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Abstract: Typically, the structure of old monumental buildings differs significantly from that of contemporary ones. The massive walls, large indoor air volume and the small windows, compared to the opaque portion, drastically affect the microclimates of such constructions.
In such buildings is often quite difficult to perform a detailed monitoring campaign of the main microclimatic parameters. In this regard, experimental methodologies and non-invasive equipment, able to minimize the impacts on the building and on its users, should be adopted.
This research describes the methodology applied to carry out the monitoring campaign on the Milan Duomo, one of the biggest Cathedrals in Italy. The campaign was carried out by means of non-invasive measuring instruments, in order to keep the building intact and ensure the smooth running of the activities. In a second stage, sensors for the long-term monitoring were installed according to the most significant and accessible points inside the Cathedral.
The data collected during one year of monitoring was used to characterize the hygrothermal behaviour of the Cathedral, in order to assess the risks for the main materials which sacred objects, artworks, organs, sculptures and furnishing are made of.
The future developments of this work are oriented towards the realization of a simulation model aimed at designing and planning proper active or passive solutions to improve the microclimatic conditions for both artwork conservation and the comfort of visitors.

**COVER LETTER**

Dear Editor,

historic buildings have an inestimable cultural and artistic value, and contribute to provide a sense of identity for the cities and their inhabitants. The indoor microclimate of such buildings play a significant role in the conservation of the finishing, the construction elements and the artifacts contained in such spaces.

In this respect, the present paper aims to analyze the environmental behavior of the Duomo (Milan Cathedral), through an experimental monitoring using non-invasive measuring instruments, in order to keep the building intact and ensure a negligible interaction with other activities.

The characterization of the indoor microclimate is fundamental to evaluate the risks and subsequently ensure the proper conservation conditions for the church's materials.

The present study aims to analyze the environmental behavior of the Milan Duomo, one of the most famous masonry monument in Italy, using a methodology to characterize the internal microclimate. The selected case-study is particularly relevant due to its size (i.e. the second largest church in Italy), building typology (huge thermal mass), turnout of visitors and churchgoers (more than 4.000.000/year) and presence of different materials (e.g. marble, iron, wood, canvas, etc.). The research work represents the first comprehensive microclimate assessment in the Duomo ever carried out, with the scope to analyse in detail the possible risks for the artefacts and the building itself.

The methodology adopted could be used by researchers, specialists, policy-makers and building owners involved in the conservation of buildings' heritage.

***Detailed Response to Reviewers**

Reviewer #1: This is a well-written paper which needs a few important improvements and other minor improvement.

Thanks you for your useful suggestions

Major improvements

* It is very important to consider how tourists impact the microclimate under investigation. You should take into account in the analysis and in the discussion the number of visitors in the Duomo, and how they contribute to modify the microclimate in terms of T and RH. This is not mentioned, on the contrary, it is stated in line 329 that "visitors are not very influential on the internal conditions". This is not true (extensively literature on this topic) and should be carefully address before considering the paper for publication because the Duomo is one of the most important visited and crowed churches in Milan.

As noted by the reviewer, the presence of people is typically not negligible. For such reason we changed the misleading sentence in the paper and we added a more detailed analysis on such topic. However, it should be noted the analysed building is characterized by a huge volume, equal to about 300,000 $m^3$: in such particular condition, the simultaneous presence of a large number of people in a certain moment of the day and in a certain part of the church has a relevant influence on the local microclimate and is thus dependent from the precise location and the number of people; This phenomenon was experimentally described and a new section (Section 5.1) was added in such respect.

* Please clearly divide the Methods from the results sections. In the result section, there should not be part of the introduction. As example, Section 6 contains much information that should be before in the introduction, table 2 included.

Thanks for the suggestion. The part related to the risk analysis method was moved in the section 2.

* The abstract of this paper should be reduced in the first part. In this form, there are 11 lines of introduction. A sentence for introduction is sufficient. More emphasis should be given to the aims of the research, the methodology and the results. The fact that data were collected by "the Politecnico di Milano in co-operation with… " should be removed from the abstract. Saying that the methodology is innovative is misleading. Please remove.

The abstract was modified according to the reviewer's comments.

* It should be more clearly stated the aim of this research and why you did collect this data. Saying that it increases the knowledge on the topic is not sufficient, it should be emphasized the novelty of this study and what it brings to the scientific community.

The novelty of the paper has been better described in section 1.

* Section 6: Artworks should be located and mapped inside the Duomo when discussing the effect of the microclimate to the artwork conservation. Please consider: DAgostino, Congedoa, Cataldo, Computational fluid dynamics (CFD) modeling of microclimate for salts crystallization control and artworks conservation, Journal of Cultural Heritage 15 (2014) 448-457.

Thanks for the suggestion. The displacement of the artworks along the church has been added in the map (Figure 19).

Minor improvements

* The word "microclimatic" data acquisition/monitoring/parameters should be used instead of the word "environmental" throughout the paper, because environmental suggests also the investigation of other parameters that are not take into account in this study.

The word has been modified.

* In the Highlights, I should avoid the word "fast". It is actually a long campaign.

The highlight has been modified according to the suggestion

* Line 95: eliminate "the"

The word has been removed.

* Line 212: North, South with capital letter

The corrections have been applied.

* The word "significant " is too much used (line 249, 281, 53, 559 …etc) and it is misleading. Please rephrase.

The corrections have been applied.

* Lin2 62, Line 580-583 the suggestion of implementing energy efficiency or HVAC systems is risky without any dedicated study and should be eliminated as it may cause even worse problems.

The sentences have been modified.

* Fig.17: the presence of efflorescence can be due to rising dump or other phenomena that are not investigated in this paper. This has to be clearly stated.

A sentence that clarify the suggested issue has been added.

* Line 265: Section, no Chapter.

The word has been modified.

* Line 257-271 (276-277): gradients should be more carefully analyzed as the accuracy of the used instrumentation strongly affect what you call "significant" . please consider the accuracy of your instruments, include it in the gradient discussion and reconsider the comments you made.

The sentence was modified according to the reviewer’s comment. In particular, the accuracy of the instrumentation was added in the section and considered in the analysis.

* Line 314: why only one sensor is reported in the results? What about the other? What difference are there? Information should be given on all the sensors.

A precise explanation about the choice to base the assessment on the data of a representative sensor (Sensor 3) was added in the section. In addition, according to the reviewer's suggestion the band-gap between the data acquired from sensor 3 and the other sensors has been added.

* Line 352: "is shown below" should be substitute by the Figure number. However, the mixing ratio is not shown in that figure.

The errors have been fixed

* Figure 10: December with capital letter.

The error has been fixed

* When referring to the Duomo, Cathedral with capitol letter.

The error has been fixed

Reviewer #2: The research investigates the environmental behavior of the Milan Duomo using a short- and a long-term monitoring, then, a risk-based analysis carried out, to determine the range for the conservation of the church's materials.

- First of all, the paper with relevance to the scope of the Building and Environment Journal, but the paper will likely not create new insights because it is a restatement of obvious and relatively well-understood claims and/or relationships.

The novelty of the paper has been better described in section 1. First of all, it is better specified that the research work represents the first comprehensive microclimate assessment in the Duomo ever carried out, with the scope to analyse in detail the possible risks for the artefacts and the building itself. It is also noted that the selected case-study is particularly relevant due to its size (i.e. the second largest church in Italy), building typology (huge thermal mass), turnout of visitors and churchgoers (more than 4.000.000/year) and presence of different materials (e.g. marble, iron, wood, canvas, etc.), which make it different from other historic buildings already analysed in literature. In addition, the acquired monitoring data can also support the development of a virtual simulation model aimed at characterizing the environment according to the change in the boundary conditions and at evaluating possible energy-efficient solutions, designed to improve the user's comfort and/or to achieve optimal microclimatic conditions for the conservation of the artefacts.

- It is normal to be the aim of any research work is to increase the scientific knowledge, so, I prefer to delete the two lines 56 and 57 (The aim of this research work is indeed to increase the scientific knowledge on such topic, based on experimental data acquired in the field).

The sentence has been modified

- (building owners) should be deleted, so as to there are not owners for the heritage.

The sentence has been modified

- I don't see or understand the relationship between the preliminary monitoring phase and the positioning of point some sensors for long-term data acquisition.

The experimental monitoring campaign presented is divided into a preliminary analysis (short-term) and a long-term monitoring. The first phase allows to obtain an initial and sufficiently detailed characterization of the internal microclimate along the entire volume of the church, by using portable and moveable instruments, according to a regular three-dimensional grid of monitoring points; its aim is to identify the most relevant areas for the subsequent positioning of fixed and permanent sensors for the second phase, the long-term monitoring. In fact, due to the type of building and all the existing constraints, the possible installation points for permanent sensors were limited and the most representative ones had to be selected.

A more detailed explanation was added both at the end of section 2 and in section 4.

- In page 15 (pag. 20), I think that the thermal mass also has an important role as well as the air exchange rate to keep the hourly variations of the internal temperature is low.

The sentence was implemented specifying the effect of the thermal mass on the indoor microclimate variations.

- Some sections have very long paragraphs. Also, results and the discussion are unclear and confusing due to these long paragraphs.

In such respect, the part related to the conservation ranges was moved in the section 2, while section 5 have been reduced and simplified.

- The figures and charts have a low resolution.

The figures and charts with low resolution were changed

**Highlights**

- Microclimate's monitoring is essential for assess the building's conservation state;
- Non-invasive, cheap, sufficiently accurate microclimate's characterization is allowed;
- A risk analysis based on conservation limits according several sources is presented;
- A large and representative historic church in Italy has been taken as case study;
- Information and data collected support the realization of a building energy model.

# Microclimatic monitoring of the Duomo (Milan Cathedral): risks-based analysis for the conservation of its cultural heritage

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**Nomenclature**

T: air temperature [°C]

RH: relative air humidity [%]

MR: mixing ratio [g/kg]

Δmax temp. - Internal: difference between minimum and maximum daily indoor temperature;

Δmax temp. - External: difference between minimum and maximum daily outdoor temperature;

Δmax RH - Internal: difference between the minimum and maximum daily indoor relative humidity;

Δmax RH - External: difference between the minimum and maximum daily outdoor relative humidity;

Temp. Average - Internal: average daily indoor temperature;

Temp. Average - External: average daily outdoor temperature;

RH Average - Internal: average daily indoor relative humidity;

RH Average - External: average daily outdoor relative humidity.

## 1. Introduction

Historic buildings have an inestimable cultural and artistic value, and contribute to provide a sense of identity for the cities and their inhabitants. The indoor microclimate of such buildings plays a significant role in the conservation of the finishing, the construction elements and the artefacts contained in such spaces.

In the last decades, many studies were carried out for several types of building (churches, museums, etc.), in order to analyze and define the best strategy to preserve and protect these constructions and their artworks [1–21]. The starting point for all these studies is a detailed understanding of the indoor environment compared to the different boundary conditions, in the short and the long period.

Within such context, among the historic buildings, ancient churches are those that most frequently are still practically unaltered at the present day. This allowed the preservation of their considerable

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artistic and architectural features, with particular reference to the artworks they contain (paintings, frescoes, sculptures, wooden panels, sacred objects, furnishings, organs, etc.) [8].

It should be noted that the objects constituting the interior artistic heritage of a church are generally quite sensitive to environmental factors such as air and surface temperature, relative humidity, light and physical agents, whose balance is crucial in order to ensure the maintenance and protection of artworks and materials [22,23]. In more detail, periodic air temperature and relative humidity changes may cause dry and wet cycles and air movements that are usually responsible for deterioration and soiling processes [24][25–27].

To acquire the knowledge about the state of conservation of a historic church, the current deterioration of the materials and the main behaviour of the microclimate over the time, it is essential to carry out a monitoring campaign, using non-destructive methods to avoid damaging any valuable historic surfaces and objects, and also to minimize any interference with the users.

The knowledge of the microclimate behavior inside monumental churches and the identification and definition of the deterioration processes on structures and materials are the prerequisites for the definition of a proper plan and strategy of intervention, to preserve such heritage.

In such context, the present study aims to analyze the environmental behavior of the Milan Duomo, one of the most famous masonry monument in Italy, using a methodology to characterize the internal microclimate. The selected case-study is particularly relevant due to its size (i.e. the second largest church in Italy), building typology (huge thermal mass), turnout of visitors and churchgoers (more than 4.000.000/year) and presence of different materials (e.g. marble, iron, wood, canvas, etc.). The research work represents the first comprehensive microclimate assessment in the Duomo ever carried out, with the scope to analyse in detail the possible risks for the artefacts and the building itself.

In particular, the work shows the results of an in-field experimental campaign carried out through non-invasive measuring instruments that don’t interfere with the regular performance of activities inside the church.

In such respect, the experimental data acquired on the field can also provide useful information for a better understanding of the behaviour of similar historic buildings. The latter, in fact, are often characterized by uncommon features such as considerable dimensions, singular architecture complexity and huge wall thickness that make them unique and not comparable with common buildings. Moreover, really often such buildings host also numerous artefacts such as paintings, sculptures, ancient books that require specific microclimatic conditions. In such respect, it is compulsory evaluate the possible risks for the preservation of artworks/materials, according to the conditions prescribed by the technical literature [22–24,28–38] and regulatory sources [39,40].

The acquired monitoring data can also support the development of a virtual simulation model aimed at characterizing the environment according to the change in the boundary conditions and at evaluating possible energy-efficient solutions, designed to improve the user's comfort and to achieve optimal microclimatic conditions for the conservation of the artefacts.

This methodology could be used by researchers, specialists and policy-makers involved in the conservation of a building's heritage. The main results of the in-field measurements are shown and discussed.

## 2. State of the art on microclimatic monitoring of historic churches and the optimal environmental conditions for their artworks conservation

The hygrothermal behavior of historic churches is often the result of complex energy balances, due to several different causes. The environmental characterization of these buildings is a task that requires a detailed and carefully planned study, based on the analysis of specific problems to be solved. In detail, the European reference standards concerning the measurement of the microclimatic parameters of cultural heritage [41,42] do not define a precise methodology to be used, but describe general procedures, based on the phenomenon to be investigated.

In this respect, over the years, the surveys of historic buildings were carried out by applying different methodologies and tools [1–3,5,10,14,20,21,43–47]. The following section describes the main procedures and methodologies adopted to carry out reliable monitoring campaigns and microclimatic characterizations of some European historic churches.

The monitoring carried out by M.J. Varas-Muriel et al. at the Church of San Juan Bautista in Spain [3,19] investigated the effect on the microclimate of a traditional heating system. For this purpose, nine balloons were inflated with helium gas and distributed at different points in the church. Each balloon had fixed slots supporting 6-7 temperature and relative humidity sensors, spaced 1.5 meters apart. Data was monitored during one day in February and one in March, over a time interval of about 4 hours, with a sampling time of 1 minute. Air flow from the system was measured by an air speed meter.

In the microclimatic analysis of the church of St. Christopher in Lisbon [5,21], numerous sensors were used to measure the internal distribution of temperature and relative humidity of the air, in plan and elevation. The sensors used in this study complied with the minimum requirements suggested by the EN 15758 and EN 16242 standards on the instrumentation to be used for the environmental survey of cultural heritage.

At Santa Maria Nascente in Agordo, on the Italian Alps, the monitoring carried out by Camuffo et al. [2] illustrates some survey methods for the microclimatic characterization of historic churches. In particular, a distinction is made between long-term monitoring, through sensors equipped with data loggers, and punctual (spot) monitoring, in which data is manually taken over a specific period, in order to verify particular conditions. Specifically, the measurement of the profiles of temperature and relative humidity of the air was carried out through casing-free sensors fixed to the ropes, in order to improve the response time. The monitoring of surface temperatures was made using IR thermometers and quasi-contact thermometers, for the most accurate measurements. Finally, thermal images of some selected surfaces were captured through an infrared camera, to evaluate impact of hot air on the different surfaces.

In the study carried out for the church of San Francisco de Asís in Seville, Spain [10], in order to obtain environmental data representative of the internal microclimate, some sensors were positioned in areas not influenced by any source of radiation, air flows coming from outside, etc. The external microclimatic parameters were instead acquired through the closest weather stations.

The different methodologies described above underline the need to install a large number of sensors, uniformly spaced, often hooked to ropes suspended by means of balloon probes, or fixed to the roof of the building. Despite allowing to represent the spatial distribution of the microclimatic parameters, such systems involve the physical and visual occupation of some areas or the entire building for a specific period.

The characterization of the microclimate through the mapping of microclimatic parameters should be considered an indispensable condition for the assessment of the state of conservation of the building and the precious objects stored therein.

In general, the transformation processes affecting these objects can be of different origins [23]:

- physiological, namely the natural aging of materials, which can be slowed down through proper conservation;
- pathological, due to the formation of degradation: causes may be internal – for example due to the instability of the material or the processes to which they were subjected – or external, related to the environmental conditions of surroundings.

