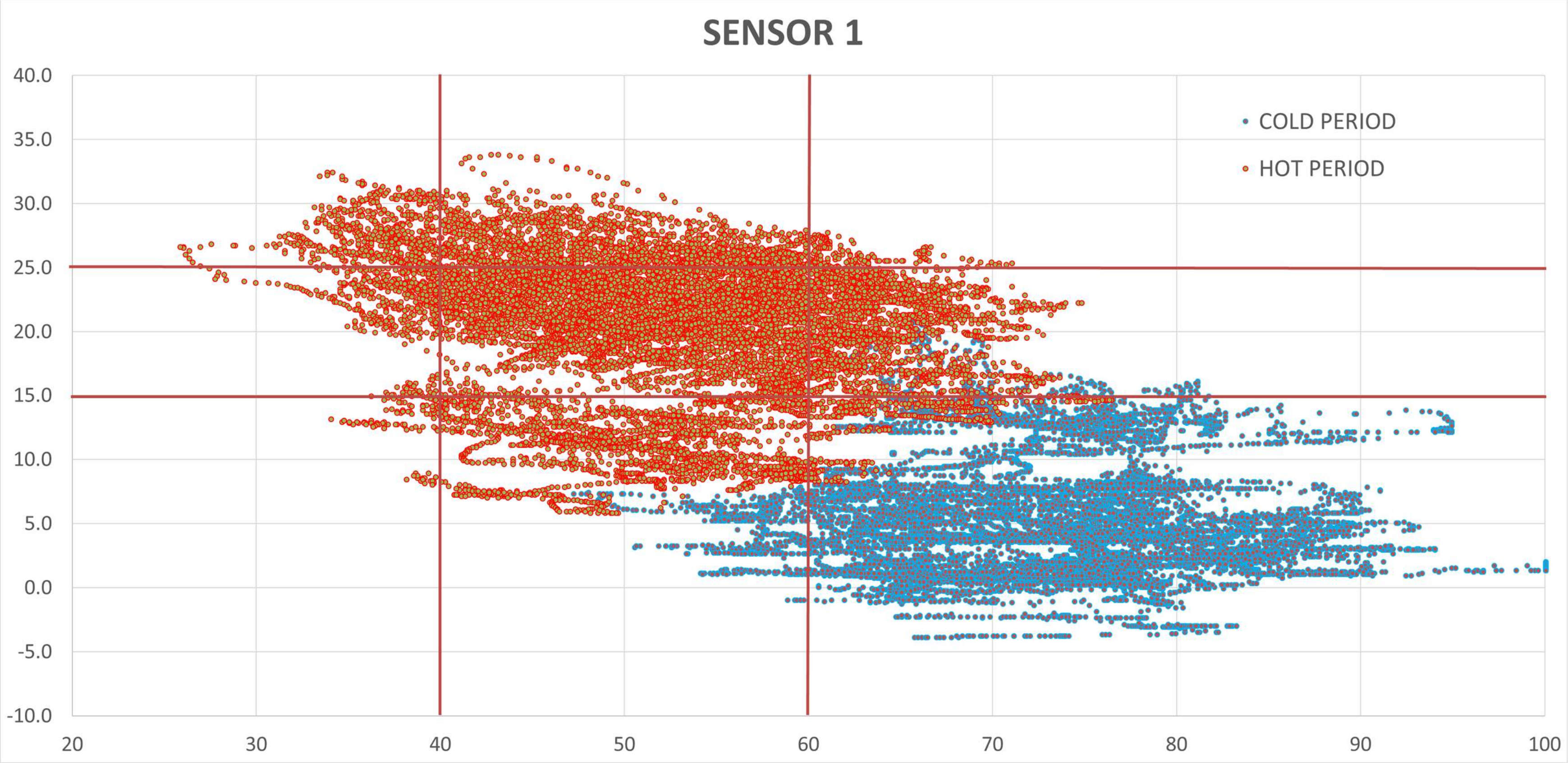


Figure 18 - Sensor number 1 showing the amount of readings into the tolerated range in the cold period, versus the amount of readings out of the tolerated range in the hot period

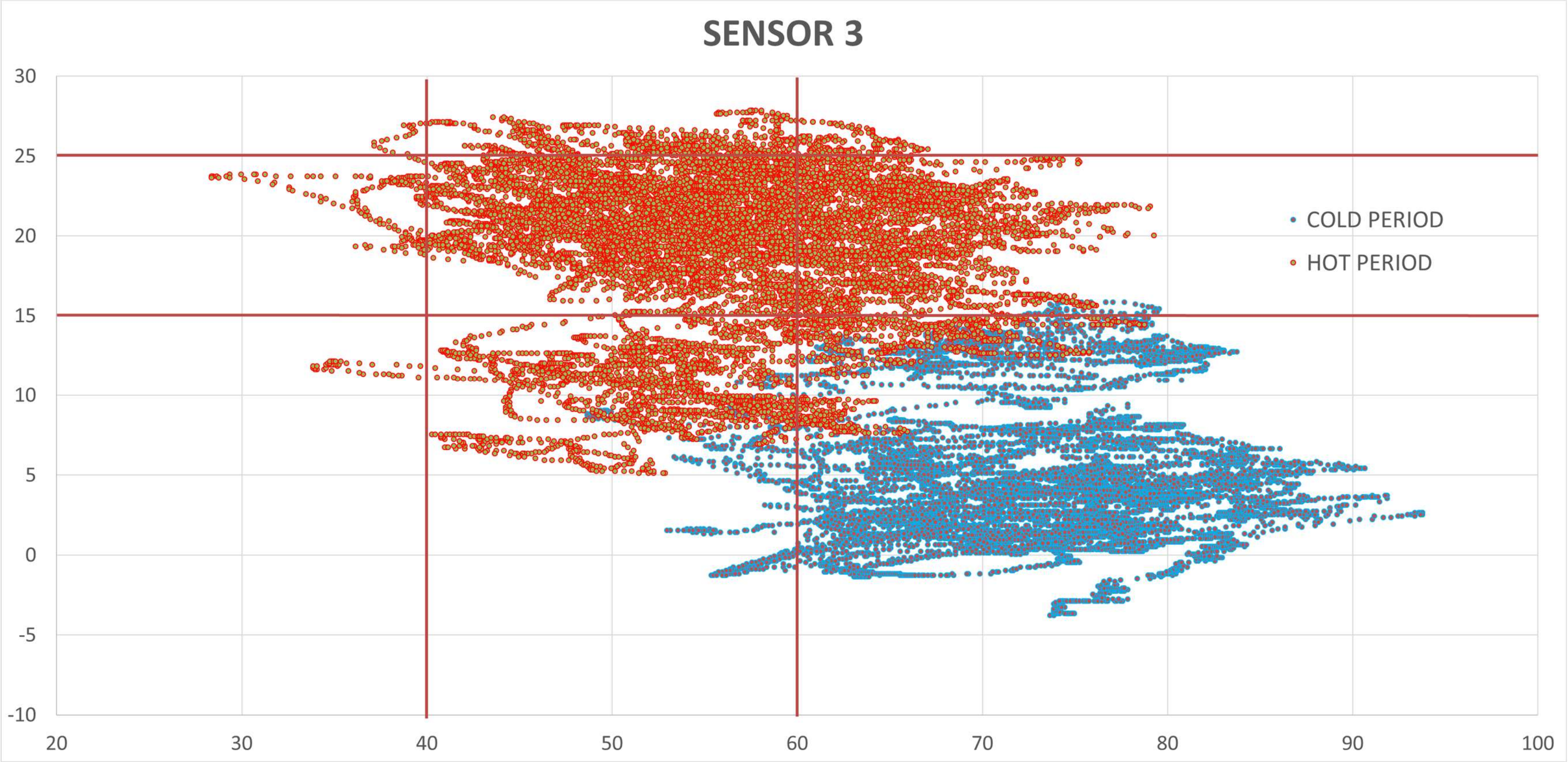


Figure 19 - Sensor number 3 showing the amount of readings into the tolerated range in the cold period, versus the amount of readings out of the tolerated range in the hot period