In general, the main environmental parameters to study and monitor are: relative humidity, temperature, light and the pollution in the air [22]. However, in this work, the effects related to temperature and relative humidity of the air on the conservation of the building are taken into account and discussed in detail. Such parameters, in fact, can lead to physical, chemical or biological degradation processes that can irreparably damage the artworks and the building itself.

Although both technical literature [22-29,35-40] and regulations [27,28] sets the optimal range to avoid the deterioration of different materials (Table 1), very often the suggested values do not correspond to each other. For such reasons, in table 1 the optimal environmental conditions of three main families of materials (woods, stones and metals), among the main ones the majority of the artefacts inside of historic churches are made of, are reported and subsequently discussed in detail in section 6.

*Table 1 – Comparison of optimal conservation ranges for woods, stones and metals, as suggested by various sources.*

| | ***Material*** | ***Air T [°C]*** | ***Max daily fluctuation of T [°C]*** | ***Air RH [%]*** | ***Max daily fluctuation of RH [%]*** | ***Sources*** | ***References*** |
|---|---|---|---|---|---|---|---|
| Woods | Polychrome wooden sculptures, painted wood, paintings on wood, icons, wooden pendulum, musical instruments of wood | From 19 to 24 | <1,5 | From 50 to 60 | <4 | UNI10829- UNI10586 | [39,40] |
| | - | <20[a] | - | <70[a] | -[b] | Carbonara | [24] |
| | Wood, tissue, paper | <18-20[a] | - | <65[a] | -[b] | Camuffo | [34,38] |
| | - | - | - | From 30 to 65 | -[b] | PAS 198 | [22] |
| | - | From 19 to 24 | - | From 45 to 60 | - | MIBAC-Petrelli, Fabbri | [29,30] |
| | Polychrome wooden sculptures, painted wood | - | - | From 45 to 60 | - | AAM - Haiad, Druzik, Ayres, Lau - IFROA - Jhonson-Horgan | [31,32] |
| | = | - | - | From 55 to 65 | - | Banchmann | [31,32] |
| | = | - | - | From 50 to 65 | - | Cavallini, Massa - Gambalunga | [31,32] |
| | = | - | - | From 45 to 65 | - | Coccitto | [31,32] |
| | = | - | - | From 50 to 65 | - | ICCROM | [31,32] |
| | = | 20 | - | From 45 to 55 | <5 | Musée de France | [31,32] |
| | = | 20 | - | From 45 to 60 | - | Stolow | [31,32] |
| | = | - | - | From 50 to 60 | <5 | Thomson | [31,32] |
| | Painted panel wood and musical instruments | From 19 to 24 | - | From 45 to 55 | <2 | Baumont-Laurie | [31,32] |
| | polychrome wooden objects | From 19 to 24 | - | From 35 to 50 | <6 | Baumont-Laurie | [31,32] |
| | painted panel wood | From 21 to 23,5 | - | From 45 to 55 | <6 | ROM | [31,32] |
| Stones | Mosaics, stones, rocks, minerals, meteorites (not porous), fossils and stone collections | From 15 to 25 | - | From 20 to 60 | <10 | UNI10829 and UNI10586 | [39,40] |
| | mineralogical collections, marbles and stones | <30 | - | From 40 to 65 | - | MIBAC-Petrelli, Fabbri | [29,30] |
| | - | >5[c] | - | - | - | Carbonara | [24] |
| | - | >5[c] | - | <55[d] | -[b] | PAS 198 | [22] |
| | = | - | - | <45 | - | Banchmann | [31,46] |
| | = | - | - | From 40 to 45 | - | Cavallini, Massa | [31,32] |
| | = | - | - | From 20 to 40 | - | Coccitto | [31,32] |
| | = | - | - | From 0 to 45 | - | De Guichen -Gambalunga - ICCROM | [31,32] |
| | = | From 21 to 23,5 | - | From 25 to 50 | <10 | ROM | [31,32] |
| | = | - | - | From 20 to 60 | - | Stolow | [31,32] |
| | = | From 10 to 25 | - | From 65 to 70 | - | Thomson | [31,32] |
| Metals | Metals, honed metals, metal alloys, silver, armor, weapons, bronzes, coins, copper objects, tin, iron, steel, lead, pewter | - | - | <50 | - | UNI10829 and UNI10586 | [39,40] |
| | - | - | - | <60 | - | Carbonara | [24] |

| | | | | | | |
|---|---|---|---|---|---|---|
| Metals (except archaeological metals) | - | - | <65-70 | - | PAS 198 | [22] |
| honed metals and alloys, brass, silver, pewter, lead, copper | - | - | <45 | | MIBAC-Petrelli, Fabbri – Banchmann - ICCROM | [29,30] |
| iron armor and weapons, bronze, honed metals and alloys, brass, silver, pewter, lead, copper | - | - | <30 | - | AAM - Haiad, Druzik, Ayres, Lau | [31,32] |
| = | - | - | From 50 to 55 | - | British Museum | [31,32] |
| = | - | - | From 40 to 45 | - | Cavallini, Massa - | [31,32] |
| = | - | - | <60 | - | Coccitto | [31,32] |
| = | - | - | From 0 to 45 | - | De Guichen - Gambalunga | [31,32] |
| = | - | - | From 50 to 65 | - | Musée de France | [31,32] |
| = | - | - | From 40 to 45 | - | Thomson | [31,32] |

a. To avoid biological degradation;
b. High and repeated variations in a short period of time must be avoided;
c. The minimum safe temperature to avoid possible freezing of the water contained in the material;
d. To avoid the oxidation of some minerals present in the stones.

After the description of the case study (section 3), the paper presents the methodology adopted to carry out the experimental monitoring campaign, which is divided into two phases: a preliminary analysis and a long-term monitoring (section 4). The first phase allows to obtain an initial and sufficiently detailed characterization of the internal microclimate, by using portable and moveable instruments placed along a three-dimensional grid of monitoring points; its aim is to identify the most relevant areas for the subsequent positioning of fixed sensors for the second phase (the long-term monitoring). In fact, due to the particular building typology and all the existing constraints, the possible installation points for permanent sensors were limited and the most representative ones had to be selected.

Finally, according to the data acquired during the monitoring, shown in section 5, a risk analysis related to the conservation of the main materials and artefact has been carried out (section 6).

## 3. The case-study: Milan Cathedral (Duomo di Milano)

The *Duomo di Milano*, one of the largest Cathedrals in Italy, is located in the homonymous square, in the heart of the city. The building construction started toward the end of the 14$^{th}$ century and lasted for more than four centuries, but its maintenance works still continue today.

This section reports the main dimensional and material information on the Duomo. Internally, the Cathedral spreads over an area of 8,500 m$^2$ in plan, with a volume of about 300,000 m$^3$, with internal heights ranging from 20 to 45 m for the side aisles and the central one, respectively, and up to 65 m in correspondence with the dome. The building envelope is made of dry masonry walls of varying thickness (between 1 and 5.7 m), with external sides made of Candoglia marble ashlars, one further internal supporting stone layer of relatively lower quality, and an internal filling consisting of a mixture of aggregates and crushed stone from lime mortar. The total number of stained glass windows are 49, including 43 decorated and 6 without decoration. The glazed surface to wall surface ratio is approximately 20%. The roof construction system is composed of a double system of overlapping brick vaults, which form walkable attic spaces called “sordis”. These areas are in direct contact with the internal environment of the Cathedral, thanks to the numerous holes in the vault system.

The air ventilation across the building is primary related to the opening’s management. More in detail, two different strategies are currently applied during the year:

1. the first one, used during cold months, consists in keeping all the windows closed. In such condition, the main flow rate is due to the entrance gates, when churchgoers and tourists go through them;

2. the second one, adopted exclusively in the summer months (from mid-June to mid-September), aim to increase as much as possible the flow rate through the openings of the windows located in the ambulatory (around the choir and the apse) and in the transept;

In such respect, the total area of windows and doors opened is approximately 30 $m^2$ and 100 $m^2$ during cold and hot months, respectively.

Inside the Cathedral there are numerous artifacts of various nature, age and material. The marble covers the entire envelope, and is one of the stone materials used to create the numerous sculptures and decorations that enrich the Cathedral; wood was used for the benches, confessionals, choir stalls and organ cases, both the older and more recent ones of which have large oil-painted wooden doors. In the numerous altars of the side aisles there are also various artifacts of different origins and materials, including: silver, copper and bronze relics, bodies of buried Saints kept in glass cases, etc. [48].

The geometric and constructive characteristics of the Duomo have a notable impact on the internal microclimate which, in turn, influences the conservation of the materials and artifacts, as described in the following sections.

It should be noted that, currently, no heating, cooling or mechanical ventilation systems are present in the Cathedral.

## 4. Methodology and monitoring process

The microclimatic data acquisition was carried out through the use of non-invasive instruments, in order to keep the finishes and artifacts intact and to ensure the smooth running of the activities inside the Duomo. The mobile instrumentation used during the preliminary monitoring phase allowed to have a first characterization of the internal microclimate, by monitoring some sample days, highlighting the main behavior of the microclimatic parameters on the entire volume of the building. During this phase, it was possible to identify the main gradients of temperature and relative humidity on the whole church volume. According to such preliminary microclimatic characterization, the permanent sensors for the long-term monitoring were located in some representative points, easily accessible inside the Cathedral.

The measurement methods adopted in the two phases of the monitoring campaign are described below:

- preliminary acquisition of microclimatic parameters (February-July 2016), based on a three-dimensional grid of monitoring points; this phase aimed at the general characterization and mapping of temperature and relative humidity profiles, using portable sensors, in order to properly plan the long-term monitoring;

- continuous long-term monitoring, (July 2016-June 2017), with fixed sensors positioned at relevant points and able to store the information collected. The aim of this phase was to carry out a comprehensive microclimatic monitoring.

The measuring instruments used and the methodologies adopted are described in detail here below.

### 4.1 Measurement instruments

The instruments used for the monitoring activities were carefully selected, to ensure the best compromise between accuracy and compatibility with the installation conditions; in detail, they consist of:

- temperature and relative humidity sensors for indoor air;
- infrared temperature sensors, for the measurement of the surface temperature of materials;
- hot-wire anemometer, for the measurement of air velocity.

In particular, the main features of the different types of instruments used are shown in Table 2.

*Table 2 - Types of instruments used for the microclimatic monitoring.*

| | *Instrument model* | *Measured parameters* | *Measurement range* | *Accuracy* | *Resolution* | *Response time* |
|---|---|---|---|---|---|---|
| 1 | Episensor TES-11/HTS-10: (Wireless sensor) | T | from -20 to +60°C | +/- 0.2°C | 0.1°C | few min.* |
| | | RH | from 11 to 89% | +/- 3% | 0.1% | few min.* |
| 2 | HOBO UX100-011 (sensor with datalogger) | T | from 20 to +70°C | +/-0.21°C (0 … +50°C) | 0.024°C (at 25°C) | 4 min. |
| | | RH | from 0 to 95% | +/- 2.5% (10 … 90%) | 0.05% (at 25°C) | 11 sec. |
| 3 | HOBO U12-011 (sensor with datalogger) | T | from -20 to +70°C | +/-0.35°C (0 … +50°C) | 0.03°C (at +25°C) | 6 min. |
| | | RH | from 5 to 95% | +/- 2.5% (10 … 90%) | 0.03% | 1 min. |
| 4 | HORIBA IT-545 NH/N/S (infrared thermometer) | Superficial T | from -50 to +1000°C | +/-1.0°C (0 … +199.9°C) | 0.1°C (0 … +199.9°C) | < 0.8 sec. |
| 5 | Thermo-anemometer Testo 405-V1 | Air velocity | from 0 to +10m/s | +/- 0.1m/s (0 … +2m/s) | 0.01m/s | - |
| | | T | from -20 to +50°C | +/-0.5°C | 0.1°C | - |

* Evaluated during the monitoring phase

Instruments 2, 3 and 4 in Table 2 complied within the minimum requirements suggested by European regulations [41,42] on the measurement of the microclimatic parameters for the conservation of cultural heritage. Sensor 1, used during the preliminary monitoring phase, complied within the requirements suggested by these regulations, except for the relative humidity measurement range; however, values above the instrument limits (11% and 89%) have never been recorded. In order to improve the response time of instrument 1, its plastic cover was removed, so as to leave it more exposed to the flow of air, and limit the influence of the thermal inertia of the building. Instrument 5, on the other hand, was used only for internal air velocity measurements.

### 4.2 Preliminary acquisition of the microclimatic parameters

During the first monitoring phase, wireless sensors (model 1 in Table 2) were attached to a balloon-probe connected through a nylon rope to a winch, for winding and unrolling the cable and then adjusting the lifting height. Thanks to a trolley, on which the winch was fixed, it was possible to easily move the equipment inside the Duomo during the measuring operations. From February to July 2016, microclimatic parameters were monitored during some sample days, representative of the various weather conditions. A computer placed on the trolley received and displayed in real time the data acquired by the sensors fixed on the balloon-probe. The system layout prepared during the preliminary acquisition phase is shown below.

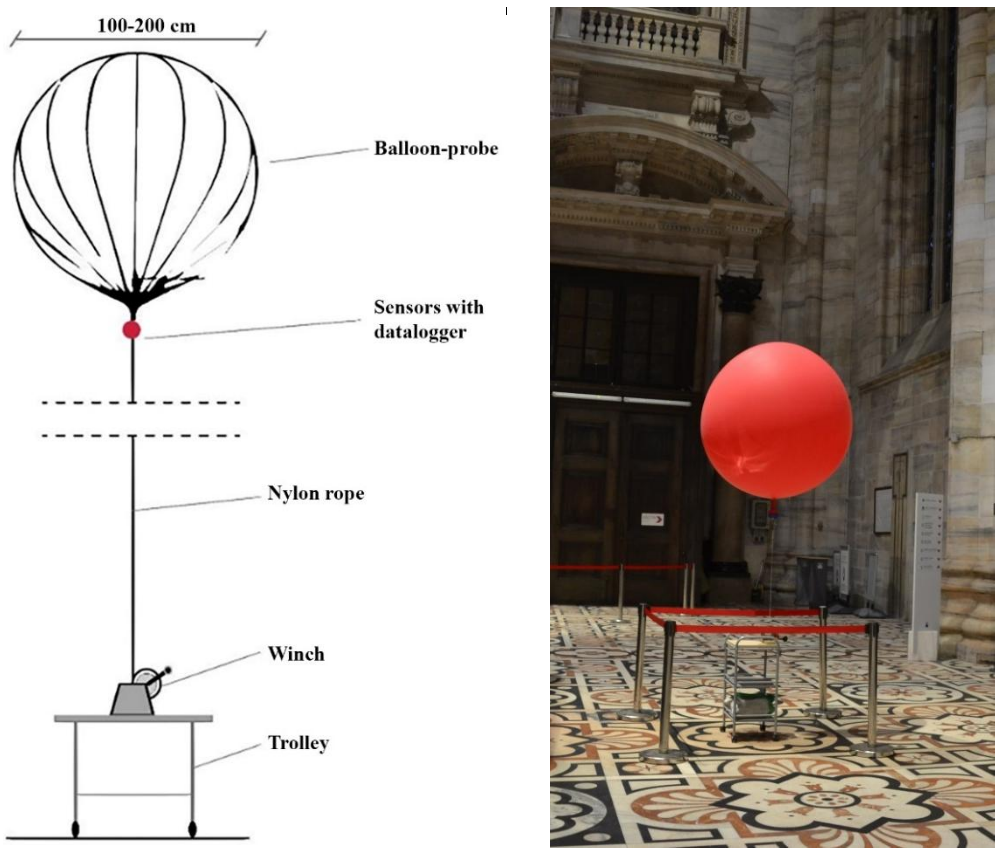


*Fig. 1 – Scheme (left) and view (right) of the system used for data acquisition during the first monitoring phase.*

In order to map and characterize the large space of the Duomo, the plan was divided into areas bounded by a virtual grid, whose columns were numbered in ascending order, while the rows were identified using the actual name of the naves and transects (Fig. 2). In addition, based on this grid, 9 representative monitoring points were defined in plan and distributed in the North, central and South naves of the Cathedral; for each of them, measurements were carried out at different heights, for a total of 42 acquisition points. In detail, in the North and South aisles, characterized by a maximum height of approximately 20 m, 4 measurements were carried out, 5, 10, 15 and 20 m from the walking surface, respectively; instead in the central nave, which is characterized by a maximum height of 45 m, two further measurements were carried out at a height of 35 and 40 m, respectively (Fig. 3).

The data monitoring at the identified points was carried out according to successive cycles, always starting from the North aisle, continuing in the direction of the transept, then in the central nave and finally in the South one, as shown in Fig. 2. Each monitoring cycle, lasting between 1 hour and 10 minutes to 1 hour and 40 minutes, was repeated 4 times daily. Data related to the outdoor environment was acquired from the Brera weather station, the closest to the Duomo among the weather stations of the ARPA (Regional Environmental Protection Agency) present in the city [49].

Internal surface temperatures were measured by taking into consideration some representative points close to the air temperature measurement points. In particular, in the North and South aisles for each point analyzed, surface temperatures were acquired in 18 positions: 8 shared between the North and South columns with respect to the measurement points of air temperature and relative humidity, 8 between the windows on the left and right of each column, and finally one measurement on the floor and the intrados of the vaults (see Fig. 2 and Fig. 3).

Spot measurements of the air velocity were acquired at the monitoring points shown in Fig. 2 (red circles), during each monitoring cycle, at a height of about 1.5 meters.

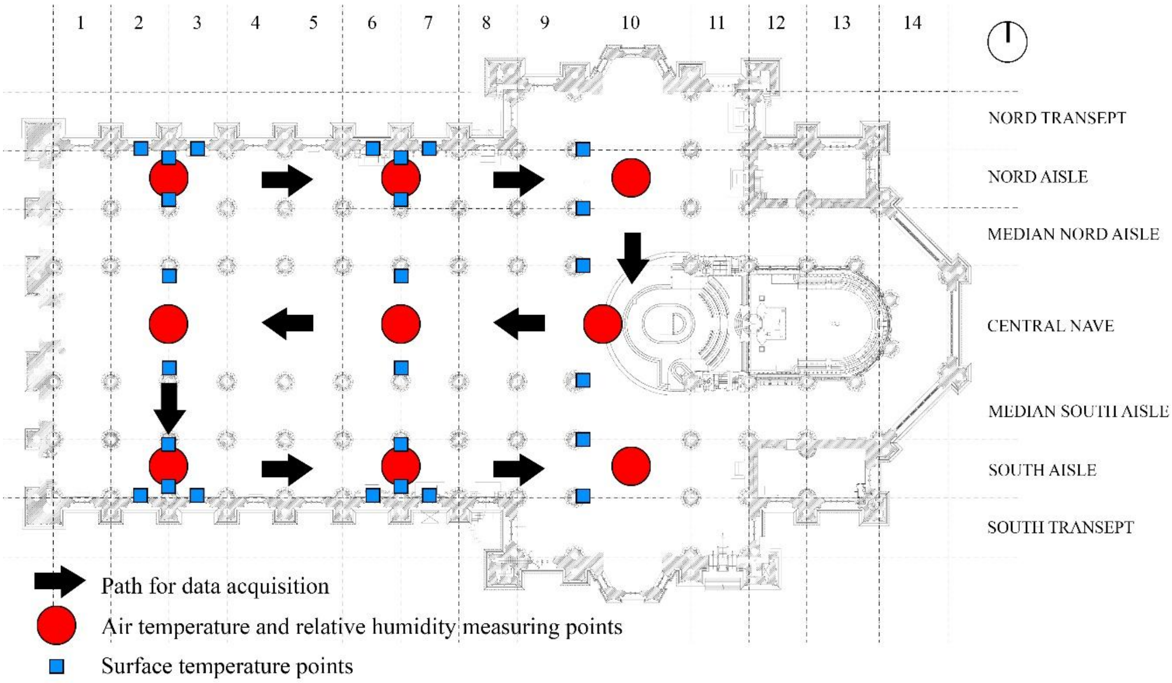


*Fig. 2 - Identification of the air T/RH measurement points in plan and surface temperatures for the preliminary monitoring activity.*

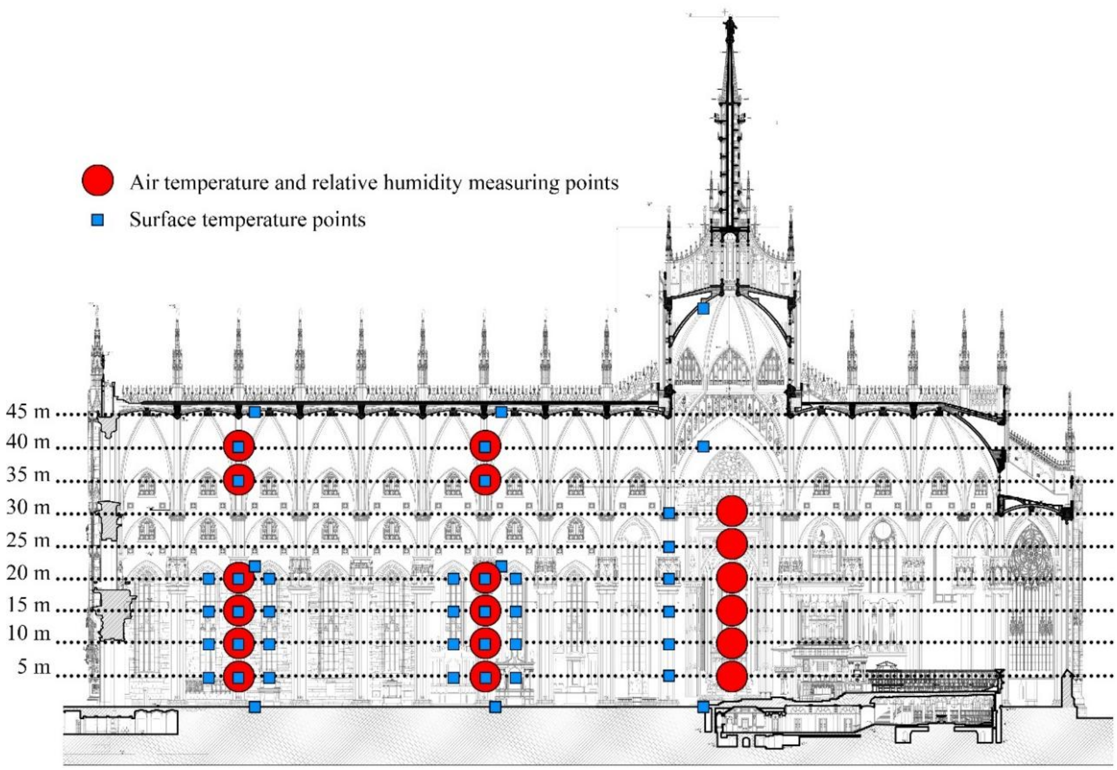


*Fig. 3 - Identification of air T/RH measuring points across height and surface temperatures for the preliminary monitoring activity.*

Once the preliminary microclimatic monitoring phase was completed, in July 2016, the information collected was used to define the position of the sensors for continuous monitoring. From the comparison of the information acquired through the campaign, it appears that the differences in temperature and relative humidity in the various measurement points are not relevant (i.e. are within or very close to the range of accuracy of the sensors, equal to +/- 0.2°C and +/- 3% for temperature and RH respectively), except for the areas near the entrance to the North aisle, which undergoes higher variations, since the gate is used as a primary entrance by churchgoers. More in detail, the most interesting results are summarized below.

- Vertical gradient of air temperature and relative humidity across the height of each point in plan (within each vertical set of measurements of about 12-15 minutes): there was no significant temperature gradient in the measurements at different heights; in fact, despite the great height of the aisles, the variations between the lowest and the highest points never exceeded 0.5°C; this behaviour is clearly related to the absence of a heating system inside the church and to the fact that internal gains are negligible in comparison with the volume;
- Horizontal gradient of air temperature and relative humidity across the plan at a certain height (within each horizontal set of measurements of about 80 minutes): as already mentioned, the temperature gradient in the measurements across the plan is limited, except for the measurements of the sensor located close to the gate of the North aisle. In detail, the variations among the measured points never exceeded 0.5°C for temperature and 2% for relative humidity, except for the areas near the entrance, where the variation achieved values up to 2°C and 6% for temperature and relative humidity respectively;
- Variation of temperature and relative humidity between average indoor and outdoor conditions in the course of the day: during each single monitored day, the internal temperatures had small variations, from a minimum of 0.6°C to a maximum of 1.4°C, in comparison to the variations in the external temperature, between 1.3°C and 7.1°C; as illustrated in detail in section 5, this is mainly due to the effect of the thermal inertia of the envelope; during the measurement day, the internal relative humidity increased or decreased between 2% and 23%. The maximum daily variation recorded corresponded to a drop in the internal relative humidity of 23%, compared to 58% of the external one;
- Air speed: the air velocities recorded at the monitoring points at a height of about 1.5 meters were between 0.01 m/s and 0.1 m/s (the accuracy of the sensor is 0.1 m/s). The highest values were measured in bays 2-3 (see Fig. 2) and, in particular, in the vicinity of the entrance gates.

From the analysis of the data acquired during this preliminary phase, it can be noted that, due to the large volume and the high thermal inertia of the envelope that characterizes the Cathedral, the internal temperature variations are small. On the contrary, relative humidity is more unsteady, as will be discussed in detail in the following sections.

### 4.3 Long-term microclimatic monitoring

The preliminary monitoring phase described above allowed to obtain an initial characterization of the hygrothermal behavior of the Duomo, to identify the most relevant measuring points, representative of the general microclimatic conditions inside the Cathedral. In these points, temperature and relative humidity fixed sensors (models 2 and 3 in Table 2) were positioned for continuous data collection, with hourly acquisition time intervals. The positioning of these probes took place in July 2016. More in detail, the six points identified were chosen in order to have a comprehensive picture of the microclimatic behavior of the Duomo, as well as to take into account the safety and accessibility criteria of the available areas (Fig. 4 and 5). In particular:

1. sensor 1 was placed on the balcony above the main entrance door in the west façade, at a height of approximately 18 m; it is representative of the average conditions in the frontal part of the church;
2. sensor 2 – positioned on the roof of the “ascolto” room, at a height of 2.2 m – recorded the data most influenced by the external air coming from the openings on the west façade;
3. sensor 3 – on the balcony of the organ, on the right side of the altar, at a height of about 9 m – acquired the hygrothermal data close to the altar, where various artworks/sensible elements are presents;
4. sensor 4 – on a table placed in the North transept – characterized the conditions in the transept;
5. sensor 5 – positioned in front of one of the openings in the South-facing median “sordis”, which overlooks the central nave, at a height of about 30 m – allowed to verify the thermal gradient compared to the values recorded at the lowest levels;
6. sensor 6 – placed behind the altar on the dividing wall towards the ambulatory – allowed to record the hygrothermal condition in the rear area of the Cathedral.

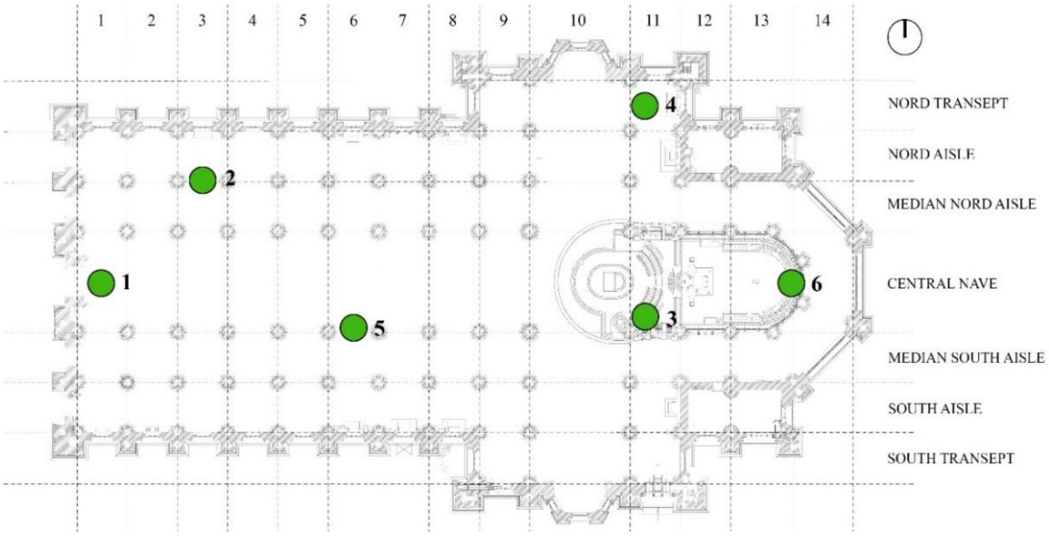


*Fig. 4 - Identification of the points in plan where the fixed T/RH probes were positioned.*

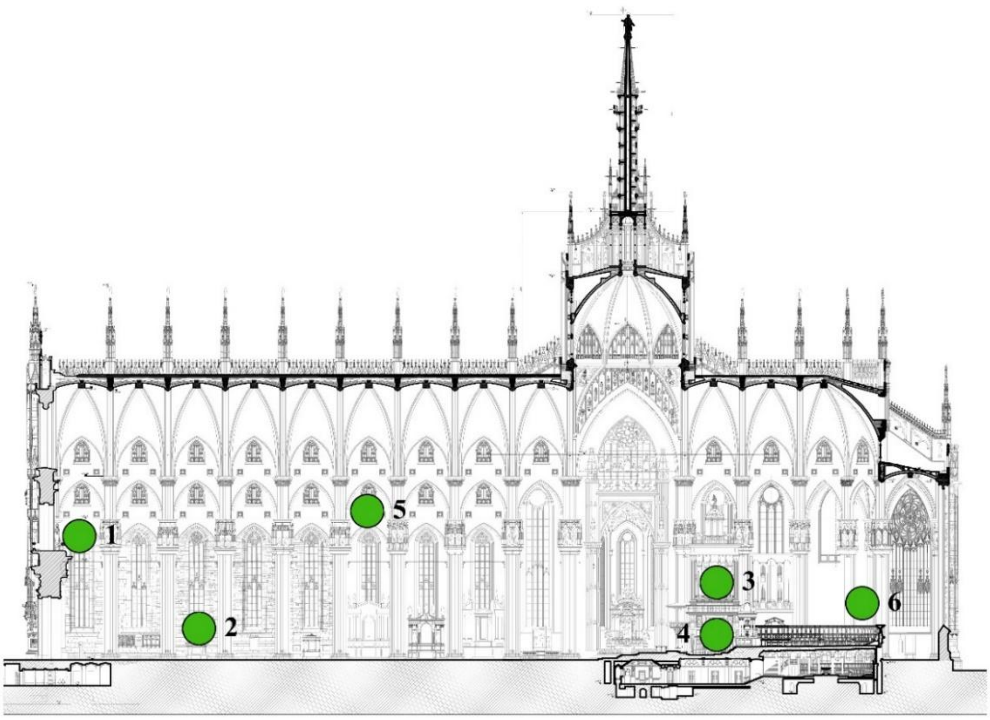


*Fig. 5 - Identification of the points across the height in which the fixed T/RH probes were positioned.*

## 5. Results and discussion on microclimate assessment

The data collected in the second phase of the monitoring were elaborated in order to characterize the behavior of the main parameters representative of the internal microclimate, with respect to the variation of the outdoor microclimatic parameters and the internal conditions of use.

## 5.1 Effect on microclimate due to the presence of people

In general, internal gain due to people is one of the parameters that affect indoor microclimate of historic buildings. As demonstrated by some research, the temporary presence of devotees and visitors in spaces, in fact, have an influence on temperature and humidity distribution according to the displacement and number of people [47]. Of course, the most influenced areas are those close to the devotees, whereas in the surroundings the variations are minor [47]. In this respect, it must be noted that the Duomo is characterized by a huge air volume comparted to other historic buildings, thus the simultaneous presence of a large number of people in a certain moment of the day and in a certain part of the church has a relevant influence on the local microclimate.

In this sense, in order to analyse the effect on the microclimate, during the preliminary monitoring a study on the local variation of internal hygrothermal parameters with respect to the simultaneous presence of high density of people in a specific section of the cathedral has been carried out. Environmental data were acquired on two days (April 16$^{th}$ and17$^{th}$) characterized by considerable overcrowding of the area in front of the altar due to the presence of important musical and religious events inside the Duomo. The balloon-probe was placed near the benches of the central nave at a height of 30 m, in a midpoint with respect to the position of the visitors. During the morning celebration of the first day, the simultaneous presence of about 750 people was documented in the nave, and an increase of the internal temperature of about 0.5 °C was recorded (Fig. 6). After the event, when most of that 750 people went out the church, the local internal temperature dropped closer to the daily average indoor value, although the external one continued to increase. Similar trend, although less significant, was observed during the afternoon events, characterized by the average presence of 200 people, and in the celebrations of the following day, attended by about 280 people in the morning and 400 in the afternoon.