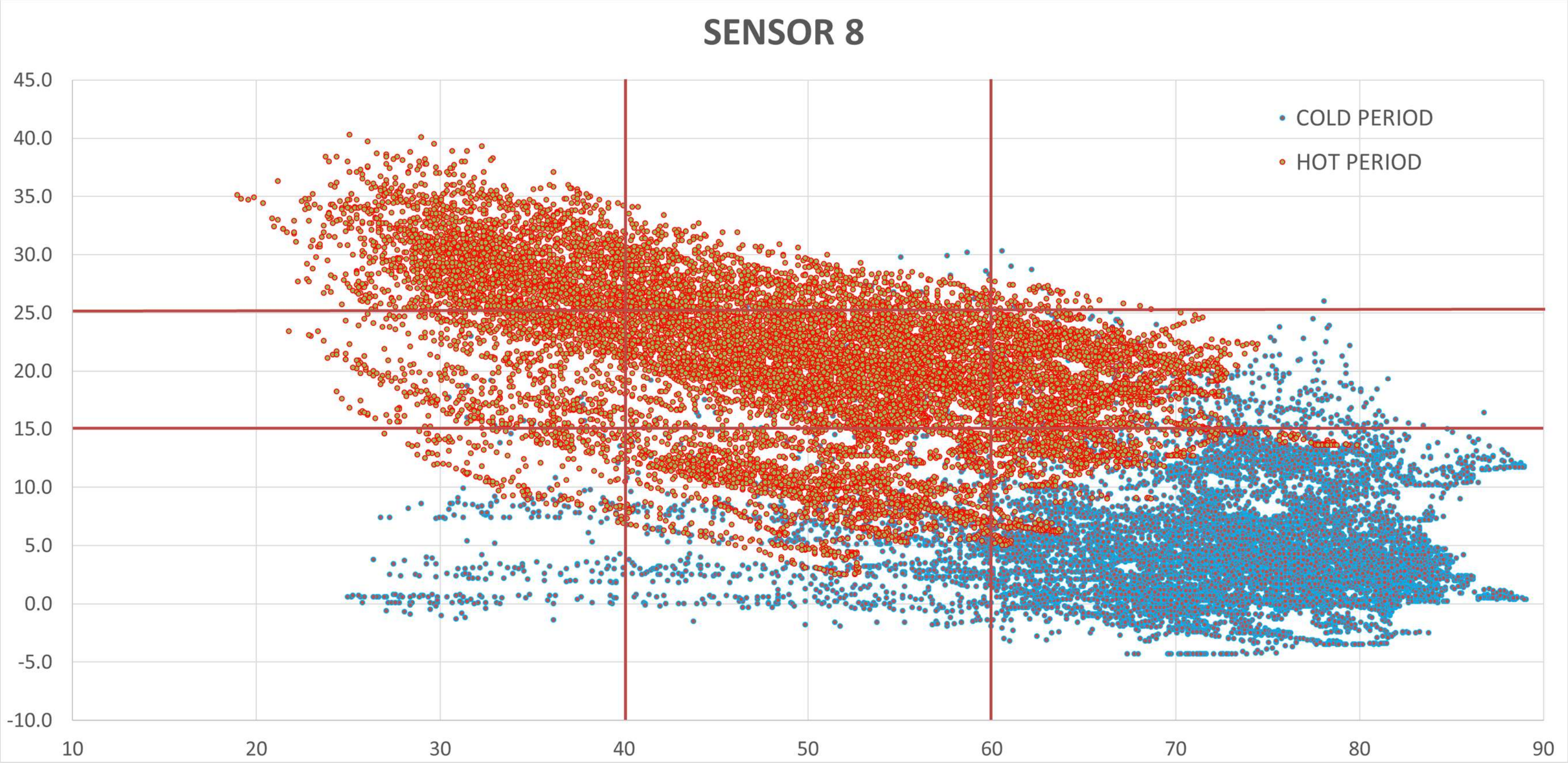


Figure 20 - Sensor number 8 showing the amount of readings into the tolerated range in the cold period, versus the amount of readings out of the tolerated range in the hot period

Then, the conclusion it is that the hot period of the year, from the middle of the spring until the end of summer, some readings are into the tolerated range, meanwhile in the cold period: autumn and winter and even the beginning of the spring, all the dots are out of the tolerated range.

It can be concluded that the perfect period for the natural preservation of the fresco it is on the warmer months, but just in some moments of the day. If the temperature it is too high, the conditions are bad as well. This is the reason why in summer time, there are some hours (specially not on the peaks) where the conditions are optimal.

Highlighting the difference in between the sensors, can be noticed, as well, that the sensor number 8 it is much more sensitive to the external variations; due to its position into the building. It can be seen on the north-western part of the graph where the dots from the hot period of the year reach higher temperatures than the other sensors. It is due to the fact that the envelopment it is not too protective.

In comparison with the other sensors, can be seen, as well, that the two extremes sensors (3 and 8), have a dots cloud shape much more extruded, meanwhile the middle one (sensor number 1) it has a softer shape. It means that perhaps the exterior variations are strong or quick, inside, the same variations are difficult to be felt. The more interior, the better. The fresco, it is not located just on the exterior skin, but it is not located on the middle of the building, neither, where the conditions will be much better or less painful.

3.2. Tolerated range trend

The first part of the conclusions, related with the temperature and relative humidity of every sensor along the year, explain just a raw overview of the readings due to the lack of dates. In order to go deeper into details (dates), the second data treatment has been performed. In this case, every sensor has been studied for every single reading (every 15 minutes) in order to find the moment of the day and/or the period of the year when the relative humidity and the temperature are into the tolerated range (15ºC – 25ºC and 40% - 60%). The idea is to find a common trend on a chronology line.

In order to draw the trend along the year in relation with the ideal range values, two numbers have been linked to two different approaches. Number 0 means that both parameters (temperature and relative humidity) are into the ideal range. Number 10 means that there is no match: one of the values or even, both of them, are out of range. It means that in this period of the year or the day, the climate conditions are not good for the fresco.

The graph bellow shows the average of all the values have been taken during each month, assuming, so, that when the values are lower, means that the vast majority of the numbers (average) are 0 instead of 10, which it means that the conditions are good. On the opposite site, if the trend reaches values close to 10, means that the vast majority of the numbers are 10, which means that the conditions in this period are not the best ones.