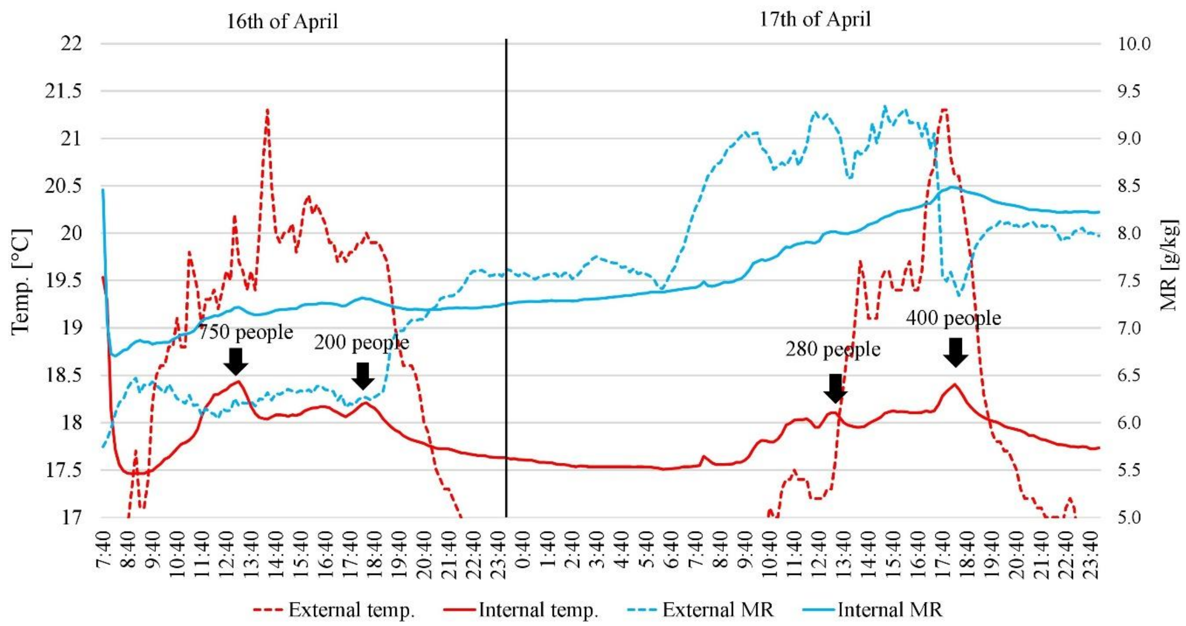

*Fig. 6 - Internal and external temperature and mixing ratio values during April 16th and 17th; the arrows indicate the number of people present when some temporary peaks of temperature and mixing ratio were recorded during the events.*

A similar behavior was observed for the mixing ratio. In particular, during the two monitored days, an increase in local values was recorded in relation to the ceremonies (Fig. 6).

From the analysis of the data collected, it can be observed that the presence of people, even if in substantial numbers, has a temporary effect on the local microclimate of the Duomo, mainly due to its large air volume, its huge thermal mass and to air change rate (see Section 3). Further analysis on this topic will be carried out in the prosecution of the research.

### 5.2 Analysis of the long-term monitored data

This section aims to discuss the obtained results of the long-term monitoring.

In order to increase the readability of the results, in the following paragraphs the data of a single sensor (sensor n. 3) placed close to the altar of the Cathedral have been reported and analysed. In fact, as stated in section 4, the differences in terms of temperature and relative humidity among the various measurement points are negligible, except for the sensor located close to the entrance in the North aisle (sensor n. 2). Accordingly, sensor n. 3 was selected since it is placed closer to many objects and artworks made of different materials, thus it was considered the most relevant for the present risk analysis. Nevertheless, the calculated average deviations between the sensor n. 3 compared to the average of the other measurements, during summer months when ventilation through opening are enhanced, are equal to 0.2°C for temperature and 3% for RH (values equal/lower than the instrument accuracy). Sensor n.2 has instead a calculated average deviation compared to the average of the measurements of 0.8°C and 3% for temperature and relative humidity respectively.

In Fig. 7 the band-gap showing the maximum deviation of the acquired parameters from the 6 sensors compared to sensor n.3 is reported.

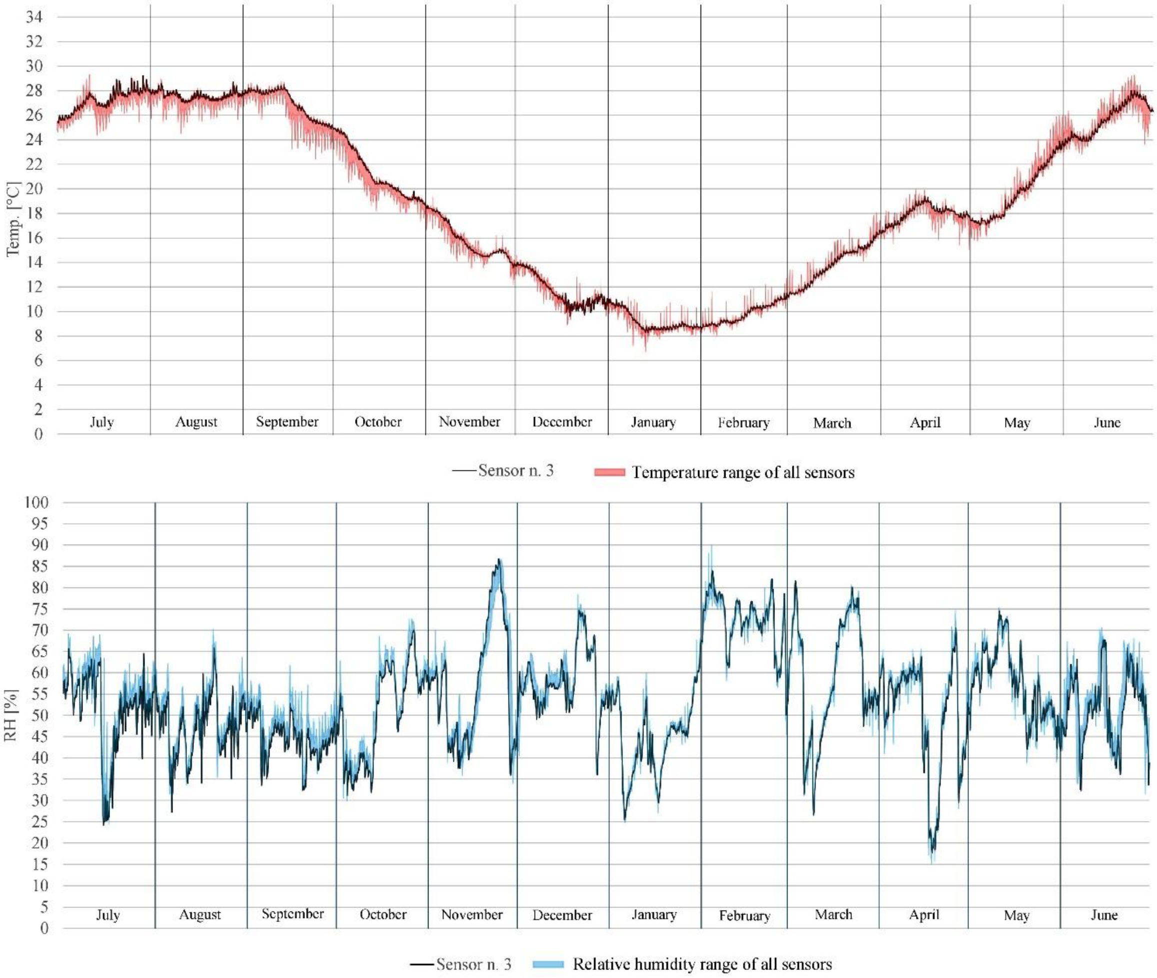


*Fig. 7 - Indoor temperature and mixing ratio range of all the sensors used for the long-term monitoring, the black lines represents the sensor n. 3 considered for the analysis.*

The graphs shows the trend of the microclimatic parameters (temperature, relative humidity and mixing ratio of water vapour in air) during the period July 2016-June 2017.

The internal temperature during the year ranges between a minimum value of 8.3°C in winter and a maximum value of 29.2°C in summer, against external ones that reached minimum and maximum values equal to -2.6°C and 35.4°C (Fig. 8), respectively. In the months of July and August, the internal temperature is quite stable, with a variation of only a few degrees. From September to January, as a result of a rapid decrement of the outside temperatures, also internal temperatures decrease; however, thanks to the huge thermal inertia of the envelope, these are attenuated, and do not fall below 8°C (in January), while externally peaks are found to be below 0°C. In the following months, the internal temperature returns to rise, following the tendency of the external one.

During the monitoring period, relative humidity reached a minimum value of 18% in the month of April, and a maximum of 87% in November. Contrary to the temperature, as can be seen in Fig. 9, relative humidity does not follow a particular trend, but may be subject to considerable variations in the course of each individual day, mainly due to the external climatic conditions.

The mixing ratio reached its peak of 15.3 g/kg in June and its minimum value of 2 g/kg in January. During the entire monitoring period the indoor mixing ratio had a trend similar to the outdoor one.

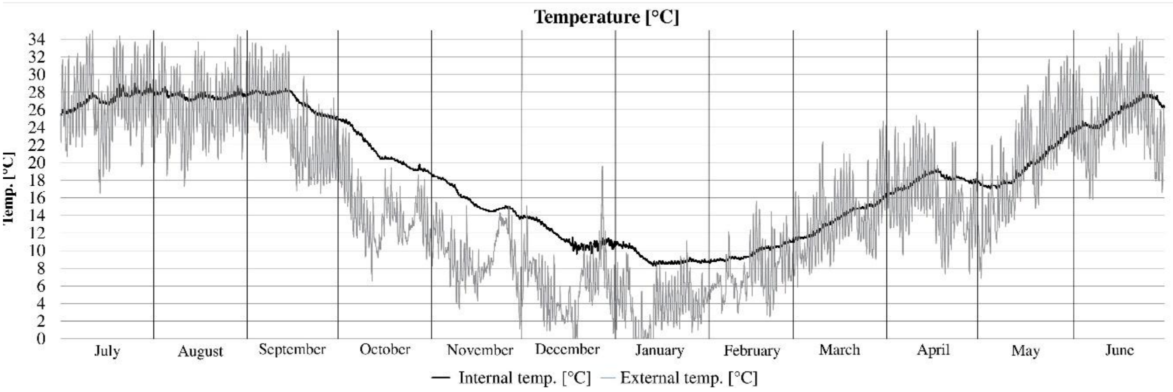


*Fig. 8 - Indoor and outdoor temperature data from July 2016 to June 2017.*

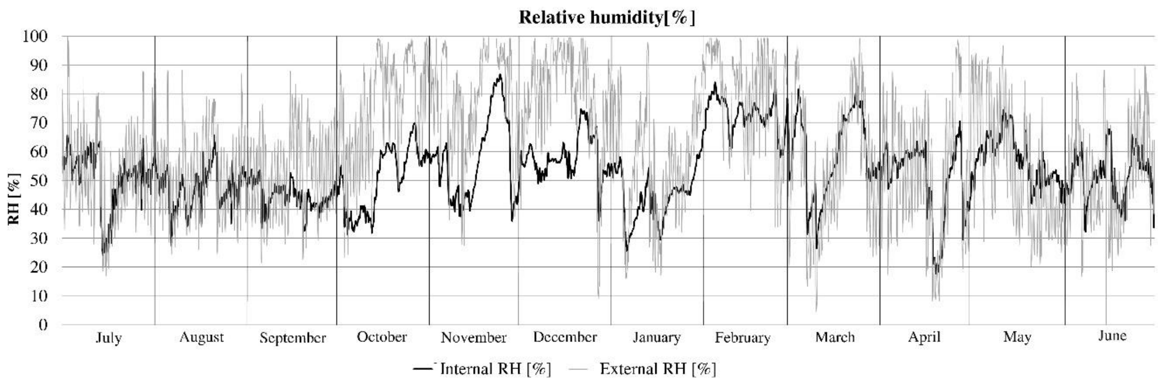


*Fig. 9 - Indoor and outdoor relative humidity data, and rainfall from July 2016 to June 2017.*

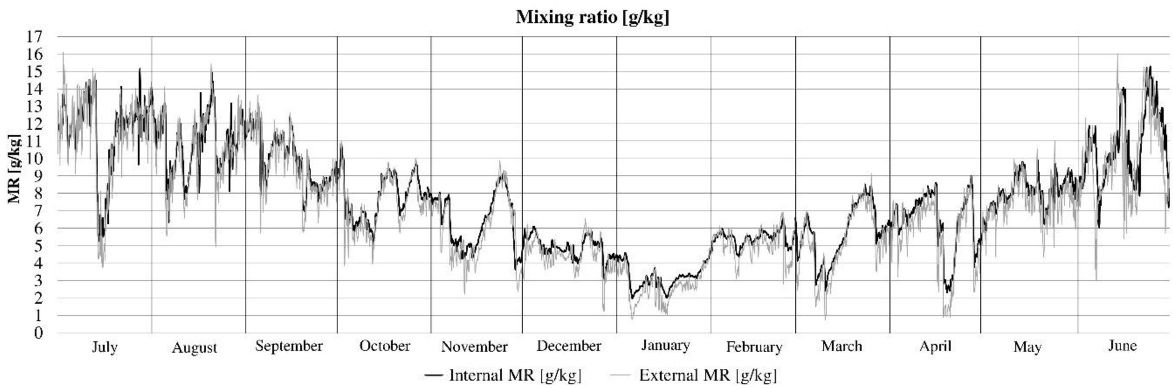


*Fig. 10 - Indoor and outdoor mixing ratio data, and rainfall from July 2016 to June 2017.*

Based on the data collected during the monitoring, a few graphs were drawn, to describe and quantify the interdependence of the internal hygro-thermometric parameters with the external ones. From the data, it is possible to draw a straight line (linear correlation line) that best interpolates the population of each variable. From this straight line, a $R^2$ index can then be calculated, which allows to quantify the quality of the interpolation. This index can have values between 0 and 1; a value close to 0 means that there is no dependence between the data, while a value close to 1 indicates that there is a strong dependence.

The dependence between outdoor and indoor air temperature, as well as that between the outdoor and indoor mixing ratios, are shown in Fig. 11 and Fig. 14; it should be noted that relative humidity is not taken into consideration, because it depends on temperature, and therefore the information is not particularly relevant.

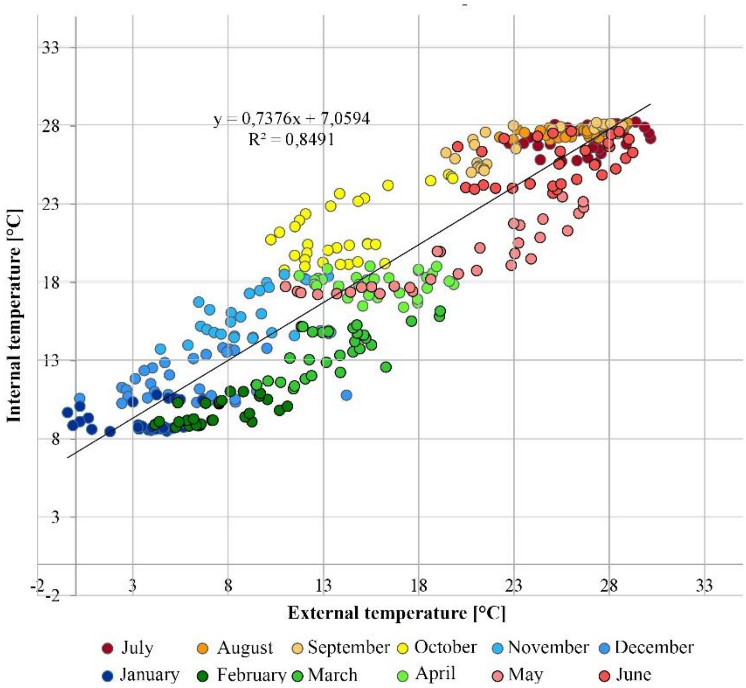


*Fig. 11 - Comparison between the average indoor and outdoor daily temperature recorded from July 2016 to June 2017: the linear correlation line obtained from the data and the corresponding $R^2$ index are shown.*

With regard to temperature, Fig. 11 shows that there is a moderate interdependence between the internal and external average daily values. In fact, the $R^2$ index is about 0.85, mainly because of the high thermal inertia of the envelope, that dampens the temperatures inside the building. In particular, it is possible to observe that, in the summer months, internal temperatures remain close to 28°C, while external ones vary between 20 and 30°C. The same behavior is evident in the months of January and February, when internal temperatures stabilize at values close to 9°C, while outside temperatures vary between -1 and +11°C.

From the observations and the analysis of the data, it can be assumed that the hourly variations of the internal temperature depend on the thermal mass of the building envelope that contributes to maintain the indoor temperature stability [50], reducing the amplitude of the hourly variations due to the air exchange rate with the outside, which occurs through the openings.

Going into details, the temperature values for four representative days of the month of December (Fig. 12) and four days of July (Fig. 13) are shown below. It can be observed that, although outside temperatures oscillate between 10°C and 1°C during the day, internal temperatures remain almost constant, between 13.5°C and 12.5°C (with daily variations not exceeding 0.5°C). This phenomenon, as previously mentioned, is mainly due to the reduced amount of external air coming from the entrance doors. In contrast, when analyzing the days of July (Fig. 13), internal temperatures undergo higher variations in the course of the single day (between 1°C and 1.5°C), due to the windows and doors being open for longer period during the summer months and to higher differences between external and internal temperatures.

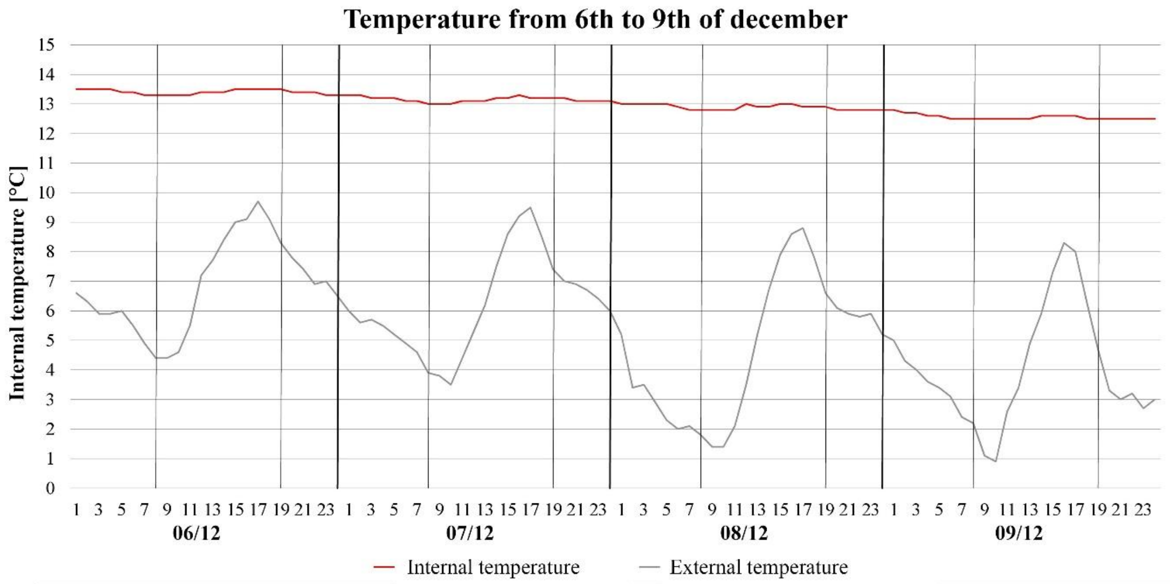


*Fig. 12 - Comparison between internal and external temperatures during selected December days.*

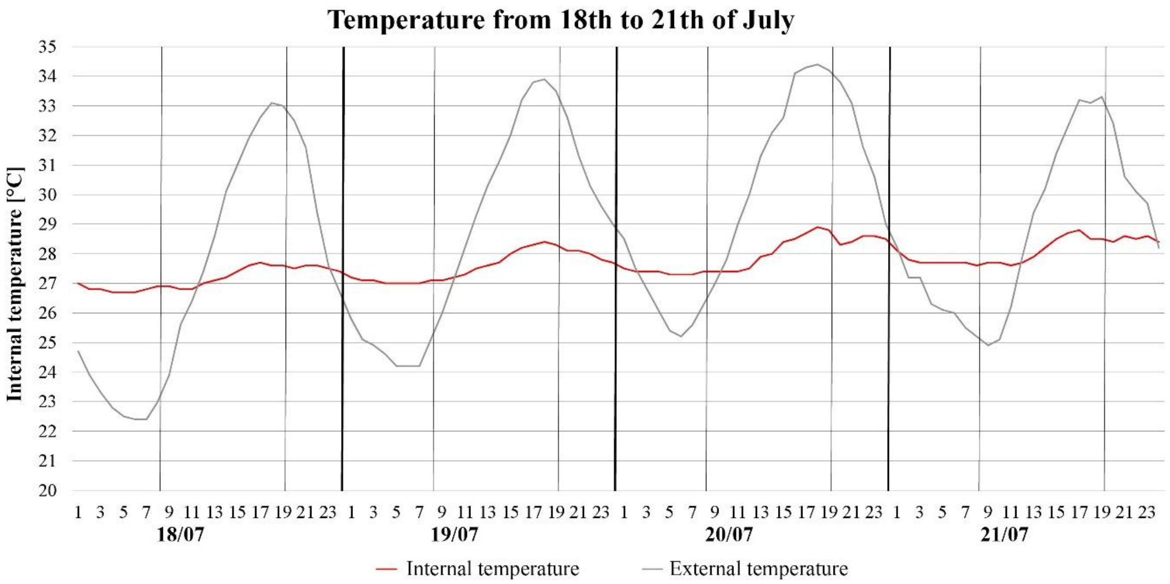

*Fig. 13 - Comparison between internal and external temperatures during selected July days.*

To complete the analysis, the dependence of the internal mixing ratio on the external one is shown in the following graph.

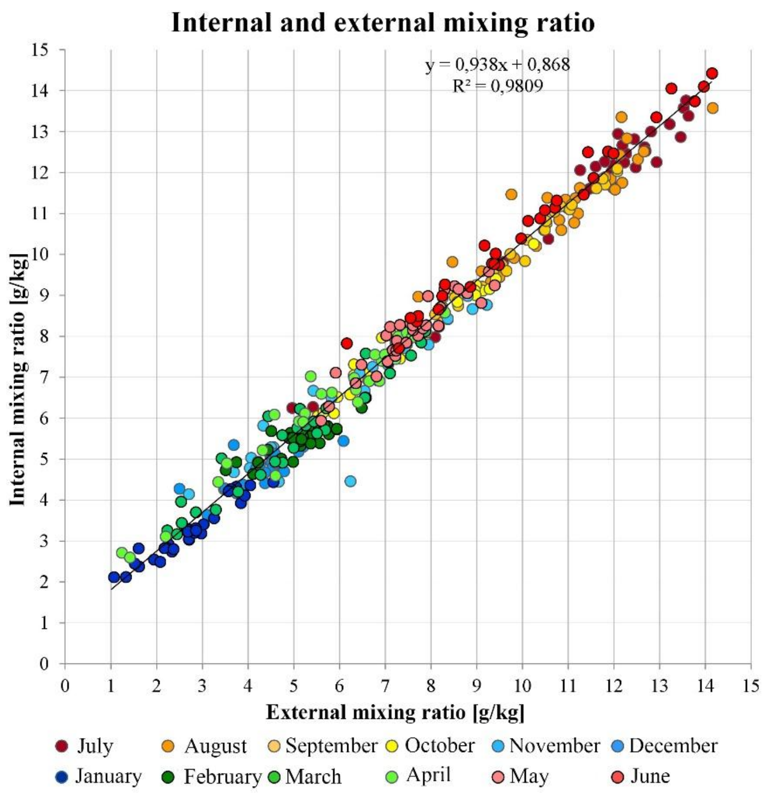


*Fig. 14 - Comparison between daily average internal and external mixing ratio values recorded from July 2016 to June 2017: the linear correlation line obtained from the data and the corresponding $R^2$ index are shown.*

As it can be observed, the $R^2$ coefficient, very near to 1, highlights that the natural ventilation inside the Duomo allows an air-change rate with the outside that sufficient to balance the internal and external daily average mixing ratio values (Fig. 14), without any evident differences between summer and winter. Unlike the internal temperature, which is subject to the effect of the thermal inertia of the envelope, the mixing ratio is mainly influenced by the exchange of air with the outside, while the water vapor produced by people compared to the volume of the building turns out to have little influence.

The microclimatic data collected can be used for different purposes, such as:

- analyze the possible risks to materials caused by specific environmental temperature and relative humidity conditions;

- estimate some parameters that cannot be easily evaluated, for example, air-change rate and infiltration, verification of surface condensation, etc.;
- create a simulation model capable of estimating different intervention scenarios according to different boundary conditions.

In particular, the following section analyzes the possible risks for each type of material used for the artifacts present inside the Duomo.

## 6. Risk-based analysis on the conservation of materials

From the data and information previously collected, it is possible to establish temperature and relative humidity ranges for the correct conservation of the artifacts present in the Duomo, taking into consideration the different causes of the degradation processes. These intervals were derived from regulations [39,40] and from the analysis and comparison of different sources of technical literature [22–24,28–38] (Table 1).

This section summarizes the problems and risks linked to the conservation of certain materials, caused by unfavorable environmental conditions inside the Duomo.

In detail three families of materials, among the main ones the majority of the artifacts inside the Duomo are made of: wood, stone and metal, have been analyzed.

According to the technical literature consulted and reported in Table 1, the most recurrent and commonly accepted conservation ranges for the three main materials analyzed were chosen.

More in detail, the optimal range for the material conservation proposed in this research are the following.

- For wooden materials: temperature between 19°C and 24°C and relative humidity between 45% and 65%, with a maximum daily fluctuation of 6%;
- For stone materials: temperature between 5°C and 25°C and relative humidity lower than 45%, with a maximum daily fluctuation of 10%;
- For metallic materials: temperature range is not considered relevant and relative humidity must to be lower than 50%.

Fig. 15 compares temperature and relative humidity to identify the riskiest periods, during which both factors exceed the suggested limits for the correct conservation of materials. The green areas represent the optimal conditions, both for temperature and relative humidity, for the conservation of the material (the clearer ones both from regulations and literature, while the darker ones only from one source), the yellow areas are where one of the two factors is beyond the conservation limits (dark yellow both from regulations and literature and light yellow only from one source), the red areas are where both microclimatic factors are beyond the conservation limits (dark red both from regulations and literature and light red only from one source): these areas represent the riskiest situations.

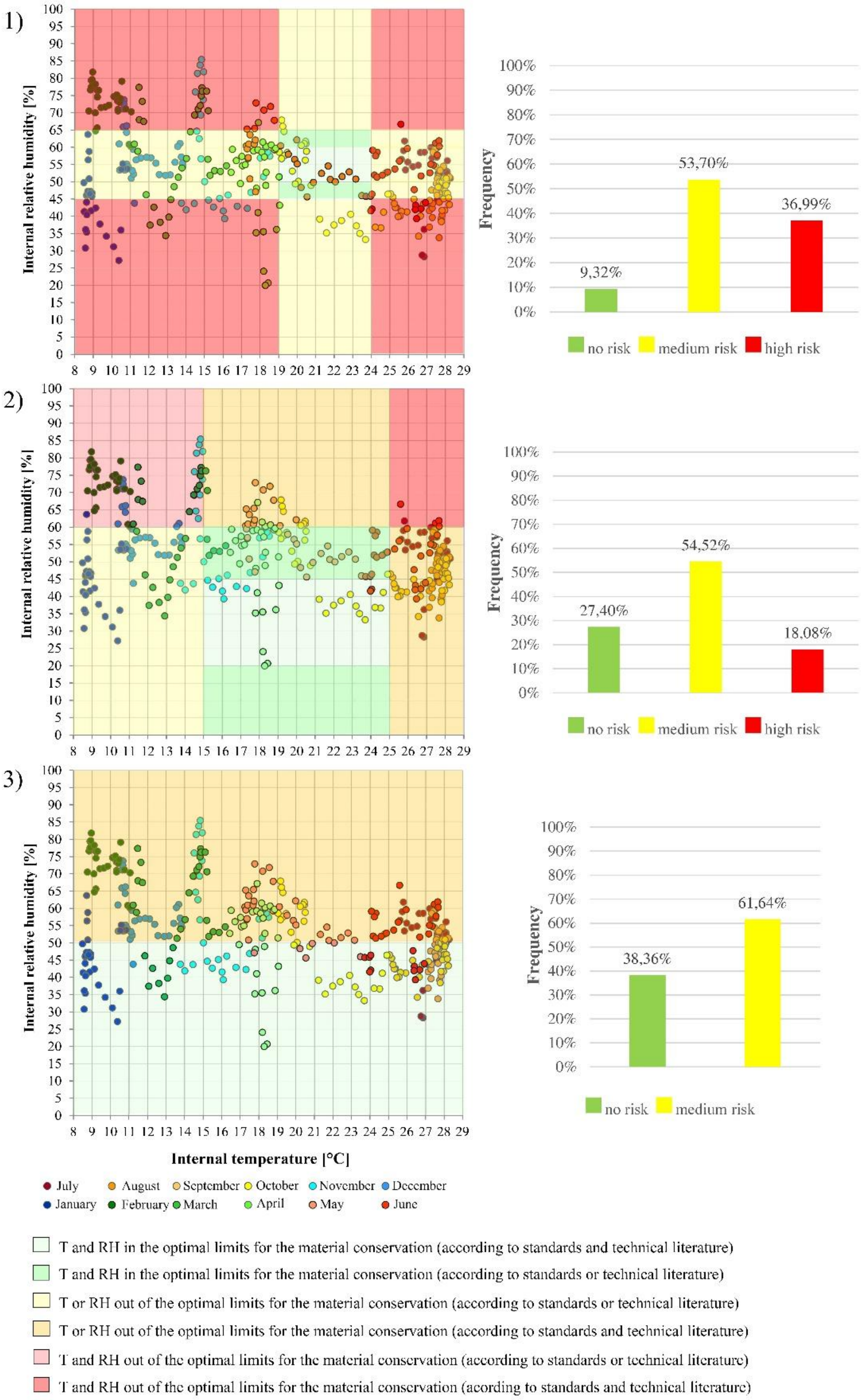


*Fig. 15 – On the right, a comparison between temperature and relative humidity through the identification of the riskiest periods during the months in which both microlimatic factors exceed*

*the intervals for the correct conservation of the material. On the left, frequency and risk level for the materials in the monitoring year (1, 2 and 3 are wooden, stone and metal materials, respectively).*

In detail, wooden materials have more restrictive conservation limits than the other materials analyzed. In the specific case, taking as reference painted wood, standards [39,40] suggest favorable temperatures between 19°C and 24°C, with maximum daily variations of 1.5°C. According to the same regulation, relative humidity must be kept between 50% and 60%, with daily variations of up to 4%. However, as briefly stated above, some literature sources [22–24,28–38] suggest a wider interval.

According to Fig. 15, it can be seen that in the summer temperatures are almost always higher than the recommended values, relative humidity often remains within the upper limit suggested by regulations and technical literature. Under these conditions, biodeteriogens, if present on the surfaces of the materials, can continue to grow, however, a higher relative humidity is required to develop a new attack of mold or fungus. During the months of February, March and December, the relative humidity inside the Duomo remains above the recommended threshold, allowing the biodeteriogens to continue to develop; however, even in this case the chances of a new attack are low, since temperatures are not high.

During some days of April, March, July, August and October, relative humidity reached values below the recommended threshold (45%); this condition, if maintained for a sufficiently long time, can make organic materials less flexible. In particular, in the months with a temperature lower than 19°C this situation can become further risky for the paintings on wooden support, due to the low temperatures that weaken the surface layer, making it subject to the formation of cracks [22].