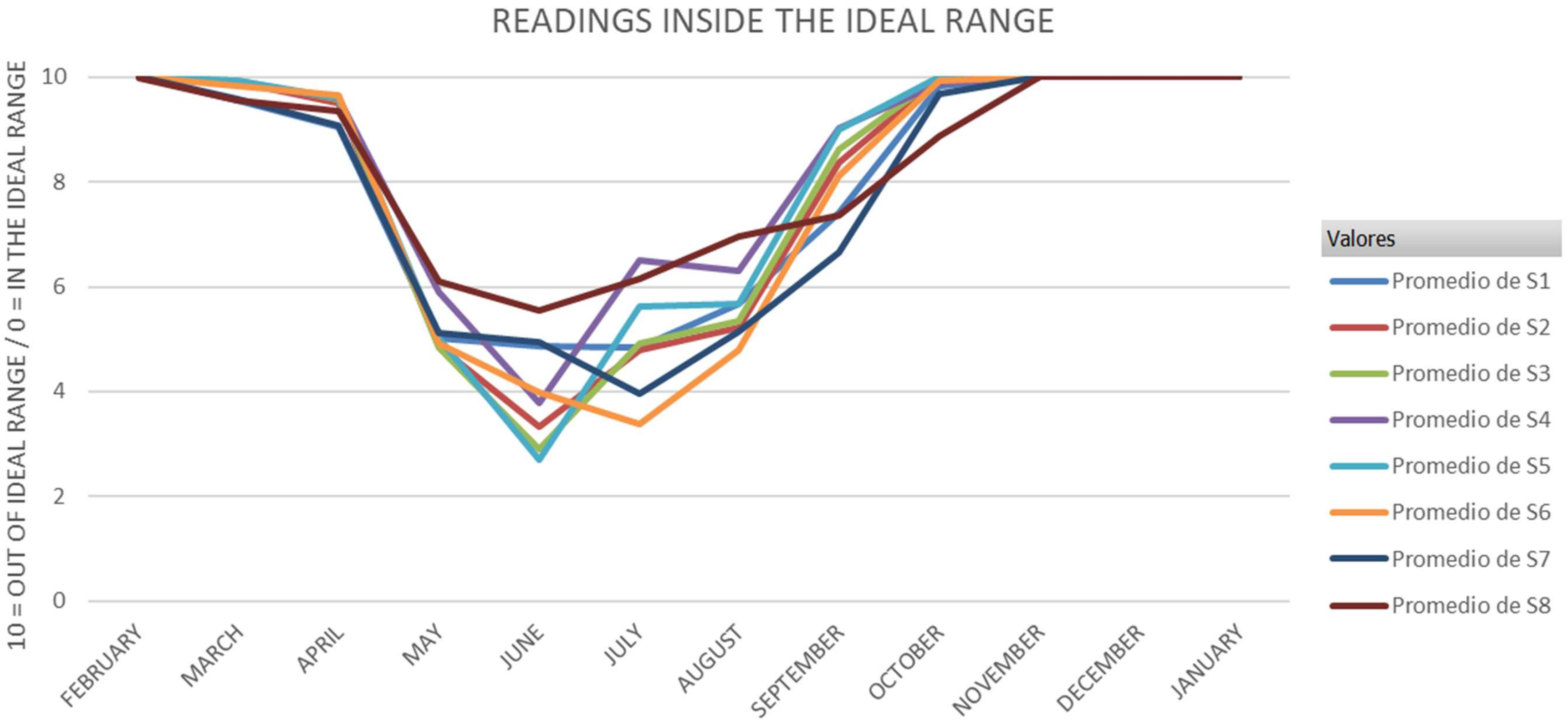


Figure 21 - Readings inside the ideal range along the year per each sensor. (Sensor 1: interior hanging on top; Sensor 2: interior hanging in the middle; Sensor 3: interior hanging down; Sensor 4: interior south door; Sensor 5: interior east side down; Sensor 6: space between the two vaults north; Sensor 7: space between the two vaults south; Sensor 8: space between the two vaults on top; Sensor 9: space between the two vaults next to the window)

What can be extracted from the graph above is that, independently of the sensor, all the trend follows the same rule. From the beginning of April until the end of August (the worm months), the vast majority of the readings are 0, which means that both parameters are good, thus the interior environment it is found into the tolerated range; while the rest of the year, from September to March (the cold months), the vast majority of the readings are 10, which means that either one of the parameters or even both of them are out of the tolerated range, thus the environment it is not in the perfect conditions for the preservation of the fresco.

It is important, also, highlight the differences in between sensors. Perhaps all of them follow the same pattern, going into details, can be noticed, as well, the different shape of the trends. There are some trends having a softer curve and another with a sharper curve. The reason it is the same explained on the point number 4.1. The location of the sensors and the sensitivity of the building to the external climate. Continuing with the same explanation, can be seen that the curves with the peaks closer to 0 (the sharpest ones) are the ones which have more good readings on the hot period, meanwhile the ones with softer curves are the ones with worst readings on the same period. Analysing the shape of the curves with the location of the sensors, can be seen, thus, a common pattern. The curves from the sensors closer to the exterior, are softer than the curves from the sensors on the middle of the building. The reason, again, it is the same than in the point number 4.1.

The best example to demonstrate it, again, goes through to the sensors number 8 and 3. On the graph number XXX are plot as a garnet line (S8) and green line (S3). It is clearly seen that the green line (S3) at the warmer months it is sharper, then, the vast majority of the reading are 0, then, the vast majority of the moments of the day are acceptable for the natural preservation of the fresco. On the other hand, the garnet line it is much softer and its average at the hottest months it is close to 6, which it means that more than 50% of the readings are 10, then, more than 50% of the readings are not into the tolerated range. Again, with this example, it is demonstrated that the position of the fresco it is so important because it is much more exposed to the climate variations from the exterior.

To summarize, what is needed, generally speaking, is increase the temperature and dry the air to try to replicate the spring-summer weather or give another envelope to the building in order to protect better the fresco, giving to the current location better environmental conditions.

3.3. Humidity trend

Another output that can be studied from the raw data it is the humidity trend. How the humidity flow behaves along the year. To analyse it, has been plot a graph showing the level of relative humidity against the dates. The year has been divided in half month marks and the data has been smoothed, daily. The line has been smoothed by using the average of the level of humidity of the day. In this way, the behaviour along the year can be studied without give much importance to the daily changes, which will be studied later on. This analysis has been carried out for every single sensor plus the exterior one. The data of the exterior sensor has been included in order to make it easier to compare them and to study its repercussion. The exterior climatic conditions are so important in order to understand the interior behaviour of the pavilion in terms of internal environment.

In the graph bellow it is shown the humidity trend along the year for the different sensors:

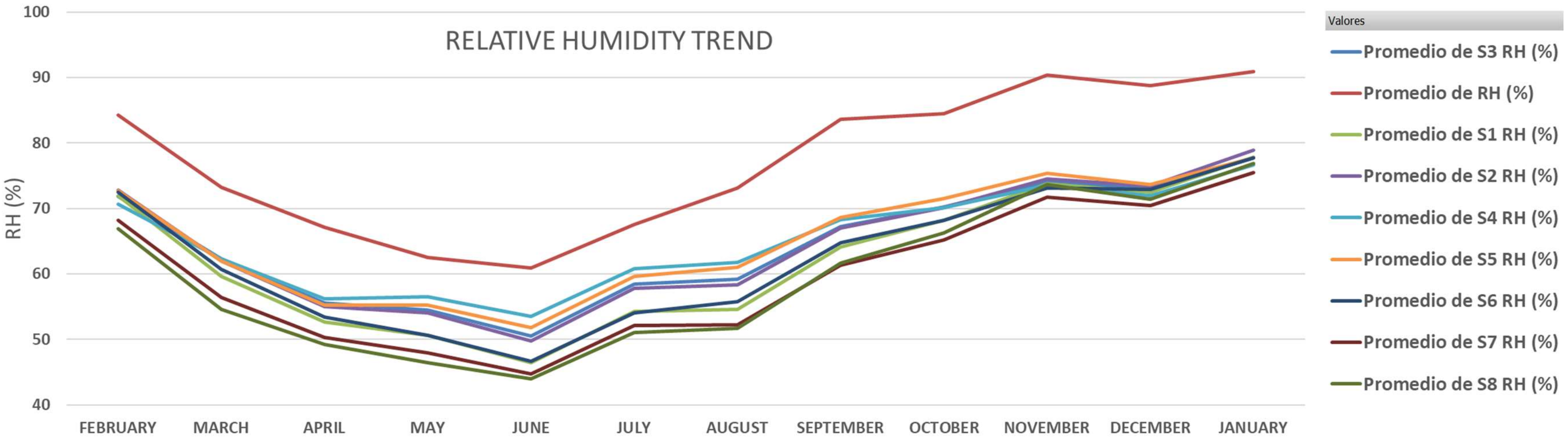


Figure 22 - RH trend along the year. (Exterior sensor; Sensor 1: interior hanging on top; Sensor 2: interior hanging in the middle; Sensor 3: interior hanging down; Sensor 4: interior south door; Sensor 5: interior east side down; Sensor 6: space between the two vaults north; Sensor 7: space between the two vaults south; Sensor 8: space between the two vaults on top; Sensor 9: space between the two vaults next to the window)

From the analysis of the figure above, can be seen that the relative humidity range between 40% to 100% along the year. Bellow of 40% there are no readings, with the exception of the sensor number 9, which has suffered some technical problems and must be avoid.

Another conclusion that can be extracted from the figure above is that from the second half of march, until the end of august (more or less), the relative humidity has lower values and range in between smaller waves (smaller range), going, the vast majority, from 40% to 75%.

On the colder months, the range is bigger and the relative humidity values also; going from 60% to 100%. It is due to the matter of the air and its capacity to absorb more humidity in higher temperatures (specific humidity). Then, if the temperature are lowers, the range of the relative humidity will be bigger. It is clearly seen on the graph bellow:

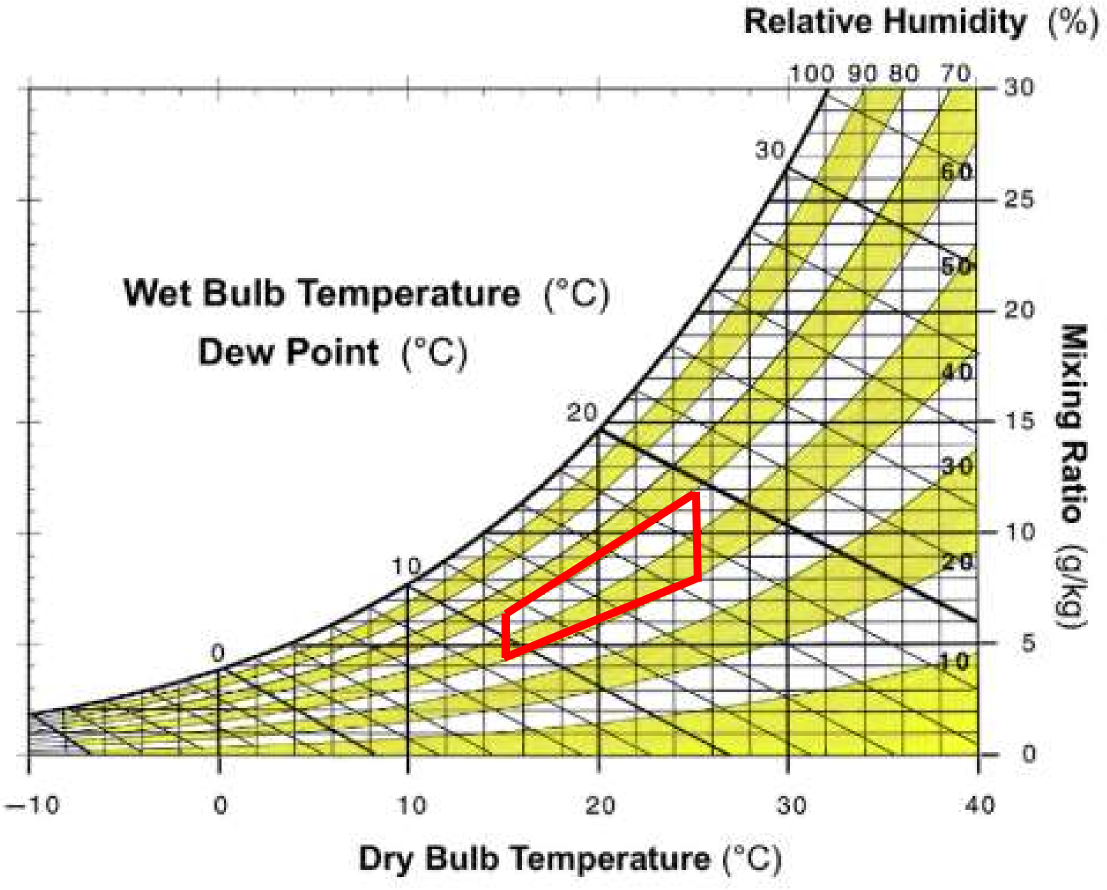


Figure 23 - The psychrometric chart with the tolerated range highlighted

To conclude, from this analysis can be assumed that, the spring-summer period is the unique one which has values ranging on the ideal scope in terms of humidity. It is clearly seen that the coldest months, there is no single value into the tolerated area.

On the case of using a real weather or climate period as a model, the spring-summer climate must be replicated.

3.4. CRITICAL FLUCTUATION (HUMIDITY DRASTIC VARIATIONS)

Another interesting output to study from the raw data is the daily variations in terms of humidity. As it has been seen before, a humidity values out of the range of 40% to 60% is not really good for the preservation of the fresco, but what can be even worst for its integrity is the dramatically quick changes in terms of humidity. The fluctuation. One of the worst thinks can happen to a lime painting is that the climate surrounding it varies, in terms of humidity, more than 15% in a short period. For example, 24 hours.

For this reason, a treatment of the data has been developed in order to understand when it happen and where. This analysis has been carried out for every single sensor and it has been studied every 96 readings, which means every 24h. By using this function, what is found is the periods when it varies more than 15%.

The aim of these analysis it is end up with a common trend in terms of location. It has been studied in order to see if the different parts of the building behave equally with the humidity changes or there is a substantially variations and why. The other goal is to see if there is a common trend in terms of chronology. Time. It is interesting to see when appears drastic humidity variations and why. If there is a common period of the year when the humidity varies drastically it is interesting find it. The hope of this analysis is find clear conclusions. The following figure shows the dangerous variations of humidity along the year in every single sensor:

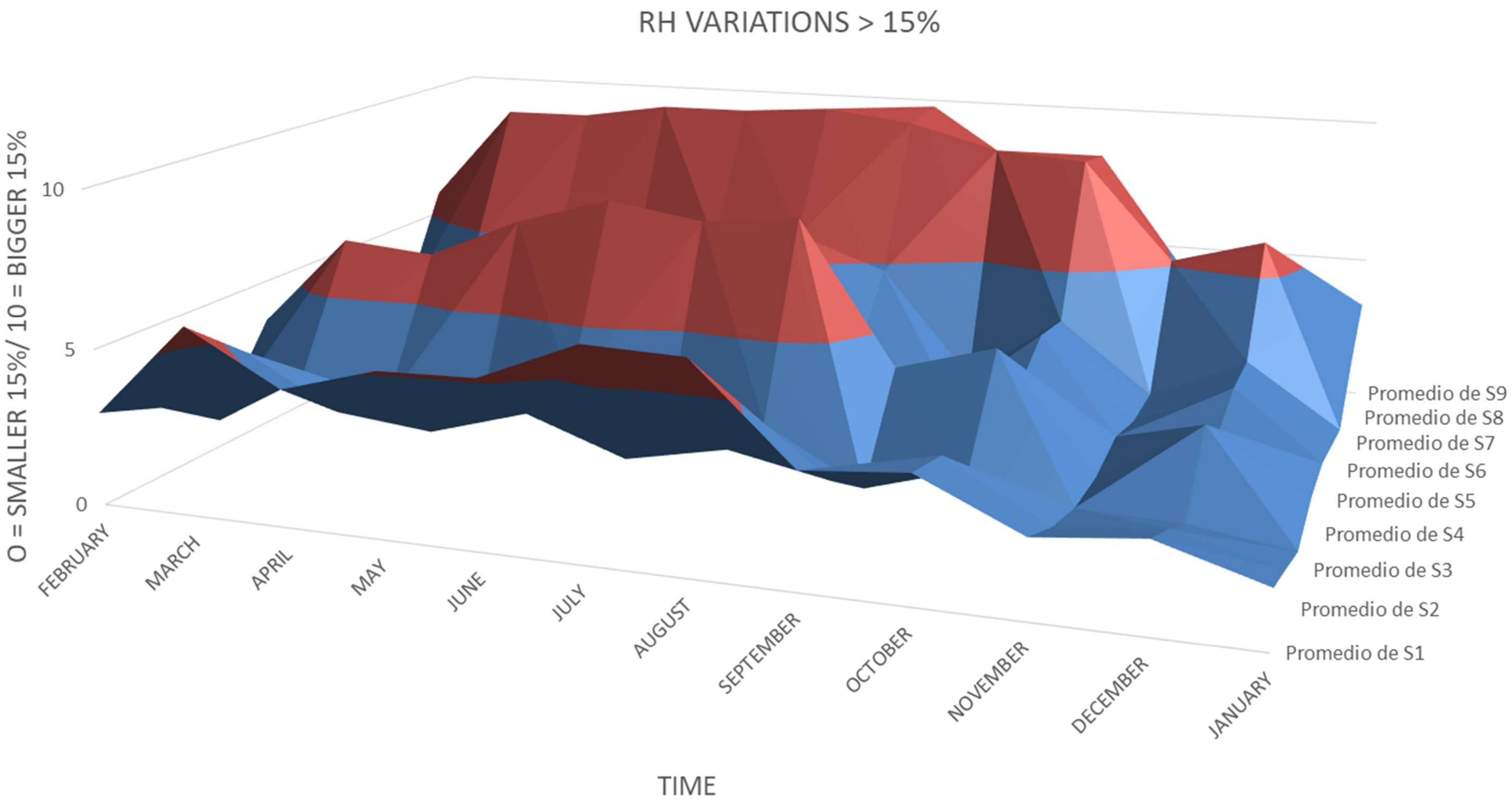


Figure 24 - Drastic and quick variations of the relative humidity along the year per sensor

On the graph above can be seen a scale from 0 to 10 on the left axe. This scale it is created to distinguish the critical variations in terms of relative humidity. The variations bigger than 15% in a time period of 24h it is appointed by the number 10 and it is plot as a red colour. The variations smaller than 15% in periods of 24h are appointed by the number 0 and plot as a blue colour. Then, to plot the graph it is made by an average value between 0 and 10 (the two unique possible numbers of the results). Obviously, by using this method, the outputs will range in between these two numbers, that is why it is shown on the graph the number 5 which represents the middle. The 50%. The way to understand the graph above, thus, it is that if the peaks are red, it means that more than 50% of the readings are bad or into the critical fluctuations, but if the peaks are blue, less than 50% of the readings are acceptable. It does not mean that the blue peaks readings have no variations above 15%, but the vast majority of its variations are not critical.