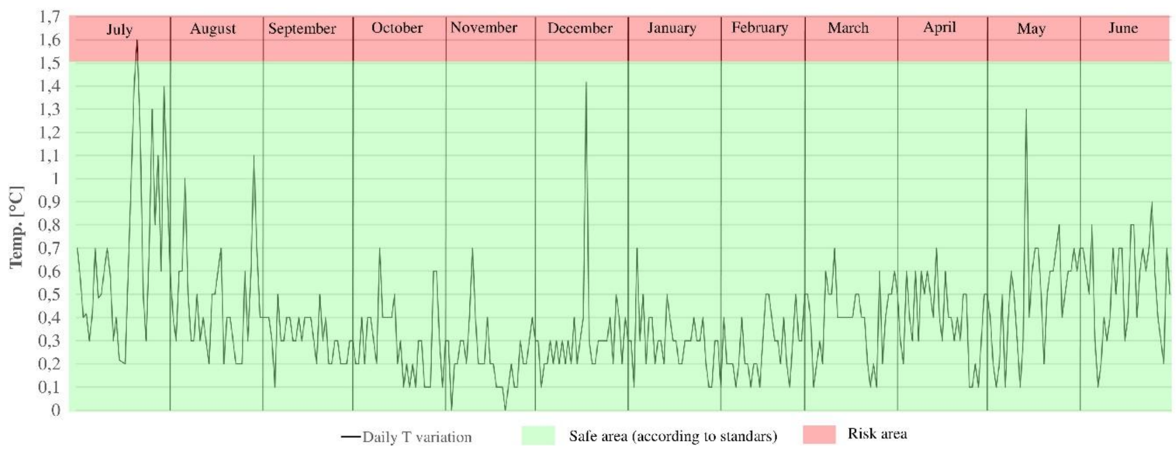


*Fig. 16 - Daily temperature variations within the Duomo in relation to the maximum daily temperature variation permitted by regulations (1.5°C).*

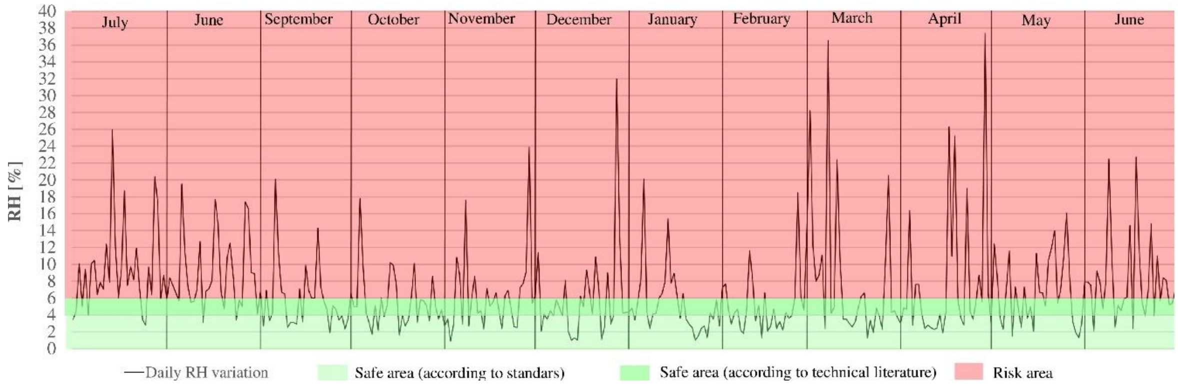


*Fig. 17 - Daily variations in relative humidity within the Duomo in relation to the maximum daily variation allowed by regulations for the correct conservation of wooden materials (4%).*

With regard to fluctuations over the short term, referring to the limits proposed by [39,40] and the technical literature, temperatures inside the Duomo do not constitute any risk for wooden materials, because the variations are always lower than 1.5°C (Fig. 16). Relative humidity (Fig. 17), on the contrary, undergoes repeated and large daily variations, often exceeding the 4% limit suggested by standards (about the 69% of the time) and the wider limits of 6% suggested by technical literature (about the 44% of the time). These continuous oscillations can cause compression-expansion stresses in the wood, which in turn can cause internal and superficial mechanical damage, with the consequent formation of cracks or detachments. This risk increases in the case of paintings on wooden support, due to the different moisture response of the different layers.

According to the acquired data, it can be stated that relative humidity is the main cause of deterioration, since it often exceeds the limits both in the short and long term. In particular, the continuous and wide fluctuation of the daily RH (Fig. 17) produces a stress on the wooden material that, over time, causes the formation of cracks on the surfaces of the objects. As far as the artifacts inside the Duomo are concerned, the presence of cracks and fissures in the choir stalls and numerous confessionals is evident (Fig. 19).

For stone materials, according to [39,40] the correct temperature and relative humidity intervals for a proper conservation are 15-25°C and 20-60%, respectively, with maximum daily variation suggested for relative humidity of 10% (referring to non-porous rocks, such as marble), while for temperature, in contrast, no daily variation limit is indicated. The technical literature consulted [22–24,28–38], on the other hand, provides less restrictive indications as shown in the above summary.

From the available data, it appears that relative humidity exceeds the limit of 60% during the months of February, December, March and May, allowing the growth of bio-organisms and increasing the risk of corrosion of some minerals present in stone materials, such as, for example, the pyrite present in Candoglia marble, with the consequent formation of stains on the material itself. The optimal conditions for the development and rapid growth of bio-organisms, however, occur when temperature and relative humidity are simultaneously above 25°C and 60%, respectively. This condition has rarely occurred, therefore the risks of rapid growth and biological diffusion on stone materials are limited.

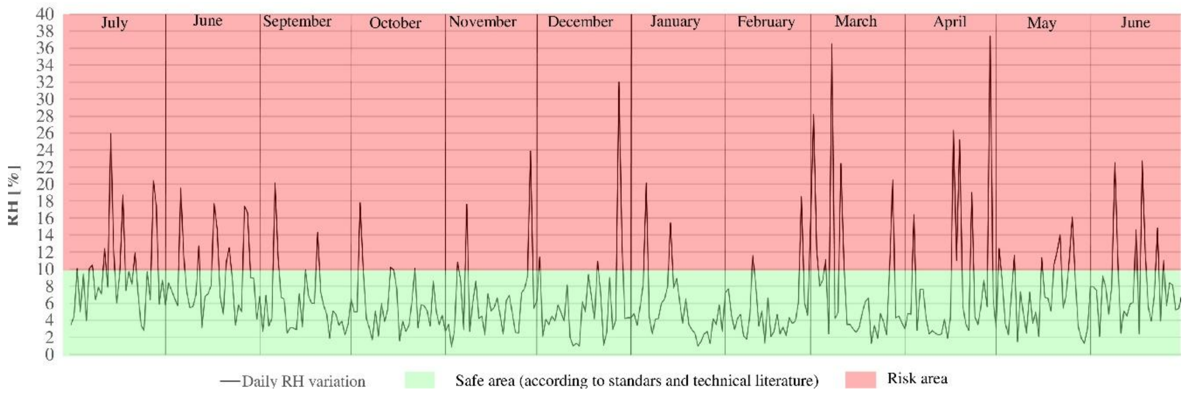


*Fig. 18 - Daily changes in relative humidity within the Duomo in relation to the maximum daily variation permitted by the stone materials regulations (10%).*

According to the analysis carried out, it appears that relative humidity often exceeds the proposed limits, both in the short and long term. In particular, a continuous and excessive fluctuation of relative humidity (Fig. 18) can cause condensation-evaporation cycles on the surface of the material, which favours the transport and accumulation of the salts contained in the stone materials (about the 18% of the time the RH exceeds the limit of 10%), with the consequent formation of efflorescence. Furthermore, if it comes into contact with the pollutants deposited on the material, water could trigger some chemical processes, such as carbonation or sulfation. Specifically, the presence of efflorescence was found in some points on the walls of the side aisles, as can be seen in Fig. 19. However, it should be noted that the rising dump and other phenomena that could cause efflorescence are not investigated in this study.

With regard to metallic materials, the standards [39,40] do not provide information regarding the optimal temperature range to be maintained for their conservation. For relative humidity, on the other hand, only the maximum value of 50% is provided, although no information is given as for the daily variations. According to the technical literature, the maximum relative humidity suggested is indicatively set at 50%, while for the minimum value no reference is provided.

During most of the months of the year, relative humidity was seen to maintain itself for several days above the recommended limit of 50%, favoring the occurrence of corrosion in the materials.

The phenomenon of corrosion in the vault chain of Duomo has been identified, as can be seen in Fig. 19.


*Fig. 19 – On the left, fissures and cracks found in the wooden stalls 1). In the middle, efflorescence found on the internal surfaces of the southern exposed walls 2). On the right, corrosion in the vault chains inside the Duomo 3). Below a map with the locations of the artefacts contained in the Cathedral*

## 7. Conclusions

This study was aimed first of all to identify a proper, non-intrusive monitoring campaign for the Duomo (Milan Cathedral), based on a preliminary acquisition of microclimatic parameters and on a subsequent long-term monitoring.

Based on the analysis of the microclimatic data collected during such monitoring, some specific considerations related to the microclimatic behavior of the Duomo were derived.

In detail, it was possible to state that the high inertia of the Cathedral envelope allows to keep temperature values almost constant during the daily cycles (with variations lower than 2°C) and causes gradual and dampened changes with respect to external conditions in the course of the seasons.

Furthermore, there were no high temperature stratifications with height (temperature differences are lower than 0.5°C) as well as on the horizontal plane, with the exception of the areas near the openings, which are more affected by the variation of the external parameters.

The average daily internal mixing ratio has values very similar to the external ones; this means that the internal air is continuously exchanged with external air through the different openings in the envelope (doors, windows, holes in the roof). Relative humidity has highly variable values over time, due to the external weather conditions; in fact, it can have large fluctuations over a single day, sometimes even higher than 30%.

With respect to the analysis carried out on the risks for the conservation of the main classes of materials present in the Duomo, by consulting the regulation sources and the technical literature, it appears that the most important microclimatic parameter constituting a danger for the conservation of the artifacts is relative humidity, due to its significant and repeated variations in the short term and the peaks reached during some months. During the monitoring year, values of temperature and relative humidity exceeding the limits suggested for the correct conservation of the materials were observed on different occasions, depending on the external climatic conditions. The development of degradation phenomena is mainly caused by the repetition of unfavorable environmental situations and therefore this condition represents a risk for the artifacts present inside the Duomo. From the on-site verification of the objects and the interior finishes, it appears that degradation phenomena are currently taking place. More in detail, in the wooden materials the presence of cracks and fissures is widespread, in the stone materials there is localized efflorescence and the metallic materials are instead subject to corrosion phenomena. In order to improve the environmental conditions inside the Duomo, it is possible to intervene, after a dedicated study, through the implementation of strategies, aimed at improving both the visitors' comfort and reducing the risk of deterioration of objects and interior finishes. These interventions should be planned according to criteria of energy saving, sustainability and conservation. Their design can be supported by the use of simulation models, realized according to the data acquired from the microclimatic monitoring. Such virtual models allow to evaluate different scenarios, depending on the different boundary conditions, in order to predict the building behavior, with the aim to identify the best interventions and solutions.

The methodology adopted in this work allowed to perform a fast, but sufficiently accurate characterization of the microclimate of the Milan Cathedral, using few instruments in comparison to the volume analyzed. The monitoring data collected is the main source of information for carrying out a risk analysis, and for the future implementation of a virtual model supporting further studies.

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# Microclimatic monitoring of the Duomo (Milan Cathedral): risks-based analysis for the conservation of its cultural heritage

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**Nomenclature**

T: air temperature [°C]

RH: relative air humidity [%]

MR: mixing ratio [g/kg]

Δmax temp. - Internal: difference between minimum and maximum daily indoor temperature;

Δmax temp. - External: difference between minimum and maximum daily outdoor temperature;

Δmax RH - Internal: difference between the minimum and maximum daily indoor relative humidity;

Δmax RH - External: difference between the minimum and maximum daily outdoor relative humidity;

Temp. Average - Internal: average daily indoor temperature;

Temp. Average - External: average daily outdoor temperature;

RH Average - Internal: average daily indoor relative humidity;

RH Average - External: average daily outdoor relative humidity.

## 1. Introduction

Historic buildings have an inestimable cultural and artistic value, and contribute to provide a sense of identity for the cities and their inhabitants. The indoor microclimate of such buildings plays a significant role in the conservation of the finishing, the construction elements and the artefacts contained in such spaces.

In the last decades, many studies were carried out for several types of building (churches, museums, etc.), in order to analyze and define the best strategy to preserve and protect these constructions and their artworks [1–21]. The starting point for all these studies is a detailed understanding of the indoor environment compared to the different boundary conditions, in the short and the long period.

Within such context, among the historic buildings, ancient churches are those that most frequently are still practically unaltered at the present day. This allowed the preservation of their considerable

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artistic and architectural features, with particular reference to the artworks they contain (paintings, frescoes, sculptures, wooden panels, sacred objects, furnishings, organs, etc.) [8].

It should be noted that the objects constituting the interior artistic heritage of a church are generally quite sensitive to environmental factors such as air and surface temperature, relative humidity, light and physical agents, whose balance is crucial in order to ensure the maintenance and protection of artworks and materials [22,23]. In more detail, periodic air temperature and relative humidity changes may cause dry and wet cycles and air movements that are usually responsible for deterioration and soiling processes [24][25–27].

To acquire the knowledge about the state of conservation of a historic church, the current deterioration of the materials and the main behaviour of the microclimate over the time, it is essential to carry out a monitoring campaign, using non-destructive methods to avoid damaging any valuable historic surfaces and objects, and also to minimize any interference with the users.

The knowledge of the microclimate behavior inside monumental churches and the identification and definition of the deterioration processes on structures and materials are the prerequisites for the definition of a proper plan and strategy of intervention, to preserve such heritage.

In such context, the present study aims to analyze the environmental behavior of the Milan Duomo, one of the most famous masonry monument in Italy, using a methodology to characterize the internal microclimate. The selected case-study is particularly relevant due to its size (i.e. the second largest church in Italy), building typology (huge thermal mass), turnout of visitors and churchgoers (more than 4.000.000/year) and presence of different materials (e.g. marble, iron, wood, canvas, etc.). The research work represents the first comprehensive microclimate assessment in the Duomo ever carried out, with the scope to analyse in detail the possible risks for the artefacts and the building itself.

In particular, the work shows the results of an in-field experimental campaign carried out through non-invasive measuring instruments that don’t interfere with the regular performance of activities inside the church.

In such respect, the experimental data acquired on the field can also provide useful information for a better understanding of the behaviour of similar historic buildings. The latter, in fact, are often characterized by uncommon features such as considerable dimensions, singular architecture complexity and huge wall thickness that make them unique and not comparable with common buildings. Moreover, really often such buildings host also numerous artefacts such as paintings, sculptures, ancient books that require specific microclimatic conditions. In such respect, it is compulsory evaluate the possible risks for the preservation of artworks/materials, according to the conditions prescribed by the technical literature [22–24,28–38] and regulatory sources [39,40].

The acquired monitoring data can also support the development of a virtual simulation model aimed at characterizing the environment according to the change in the boundary conditions and at evaluating possible energy-efficient solutions, designed to improve the user's comfort and to achieve optimal microclimatic conditions for the conservation of the artefacts.

This methodology could be used by researchers, specialists and policy-makers involved in the conservation of a building's heritage. The main results of the in-field measurements are shown and discussed.

## 2. State of the art on microclimatic monitoring of historic churches and the optimal environmental conditions for their artworks conservation

The hygrothermal behavior of historic churches is often the result of complex energy balances, due to several different causes. The environmental characterization of these buildings is a task that requires a detailed and carefully planned study, based on the analysis of specific problems to be solved. In detail, the European reference standards concerning the measurement of the microclimatic parameters of cultural heritage [41,42] do not define a precise methodology to be used, but describe general procedures, based on the phenomenon to be investigated.

In this respect, over the years, the surveys of historic buildings were carried out by applying different methodologies and tools [1–3,5,10,14,20,21,43–47]. The following section describes the main procedures and methodologies adopted to carry out reliable monitoring campaigns and microclimatic characterizations of some European historic churches.

The monitoring carried out by M.J. Varas-Muriel et al. at the Church of San Juan Bautista in Spain [3,19] investigated the effect on the microclimate of a traditional heating system. For this purpose, nine balloons were inflated with helium gas and distributed at different points in the church. Each balloon had fixed slots supporting 6-7 temperature and relative humidity sensors, spaced 1.5 meters apart. Data was monitored during one day in February and one in March, over a time interval of about 4 hours, with a sampling time of 1 minute. Air flow from the system was measured by an air speed meter.

In the microclimatic analysis of the church of St. Christopher in Lisbon [5,21], numerous sensors were used to measure the internal distribution of temperature and relative humidity of the air, in plan and elevation. The sensors used in this study complied with the minimum requirements suggested by the EN 15758 and EN 16242 standards on the instrumentation to be used for the environmental survey of cultural heritage.

At Santa Maria Nascente in Agordo, on the Italian Alps, the monitoring carried out by Camuffo et al. [2] illustrates some survey methods for the microclimatic characterization of historic churches. In particular, a distinction is made between long-term monitoring, through sensors equipped with data loggers, and punctual (spot) monitoring, in which data is manually taken over a specific period, in order to verify particular conditions. Specifically, the measurement of the profiles of temperature and relative humidity of the air was carried out through casing-free sensors fixed to the ropes, in order to improve the response time. The monitoring of surface temperatures was made using IR thermometers and quasi-contact thermometers, for the most accurate measurements. Finally, thermal images of some selected surfaces were captured through an infrared camera, to evaluate impact of hot air on the different surfaces.

In the study carried out for the church of San Francisco de Asís in Seville, Spain [10], in order to obtain environmental data representative of the internal microclimate, some sensors were positioned in areas not influenced by any source of radiation, air flows coming from outside, etc. The external microclimatic parameters were instead acquired through the closest weather stations.

The different methodologies described above underline the need to install a large number of sensors, uniformly spaced, often hooked to ropes suspended by means of balloon probes, or fixed to the roof of the building. Despite allowing to represent the spatial distribution of the microclimatic parameters, such systems involve the physical and visual occupation of some areas or the entire building for a specific period.