Following these conditions, so, can be seen on the graph above that all the sensor have a kind of same behaviour along the year. From April to August, talking in gross dates, is when the variations of the relative humidity are quicker. Quick enough to damage the fresco. On the other hand, the cold months (from the end of August until the end of January or even middle February), the changes in terms of relative humidity are either less than 15% or slow enough to consider acceptable for the fresco preservation. It can be seen on the graph number 24 where, for all the sensors, there is not a single red peak. The explanation of these phenomena is that in the spring and summer time, the climate changes at the exterior are bigger. The relative humidity variation has a bigger range and the micro climate inside the pavilion it takes much more time to equate the exterior one and it provokes material damages.

Another interesting phenomenon that can be extracted from the previous graph is that on the sensor number 2 and 3 there is no a single red peak. It means that either there are no changes bigger than 15% in periods of 24h during the whole year or there are too few. This fact is pretty interesting. The micro climate environment of the pavilion it has a perfect behaviour where these sensors are located if it is studied into details. The same fact happens with the sensors number 5. The reason it is again the same than before. The sensor number 5 it has much less external climate influence because its location. The sensor number 5, as it can be seen on the figure number 16, it is located on a low corner, almost on the floor, exactly where before has been concluded that the influence of the humidity it is much lower.

In the opposite situation, the sensors number 1, 4 and 8 are the ones with more records with dangerous peaks. Peaks with humidity changes bigger than 15% in periods of 24h. The reason of this phenomena is the location. The ones suffering more variations are the sensors just next to the building walls and the sensitivity of them is higher.

It is shown on the following graph:

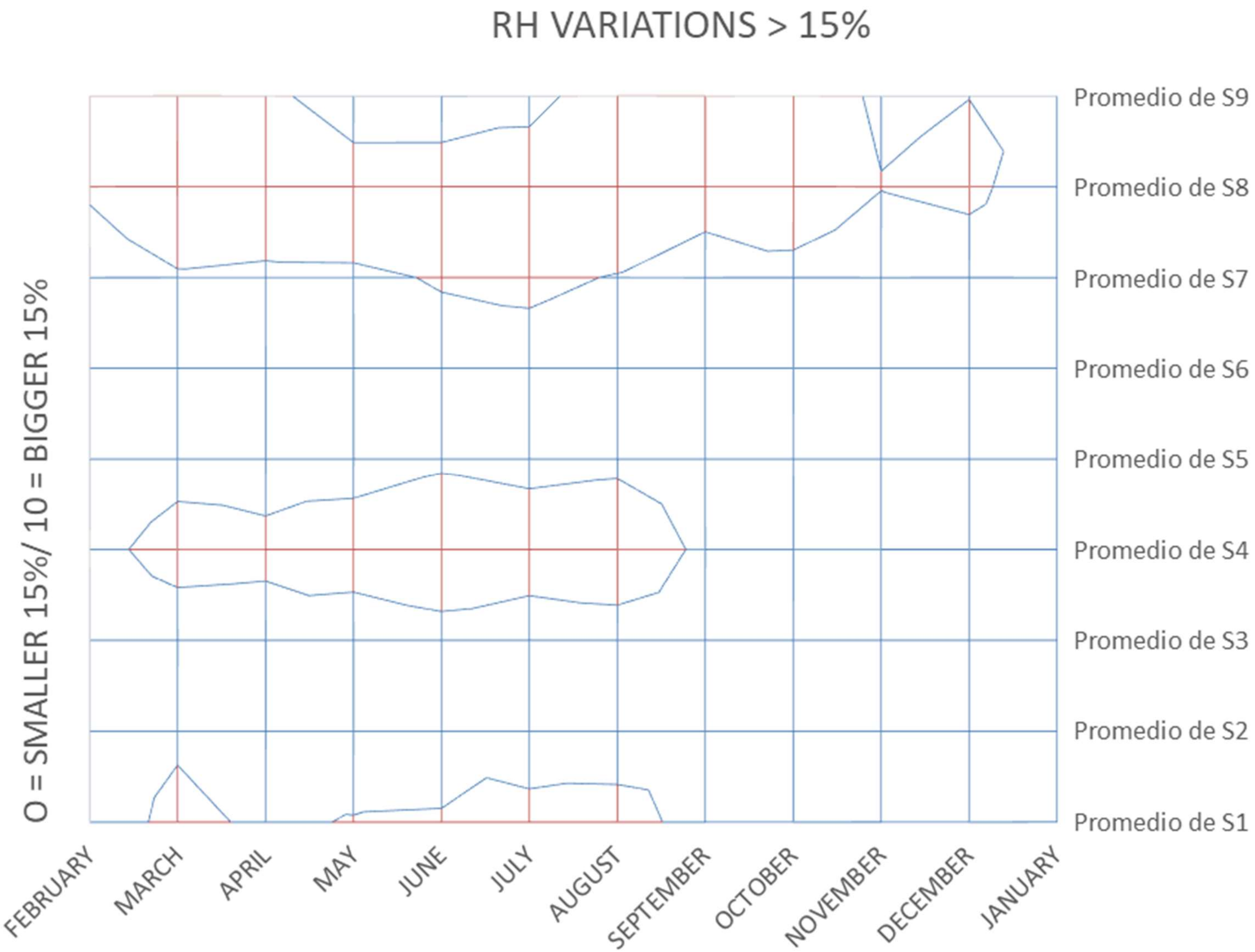


Figure 25 - Drastic and quick variations of the relative humidity along the year per sensor. Top view

The first part of the air fluctuation data analysis has been focused in the overview of the interior environment behaviour along the year. But it has been extracted, also, that depending of the period of the year and also the part of the building the records have been taken, the results can vary substantially and it can be extracted a common trend. This is the reason the following graphs are going to analyse the variations in terms of relative humidity per sensor; showing when appear the drastic variations, higher than 15%, along the year. The aim of these graphs it is to find a common trend in terms of the location of all of them.

It is expected, as could be lightly seen previously, that the sensors located on the upper part of the building have worst results than the ones are located on the bottom or lower parts. Also, the ones located closer to the envelope of the building.

The following graphs are showing, in red, the date when drastic humidity variations appear (>15%) and in green when the humidity is more stable (<15%). And also, the percentage of readings with bad results:

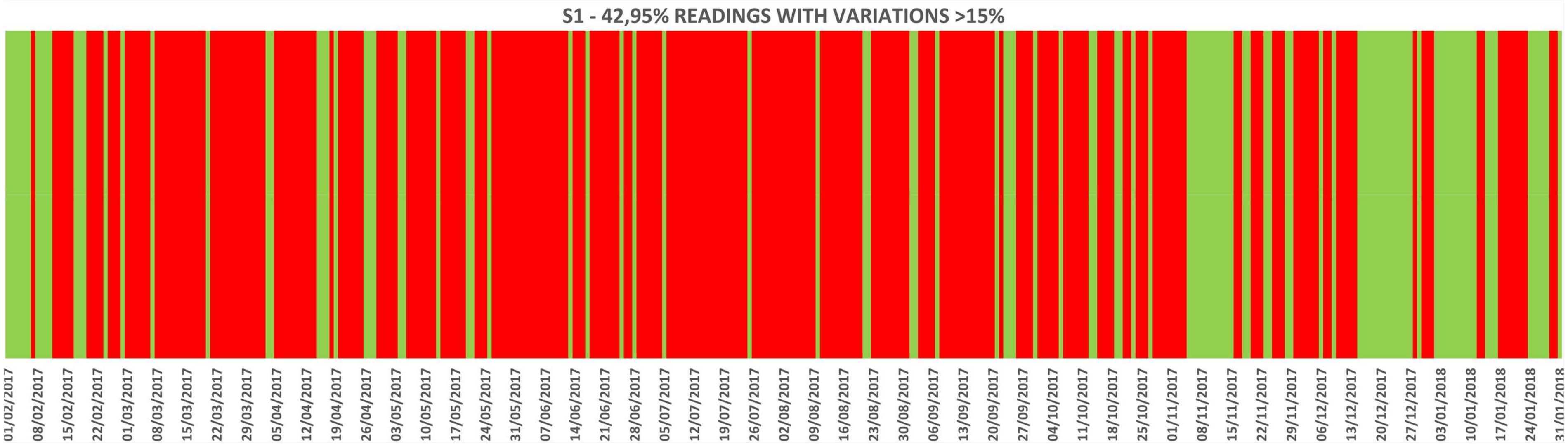


Figure 26 - Sensor 1. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

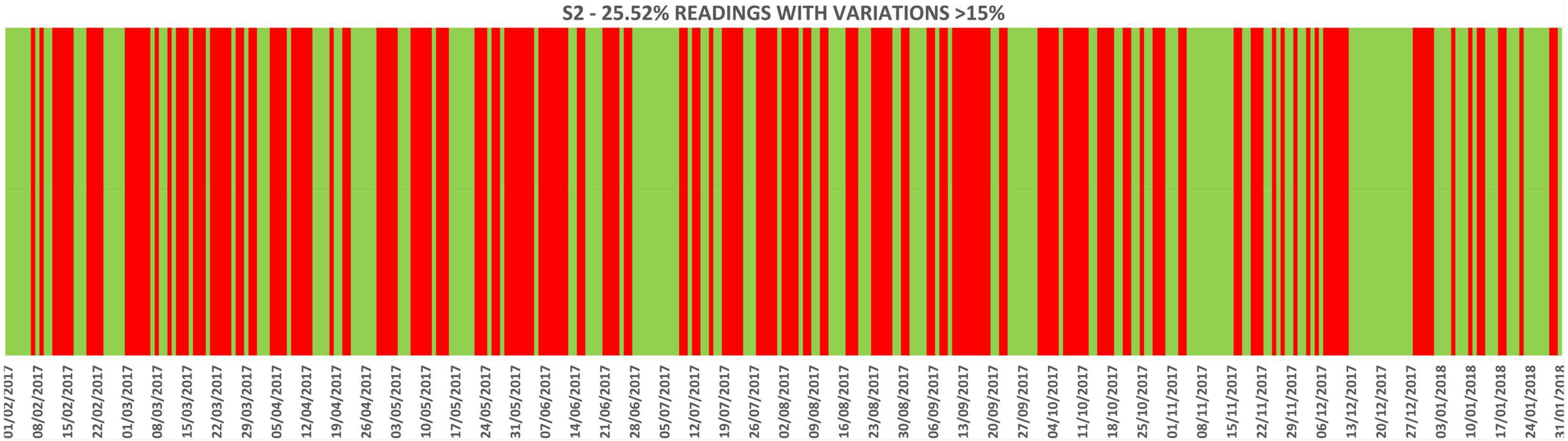


Figure 27 - Sensor 2. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

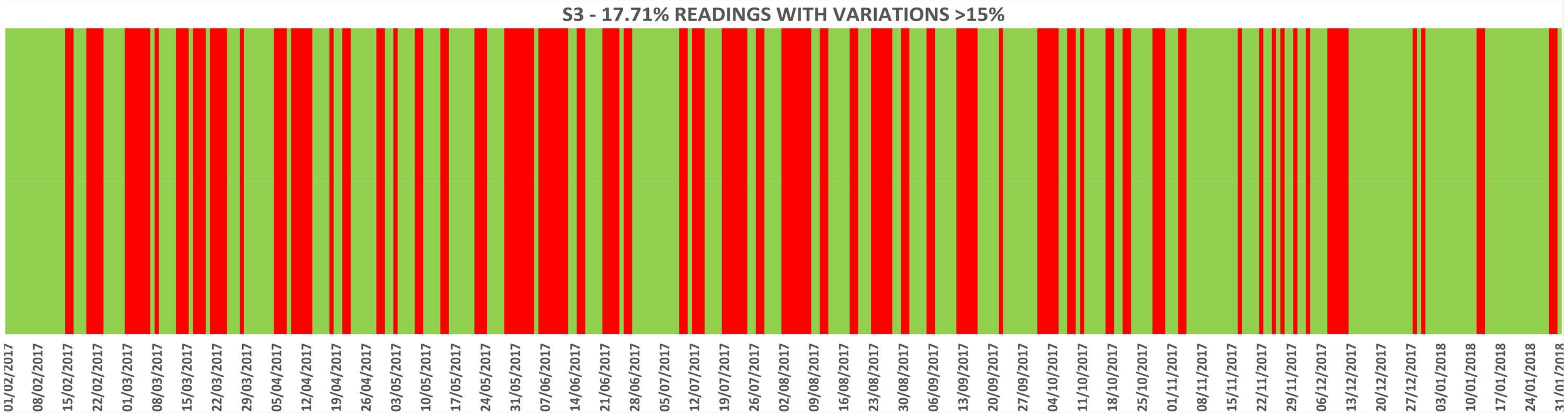


Figure 28 - Sensor 3. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

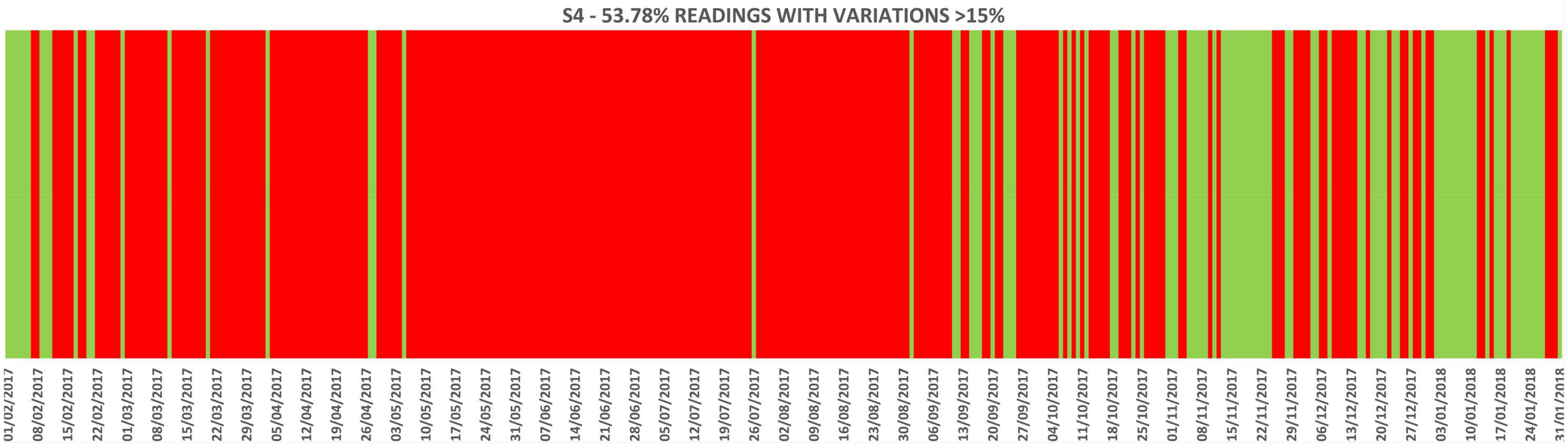


Figure 29 - Sensor 4. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

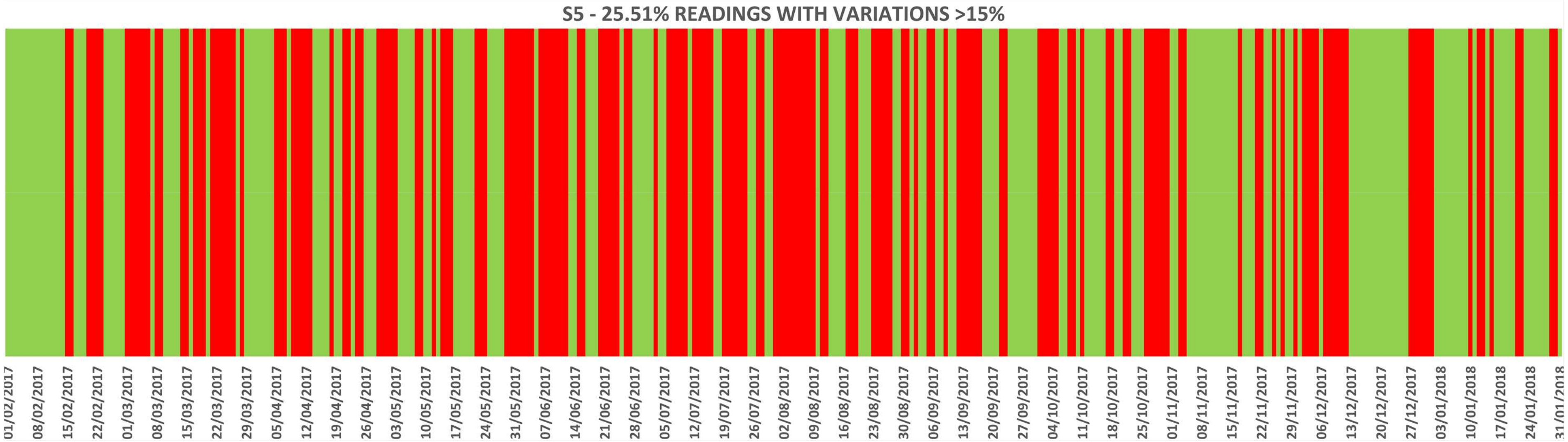


Figure 30 - Sensor 5. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

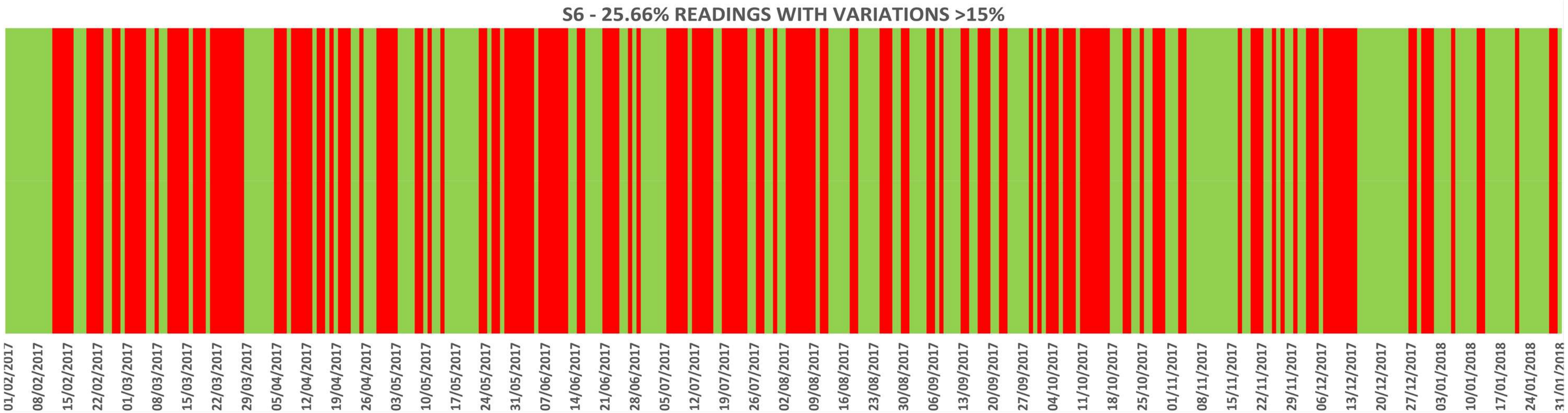


Figure 31 - Sensor 6. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

Figure 32 - Sensor 7. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

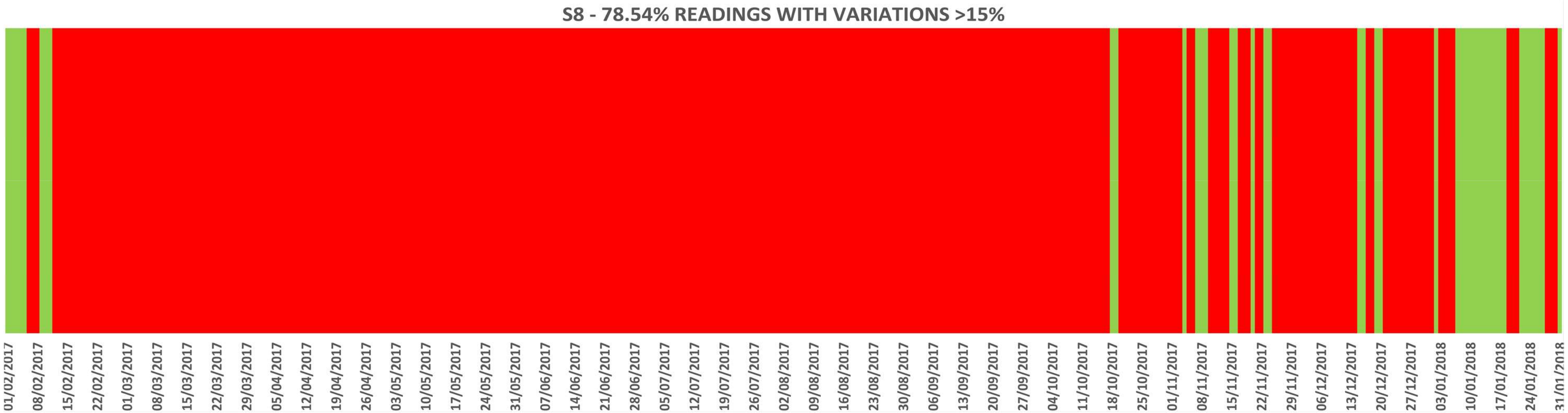


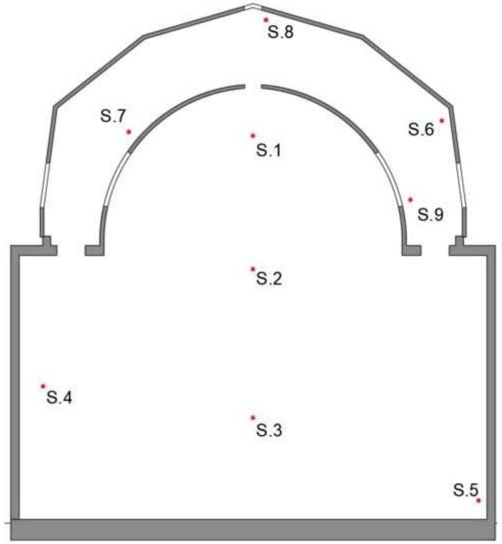
Figure 33 - Sensor 8. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%.

Figure 34 - Sensor 9. Time line with all the readings along the year with variations higher and smaller than 15% in terms of Relative humidity (RH). Green <15%; Red >15%. (There is a bad reading period into the general graph due to technical problems with the data logger)

The table below summarizes the percentages of good and bad readings (higher or lower than 15% of relative humidity variation) depending the sensor and its location. The information could be seen before, but synthetized in a table with a friendly sketch:

Table 2 - Informative sketch about the percentage of readings with RH variation above 15% per sensor. Readings every 15'

SENSOR	% Bad results
1	42.94
2	25.92
3	17.71
4	53.78
5	25.51
6	25.66
7	32.89
8	78.45
9	51.45