The characterization of the microclimate through the mapping of microclimatic parameters should be considered an indispensable condition for the assessment of the state of conservation of the building and the precious objects stored therein.

In general, the transformation processes affecting these objects can be of different origins [23]:

- physiological, namely the natural aging of materials, which can be slowed down through proper conservation;
- pathological, due to the formation of degradation: causes may be internal – for example due to the instability of the material or the processes to which they were subjected – or external, related to the environmental conditions of surroundings.

In general, the main environmental parameters to study and monitor are: relative humidity, temperature, light and the pollution in the air [22]. However, in this work, the effects related to temperature and relative humidity of the air on the conservation of the building are taken into account and discussed in detail. Such parameters, in fact, can lead to physical, chemical or biological degradation processes that can irreparably damage the artworks and the building itself.

Although both technical literature [22-29,35-40] and regulations [27,28] sets the optimal range to avoid the deterioration of different materials (Table 1), very often the suggested values do not correspond to each other. For such reasons, in table 1 the optimal environmental conditions of three main families of materials (woods, stones and metals), among the main ones the majority of the artefacts inside of historic churches are made of, are reported and subsequently discussed in detail in section 6.

*Table 1 – Comparison of optimal conservation ranges for woods, stones and metals, as suggested by various sources.*

| | *Material* | *Air T [°C]* | *Max daily fluctuation of T [°C]* | *Air RH [%]* | *Max daily fluctuation of RH [%]* | *Sources* | *References* |
|---|---|---|---|---|---|---|---|
| Woods | Polychrome wooden sculptures, painted wood, paintings on wood, icons, wooden pendulum, musical instruments of wood | From 19 to 24 | <1,5 | From 50 to 60 | <4 | UNI10829- UNI10586 | [39,40] |
| | - | <20[a] | - | <70[a] | -[b] | Carbonara | [24] |
| | Wood, tissue, paper | <18-20[a] | - | <65[a] | -[b] | Camuffo | [34,38] |
| | - | - | - | From 30 to 65 | -[b] | PAS 198 | [22] |
| | - | From 19 to 24 | - | From 45 to 60 | - | MIBAC-Petrelli, Fabbri | [29,30] |
| | Polychrome wooden sculptures, painted wood | - | - | From 45 to 60 | - | AAM - Haiad, Druzik, Ayres, Lau - IFROA - Jhonson-Horgan | [31,32] |
| | = | - | - | From 55 to 65 | - | Banchmann | [31,32] |
| | = | - | - | From 50 to 65 | - | Cavallini, Massa - Gambalunga | [31,32] |
| | = | - | - | From 45 to 65 | - | Coccitto | [31,32] |
| | = | - | - | From 50 to 65 | - | ICCROM | [31,32] |
| | = | 20 | - | From 45 to 55 | <5 | Musée de France | [31,32] |
| | = | 20 | - | From 45 to 60 | - | Stolow | [31,32] |
| | = | - | - | From 50 to 60 | <5 | Thomson | [31,32] |
| | Painted panel wood and musical instruments | From 19 to 24 | - | From 45 to 55 | <2 | Baumont-Laurie | [31,32] |
| | polychrome wooden objects | From 19 to 24 | - | From 35 to 50 | <6 | Baumont-Laurie | [31,32] |
| | painted panel wood | From 21 to 23,5 | - | From 45 to 55 | <6 | ROM | [31,32] |
| Stones | Mosaics, stones, rocks, minerals, meteorites (not porous), fossils and stone collections | From 15 to 25 | - | From 20 to 60 | <10 | UNI10829 and UNI10586 | [39,40] |
| | mineralogical collections, marbles and stones | <30 | - | From 40 to 65 | - | MIBAC-Petrelli, Fabbri | [29,30] |
| | - | >5[c] | - | - | - | Carbonara | [24] |
| | - | >5[c] | - | <55[d] | -[b] | PAS 198 | [22] |
| | = | - | - | <45 | - | Banchmann | [31,46] |
| | = | - | - | From 40 to 45 | - | Cavallini, Massa | [31,32] |
| | = | - | - | From 20 to 40 | - | Coccitto | [31,32] |
| | = | - | - | From 0 to 45 | - | De Guichen -Gambalunga - ICCROM | [31,32] |
| | = | From 21 to 23,5 | - | From 25 to 50 | <10 | ROM | [31,32] |
| | = | - | - | From 20 to 60 | - | Stolow | [31,32] |
| | = | From 10 to 25 | - | From 65 to 70 | - | Thomson | [31,32] |
| Metals | Metals, honed metals, metal alloys, silver, armor, weapons, bronzes, coins, copper objects, tin, iron, steel, lead, pewter | - | - | <50 | - | UNI10829 and UNI10586 | [39,40] |
| | - | - | - | <60 | - | Carbonara | [24] |

| | | | | | | |
|---|---|---|---|---|---|---|
| Metals (except archaeological metals) | - | - | <65-70 | - | PAS 198 | [22] |
| honed metals and alloys, brass, silver, pewter, lead, copper | - | - | <45 | | MIBAC-Petrelli, Fabbri – Banchmann - ICCROM | [29,30] |
| iron armor and weapons, bronze, honed metals and alloys, brass, silver, pewter, lead, copper | - | - | <30 | - | AAM - Haiad, Druzik, Ayres, Lau | [31,32] |
| = | - | - | From 50 to 55 | - | British Museum | [31,32] |
| = | - | - | From 40 to 45 | - | Cavallini, Massa - | [31,32] |
| = | - | - | <60 | - | Coccitto | [31,32] |
| = | - | - | From 0 to 45 | - | De Guichen - Gambalunga | [31,32] |
| = | - | - | From 50 to 65 | - | Musée de France | [31,32] |
| = | - | - | From 40 to 45 | - | Thomson | [31,32] |

a. To avoid biological degradation;
b. High and repeated variations in a short period of time must be avoided;
c. The minimum safe temperature to avoid possible freezing of the water contained in the material;
d. To avoid the oxidation of some minerals present in the stones.

After the description of the case study (section 3), the paper presents the methodology adopted to carry out the experimental monitoring campaign, which is divided into two phases: a preliminary analysis and a long-term monitoring (section 4). The first phase allows to obtain an initial and sufficiently detailed characterization of the internal microclimate, by using portable and moveable instruments placed along a three-dimensional grid of monitoring points; its aim is to identify the most relevant areas for the subsequent positioning of fixed sensors for the second phase (the long-term monitoring). In fact, due to the particular building typology and all the existing constraints, the possible installation points for permanent sensors were limited and the most representative ones had to be selected.
Finally, according to the data acquired during the monitoring, shown in section 5, a risk analysis related to the conservation of the main materials and artefact has been carried out (section 6).

## 3. The case-study: Milan Cathedral (Duomo di Milano)

The *Duomo di Milano*, one of the largest Cathedrals in Italy, is located in the homonymous square, in the heart of the city. The building construction started toward the end of the $14^{th}$ century and lasted for more than four centuries, but its maintenance works still continue today.
This section reports the main dimensional and material information on the Duomo. Internally, the Cathedral spreads over an area of 8,500 $m^2$ in plan, with a volume of about 300,000 $m^3$, with internal heights ranging from 20 to 45 m for the side aisles and the central one, respectively, and up to 65 m in correspondence with the dome. The building envelope is made of dry masonry walls of varying thickness (between 1 and 5.7 m), with external sides made of Candoglia marble ashlars, one further internal supporting stone layer of relatively lower quality, and an internal filling consisting of a mixture of aggregates and crushed stone from lime mortar. The total number of stained glass windows are 49, including 43 decorated and 6 without decoration. The glazed surface to wall surface ratio is approximately 20%. The roof construction system is composed of a double system of overlapping brick vaults, which form walkable attic spaces called “sordis”. These areas are in direct contact with the internal environment of the Cathedral, thanks to the numerous holes in the vault system.
The air ventilation across the building is primary related to the opening’s management. More in detail, two different strategies are currently applied during the year:

1. the first one, used during cold months, consists in keeping all the windows closed. In such condition, the main flow rate is due to the entrance gates, when churchgoers and tourists go through them;

2. the second one, adopted exclusively in the summer months (from mid-June to mid-September), aim to increase as much as possible the flow rate through the openings of the windows located in the ambulatory (around the choir and the apse) and in the transept;

In such respect, the total area of windows and doors opened is approximately 30 $m^2$ and 100 $m^2$ during cold and hot months, respectively.

Inside the Cathedral there are numerous artifacts of various nature, age and material. The marble covers the entire envelope, and is one of the stone materials used to create the numerous sculptures and decorations that enrich the Cathedral; wood was used for the benches, confessionals, choir stalls and organ cases, both the older and more recent ones of which have large oil-painted wooden doors. In the numerous altars of the side aisles there are also various artifacts of different origins and materials, including: silver, copper and bronze relics, bodies of buried Saints kept in glass cases, etc. [48].

The geometric and constructive characteristics of the Duomo have a notable impact on the internal microclimate which, in turn, influences the conservation of the materials and artifacts, as described in the following sections.

It should be noted that, currently, no heating, cooling or mechanical ventilation systems are present in the Cathedral.

## 4. Methodology and monitoring process

The microclimatic data acquisition was carried out through the use of non-invasive instruments, in order to keep the finishes and artifacts intact and to ensure the smooth running of the activities inside the Duomo. The mobile instrumentation used during the preliminary monitoring phase allowed to have a first characterization of the internal microclimate, by monitoring some sample days, highlighting the main behavior of the microclimatic parameters on the entire volume of the building. During this phase, it was possible to identify the main gradients of temperature and relative humidity on the whole church volume. According to such preliminary microclimatic characterization, the permanent sensors for the long-term monitoring were located in some representative points, easily accessible inside the Cathedral.

The measurement methods adopted in the two phases of the monitoring campaign are described below:

- <u>preliminary acquisition of microclimatic parameters</u> (February-July 2016), based on a three-dimensional grid of monitoring points; this phase aimed at the general characterization and mapping of temperature and relative humidity profiles, using portable sensors, in order to properly plan the long-term monitoring;

- continuous long-term monitoring, (July 2016-June 2017), with fixed sensors positioned at relevant points and able to store the information collected. The aim of this phase was to carry out a comprehensive microclimatic monitoring.

The measuring instruments used and the methodologies adopted are described in detail here below.

### 4.1 Measurement instruments

The instruments used for the monitoring activities were carefully selected, to ensure the best compromise between accuracy and compatibility with the installation conditions; in detail, they consist of:

- temperature and relative humidity sensors for indoor air;
- infrared temperature sensors, for the measurement of the surface temperature of materials;
- hot-wire anemometer, for the measurement of air velocity.

In particular, the main features of the different types of instruments used are shown in Table 2.

*Table 2 - Types of instruments used for the microclimatic monitoring.*

| | *Instrument model* | *Measured parameters* | *Measurement range* | *Accuracy* | *Resolution* | *Response time* |
|---|---|---|---|---|---|---|
| 1 | Episensor TES-11/HTS-10: (Wireless sensor) | T | from -20 to +60°C | +/- 0.2°C | 0.1°C | few min.* |
| | | RH | from 11 to 89% | +/- 3% | 0.1% | few min.* |
| 2 | HOBO UX100-011 (sensor with datalogger) | T | from 20 to +70°C | +/-0.21°C (0 … +50°C) | 0.024°C (at 25°C) | 4 min. |
| | | RH | from 0 to 95% | +/- 2.5% (10 … 90%) | 0.05% (at 25°C) | 11 sec. |
| 3 | HOBO U12-011 (sensor with datalogger) | T | from -20 to +70°C | +/-0.35°C (0 … +50°C) | 0.03°C (at +25°C) | 6 min. |
| | | RH | from 5 to 95% | +/- 2.5% (10 … 90%) | 0.03% | 1 min. |
| 4 | HORIBA IT-545 NH/N/S (infrared thermometer) | Superficial T | from -50 to +1000°C | +/-1.0°C (0 … +199.9°C) | 0.1°C (0 … +199.9°C) | < 0.8 sec. |
| 5 | Thermo-anemometer Testo 405-V1 | Air velocity | from 0 to +10m/s | +/- 0.1m/s (0 … +2m/s) | 0.01m/s | - |
| | | T | from -20 to +50°C | +/-0.5°C | 0.1°C | - |

* Evaluated during the monitoring phase

Instruments 2, 3 and 4 in Table 2 complied within the minimum requirements suggested by European regulations [41,42] on the measurement of the microclimatic parameters for the conservation of cultural heritage. Sensor 1, used during the preliminary monitoring phase, complied within the requirements suggested by these regulations, except for the relative humidity measurement range; however, values above the instrument limits (11% and 89%) have never been recorded. In order to improve the response time of instrument 1, its plastic cover was removed, so as to leave it more exposed to the flow of air, and limit the influence of the thermal inertia of the building. Instrument 5, on the other hand, was used only for internal air velocity measurements.

### 4.2 Preliminary acquisition of the microclimatic parameters

During the first monitoring phase, wireless sensors (model 1 in Table 2) were attached to a balloon-probe connected through a nylon rope to a winch, for winding and unrolling the cable and then adjusting the lifting height. Thanks to a trolley, on which the winch was fixed, it was possible to easily move the equipment inside the Duomo during the measuring operations. From February to July 2016, microclimatic parameters were monitored during some sample days, representative of the various weather conditions. A computer placed on the trolley received and displayed in real time the data acquired by the sensors fixed on the balloon-probe. The system layout prepared during the preliminary acquisition phase is shown below.

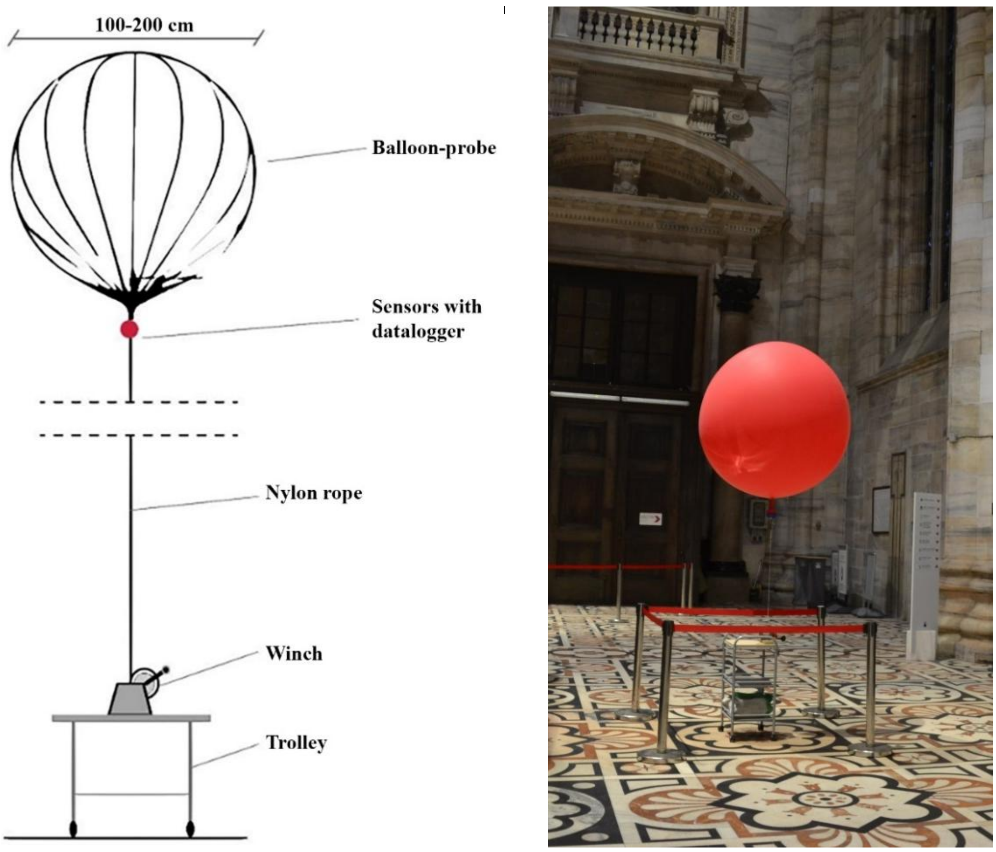


*Fig. 1 – Scheme (left) and view (right) of the system used for data acquisition during the first monitoring phase.*

In order to map and characterize the large space of the Duomo, the plan was divided into areas bounded by a virtual grid, whose columns were numbered in ascending order, while the rows were identified using the actual name of the naves and transects (Fig. 2). In addition, based on this grid, 9 representative monitoring points were defined in plan and distributed in the North, central and South naves of the Cathedral; for each of them, measurements were carried out at different heights, for a total of 42 acquisition points. In detail, in the North and South aisles, characterized by a maximum height of approximately 20 m, 4 measurements were carried out, 5, 10, 15 and 20 m from the walking surface, respectively; instead in the central nave, which is characterized by a maximum height of 45 m, two further measurements were carried out at a height of 35 and 40 m, respectively (Fig. 3).