The major accumulation of bad readings is concentrated in spring-summer months. Besides it, in terms of location, it can be seen that the bigger percentages of bad results are concentrated on the higher location sensors. The lower percentages are on the bottom of the building and the higher ones are concentrated on the upper part. It is clearly seen with the centre ones. The sensors number 1, 2, 3 and 8 are located on the centre of the building and are aligned in between them. In this example can be perfectly seen that the sensor closer to the floor (S3) has the lowest percentage (17.71%) and the one which is closer to the roof (S8) has the highest percentage (78.45%). It is expected, so, that the dome has the worst conditions in terms of environment for the preservation of the fresco. Another conclusion can be extracted it is that, not just the upper sensors have worst results, but also the sensors closer to the envelopment.

Summarizing the information, can be concluded that the interior environment of the pavilion is substantially affected by the exterior one. Directly. Due to this direct affectation, the “warm” months are worst for the preservation of the fresco in terms of air fluctuation, but have better climate range and the locations of the pavilion which suffer more due to the humidity variations are the ones next to the wall.

4. CALIBRATION OF THE NUMERICAL MODEL

For the next step (the calibration of the model) the strategy followed has been to find the relation in between the numerical model and the reality, based on the exterior conditions. The real goal it is to find some days (or even weeks) where the climate conditions, in both realities, matches good enough. It means that the numerical model it is reproducing pretty good the reality.

To try to find these condition matches, two graphs have been developed. The first one, shown below (graph XXX), are the two trends together. The graphs itself, has on the Y axes the temperatures (ºC) and on the X axes, the dates. In this way, can be seen where the two temperature lines matches and can be extracted an idea if it is because of some climate matter. The blue line it reproduces the real exterior temperature. The red one, nevertheless, it reproduces the created reality via numerical model. So, where the two trends are matching together, it means that the conditions are equal in both realities: the real one and the created one. So is where the numerical model reproduces the best reality.

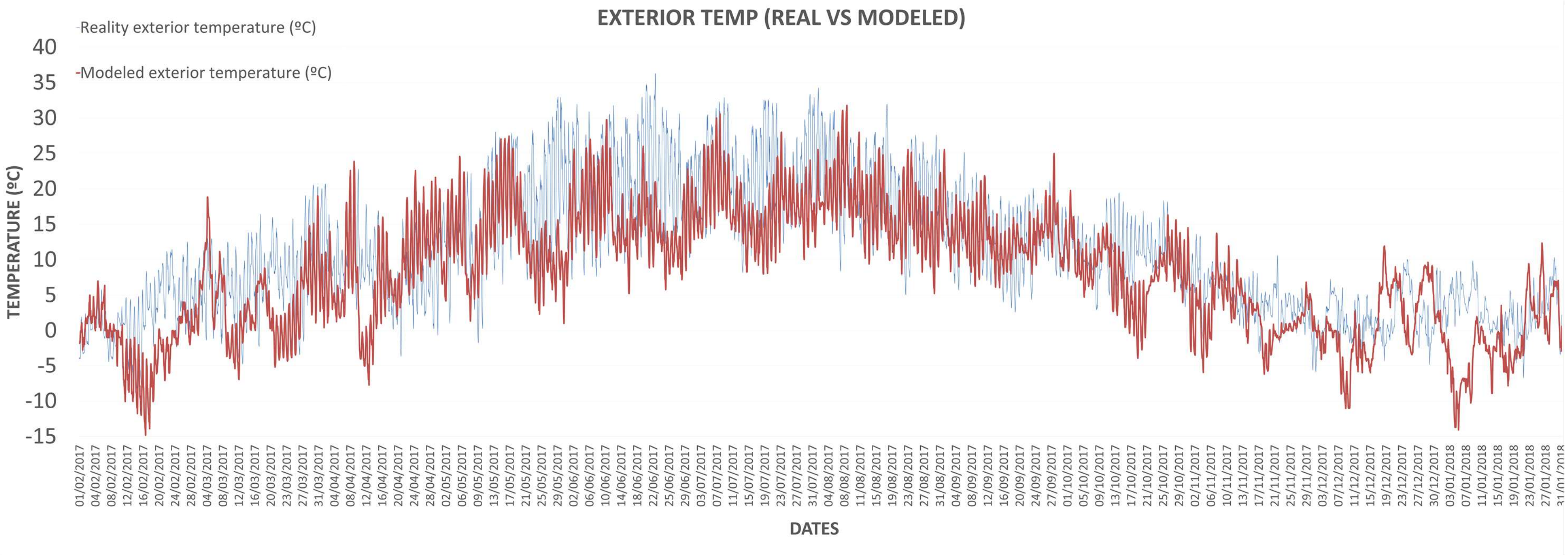


Figure 35 - Calibration graph. exterior real temperature VS exterior modelled temperature

As it can be seen in the figure above, there are some dates or some periods along the year where the two lines matches pretty good. Chronologically, the first period it can be found at the end of March and the beginning of April (28/03/2017 – 03/04/2018). The second period it is found on the middle of May (14/05/2017 – 19/05/2017). It keeps going by the beginning of June (06/06/2017 – 12/06/2017). The last short period of line matches it is found just after some weeks: at the beginning of July (05/07/2017 – 08/07/2017). After all of those short periods where both lines can find each other and move together with the same trend of temperature variation, it comes a larger period (12/08/2017 – 06/10/2017).

In this graph (two lines graph) it can be much more difficult to find the line matching, but making the difference in between them, it can be seen much easier. Where the results are 0 it means that there is no difference, so the numerical model matches perfectly with the reality. Where the difference it is close to 0 it will be accepted as a good model to reproduce the reality. On the periods where the divergence it is too much it will be considered as a bad model to calibrate it.

On the graph bellow (Graph XXX) it is shown the difference between the real temperature and the results:

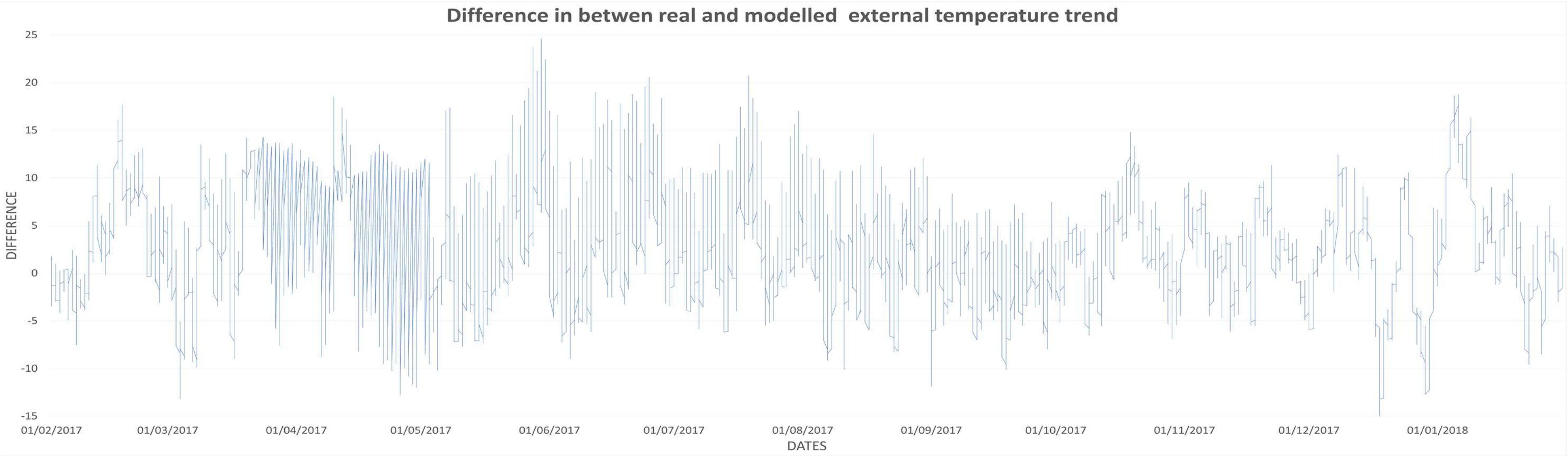


Figure 36 - Difference in between the two trends. The real external temperature and the modelled external temperature. The closer to 0, the more match it exists between them

On the graph above it is clearly seen the same it was expected from the two trends graph. The larger period of time proposed on the graph XXX it is the same one proposed from the graph XXX.

The line difference in this period it is almost 0 and also, and the most important it is that the divergence it is no so much. At least, the smallest numbers along the year-around. In this two months: August and September (the biggest period taken to the line match) the maximum deviation it is around + - 5ºC.

In order to go more into details, since the data collection has been carried out hourly, more specific study can be done. And one of the most interesting things it is that into this period, where the difference in between the numerical model and the reality it is almost 0, the moments of the day where the divergence it is smaller it is on the dark time. Where the sunshine it is out. It ca be seen a pattern. The difference in between the two lines it is 0 or almost 0 from midnight until the sunrise.

5. CONCLUSION

In order to keep a door opened for the future students or researches, the conclusion of proposal has been reached by the study and analysis of this data is that the fresco needs to be preserved in much better conditions. The interior climate environment there is inside of the pavilion is not good enough or good at all to host this painting. Thus, in this case the solution it needs to be an improvement of the interior microclimate and the environment of the interior of the building.

A HVAC system can be studied, and also a system of fresh air fluctuation, combined, probably, with a system of natural ventilation or probably even a mechanical one.

The singularity of the building it does not allow to design a simple air conditioning system with a dehumidifier extra system.

The proposal of this thesis for the next steps is that the numerical simulation in terms of air conditioning needs to be carried out by using Design Builder software, due to the numerical model it is already built by using the same software and the calibration has been developed by using the same one. In this point of the project, the building it is perfectly modelled and calibrated and, also, the real data extracted from the monitoring it has been already carefully studied. All the previous steps have been perfectly settled up and the clear next step it will be the design of the improvement system.

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