The data monitoring at the identified points was carried out according to successive cycles, always starting from the North aisle, continuing in the direction of the transept, then in the central nave and finally in the South one, as shown in Fig. 2. Each monitoring cycle, lasting between 1 hour and 10 minutes to 1 hour and 40 minutes, was repeated 4 times daily. Data related to the outdoor environment was acquired from the Brera weather station, the closest to the Duomo among the weather stations of the ARPA (Regional Environmental Protection Agency) present in the city [49].

Internal surface temperatures were measured by taking into consideration some representative points close to the air temperature measurement points. In particular, in the North and South aisles for each point analyzed, surface temperatures were acquired in 18 positions: 8 shared between the North and South columns with respect to the measurement points of air temperature and relative humidity, 8 between the windows on the left and right of each column, and finally one measurement on the floor and the intrados of the vaults (see Fig. 2 and Fig. 3).

Spot measurements of the air velocity were acquired at the monitoring points shown in Fig. 2 (red circles), during each monitoring cycle, at a height of about 1.5 meters.

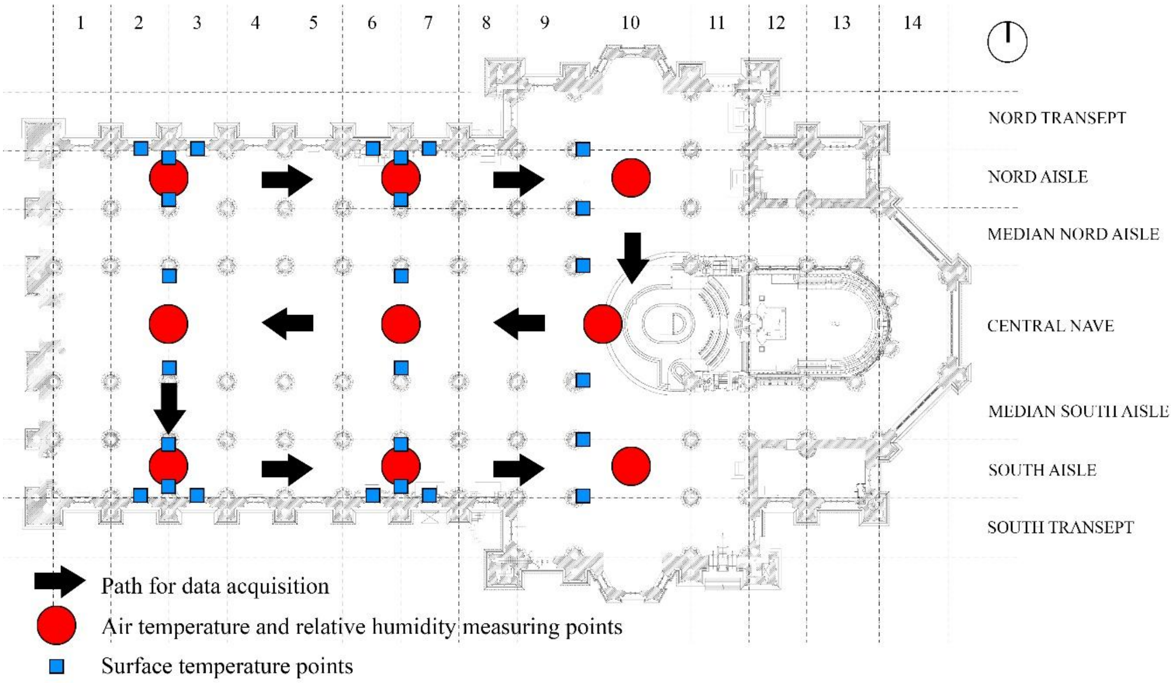


*Fig. 2 - Identification of the air T/RH measurement points in plan and surface temperatures for the preliminary monitoring activity.*

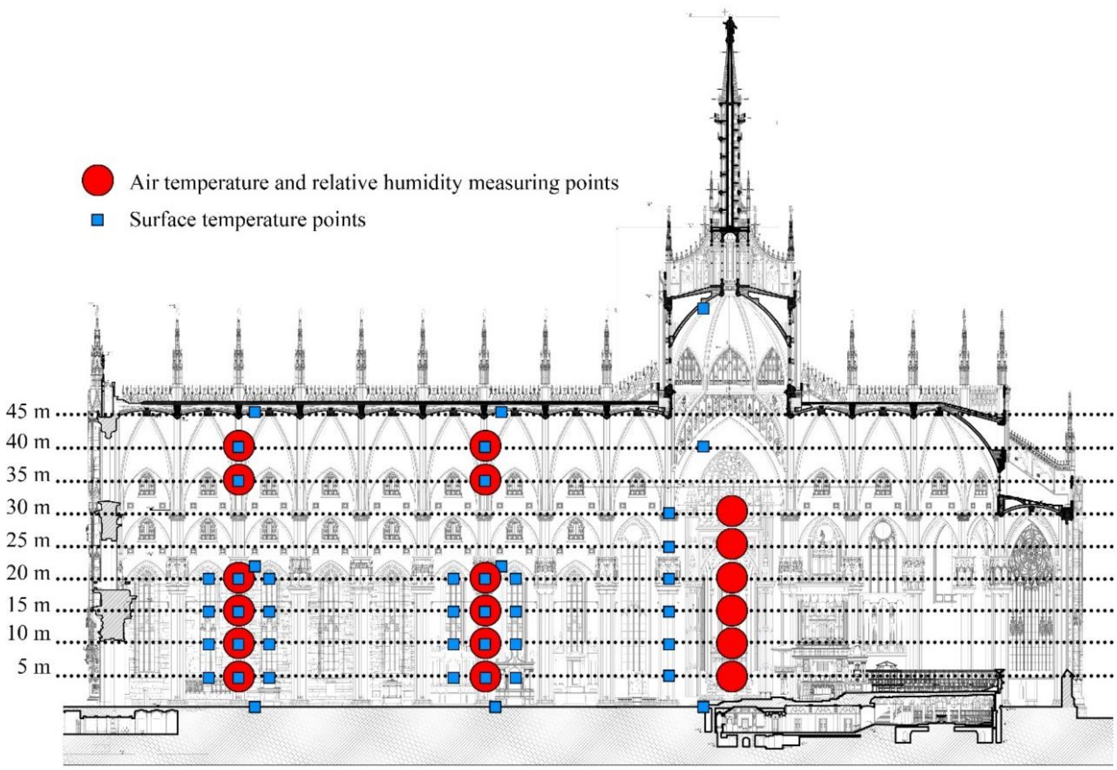


*Fig. 3 - Identification of air T/RH measuring points across height and surface temperatures for the preliminary monitoring activity.*

Once the preliminary microclimatic monitoring phase was completed, in July 2016, the information collected was used to define the position of the sensors for continuous monitoring. From the comparison of the information acquired through the campaign, it appears that the differences in temperature and relative humidity in the various measurement points are not relevant (i.e. are within or very close to the range of accuracy of the sensors, equal to +/- 0.2°C and +/- 3% for temperature and RH respectively), except for the areas near the entrance to the North aisle, which undergoes higher variations, since the gate is used as a primary entrance by churchgoers. More in detail, the most interesting results are summarized below.

- Vertical gradient of air temperature and relative humidity across the height of each point in plan (within each vertical set of measurements of about 12-15 minutes): there was no significant temperature gradient in the measurements at different heights; in fact, despite the great height of the aisles, the variations between the lowest and the highest points never exceeded 0.5°C; this behaviour is clearly related to the absence of a heating system inside the church and to the fact that internal gains are negligible in comparison with the volume;
- Horizontal gradient of air temperature and relative humidity across the plan at a certain height (within each horizontal set of measurements of about 80 minutes): as already mentioned, the temperature gradient in the measurements across the plan is limited, except for the measurements of the sensor located close to the gate of the North aisle. In detail, the variations among the measured points never exceeded 0.5°C for temperature and 2% for relative humidity, except for the areas near the entrance, where the variation achieved values up to 2°C and 6% for temperature and relative humidity respectively;
- Variation of temperature and relative humidity between average indoor and outdoor conditions in the course of the day: during each single monitored day, the internal temperatures had small variations, from a minimum of 0.6°C to a maximum of 1.4°C, in comparison to the variations in the external temperature, between 1.3°C and 7.1°C; as illustrated in detail in section 5, this is mainly due to the effect of the thermal inertia of the envelope; during the measurement day, the internal relative humidity increased or decreased between 2% and 23%. The maximum daily variation recorded corresponded to a drop in the internal relative humidity of 23%, compared to 58% of the external one;
- Air speed: the air velocities recorded at the monitoring points at a height of about 1.5 meters were between 0.01 m/s and 0.1 m/s (the accuracy of the sensor is 0.1 m/s). The highest values were measured in bays 2-3 (see Fig. 2) and, in particular, in the vicinity of the entrance gates.

From the analysis of the data acquired during this preliminary phase, it can be noted that, due to the large volume and the high thermal inertia of the envelope that characterizes the Cathedral, the internal temperature variations are small. On the contrary, relative humidity is more unsteady, as will be discussed in detail in the following sections.

### 4.3 Long-term microclimatic monitoring

The preliminary monitoring phase described above allowed to obtain an initial characterization of the hygrothermal behavior of the Duomo, to identify the most relevant measuring points, representative of the general microclimatic conditions inside the Cathedral. In these points, temperature and relative humidity fixed sensors (models 2 and 3 in Table 2) were positioned for continuous data collection, with hourly acquisition time intervals. The positioning of these probes took place in July 2016. More in detail, the six points identified were chosen in order to have a comprehensive picture of the microclimatic behavior of the Duomo, as well as to take into account the safety and accessibility criteria of the available areas (Fig. 4 and 5). In particular:

1. sensor 1 was placed on the balcony above the main entrance door in the west façade, at a height of approximately 18 m; it is representative of the average conditions in the frontal part of the church;
2. sensor 2 – positioned on the roof of the “ascolto” room, at a height of 2.2 m – recorded the data most influenced by the external air coming from the openings on the west façade;
3. sensor 3 – on the balcony of the organ, on the right side of the altar, at a height of about 9 m – acquired the hygrothermal data close to the altar, where various artworks/sensible elements are presents;
4. sensor 4 – on a table placed in the North transept – characterized the conditions in the transept;
5. sensor 5 – positioned in front of one of the openings in the South-facing median “sordis”, which overlooks the central nave, at a height of about 30 m – allowed to verify the thermal gradient compared to the values recorded at the lowest levels;
6. sensor 6 – placed behind the altar on the dividing wall towards the ambulatory – allowed to record the hygrothermal condition in the rear area of the Cathedral.

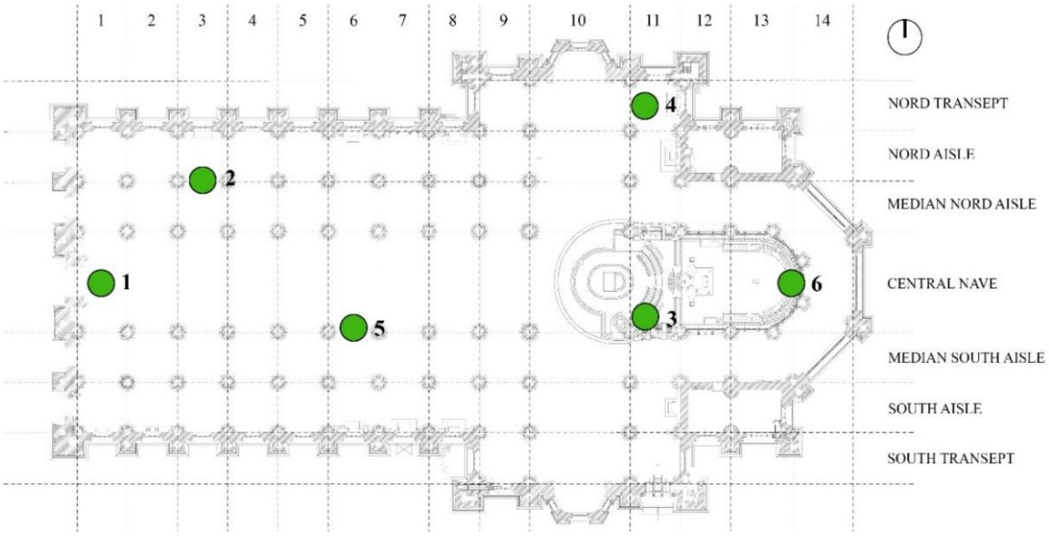


*Fig. 4 - Identification of the points in plan where the fixed T/RH probes were positioned.*

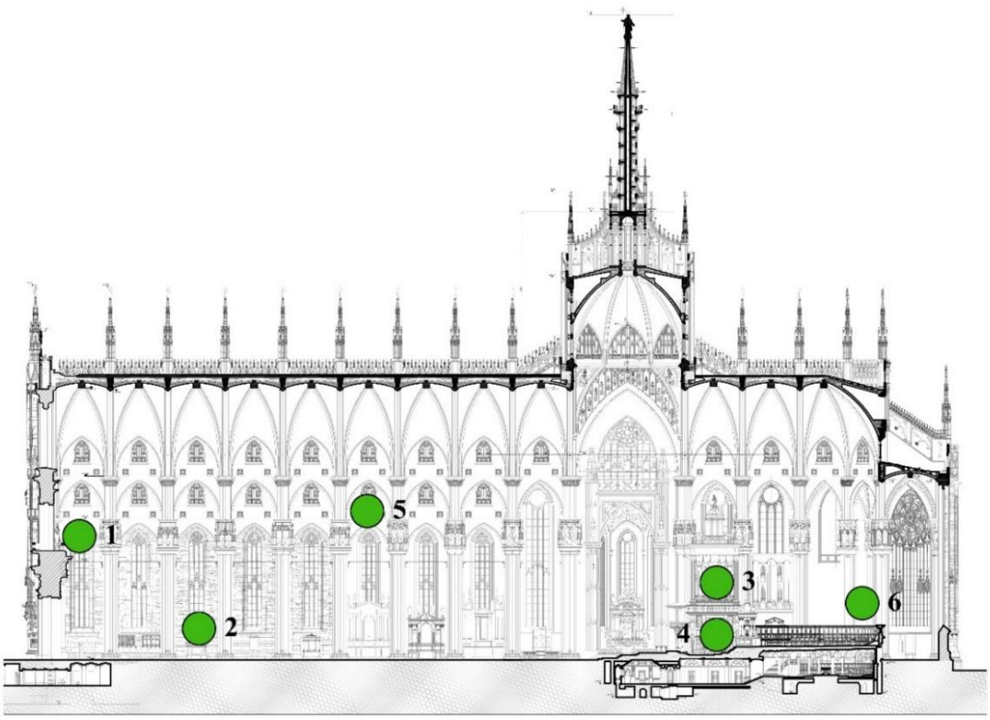

*Fig. 5 - Identification of the points across the height in which the fixed T/RH probes were positioned.*

## 5. Results and discussion on microclimate assessment

The data collected in the second phase of the monitoring were elaborated in order to characterize the behavior of the main parameters representative of the internal microclimate, with respect to the variation of the outdoor microclimatic parameters and the internal conditions of use.

### 5.1 Effect on microclimate due to the presence of people

In general, internal gain due to people is one of the parameters that affect indoor microclimate of historic buildings. As demonstrated by some research, the temporary presence of devotees and visitors in spaces, in fact, have an influence on temperature and humidity distribution according to the displacement and number of people [47]. Of course, the most influenced areas are those close to the devotees, whereas in the surroundings the variations are minor [47]. In this respect, it must be noted that the Duomo is characterized by a huge air volume comparted to other historic buildings, thus the simultaneous presence of a large number of people in a certain moment of the day and in a certain part of the church has a relevant influence on the local microclimate.

In this sense, in order to analyse the effect on the microclimate, during the preliminary monitoring a study on the local variation of internal hygrothermal parameters with respect to the simultaneous presence of high density of people in a specific section of the cathedral has been carried out. Environmental data were acquired on two days (April 16$^{th}$ and17$^{th}$) characterized by considerable overcrowding of the area in front of the altar due to the presence of important musical and religious events inside the Duomo. The balloon-probe was placed near the benches of the central nave at a height of 30 m, in a midpoint with respect to the position of the visitors. During the morning celebration of the first day, the simultaneous presence of about 750 people was documented in the nave, and an increase of the internal temperature of about 0.5 °C was recorded (Fig. 6). After the event, when most of that 750 people went out the church, the local internal temperature dropped closer to the daily average indoor value, although the external one continued to increase. Similar trend, although less significant, was observed during the afternoon events, characterized by the average presence of 200 people, and in the celebrations of the following day, attended by about 280 people in the morning and 400 in the afternoon.

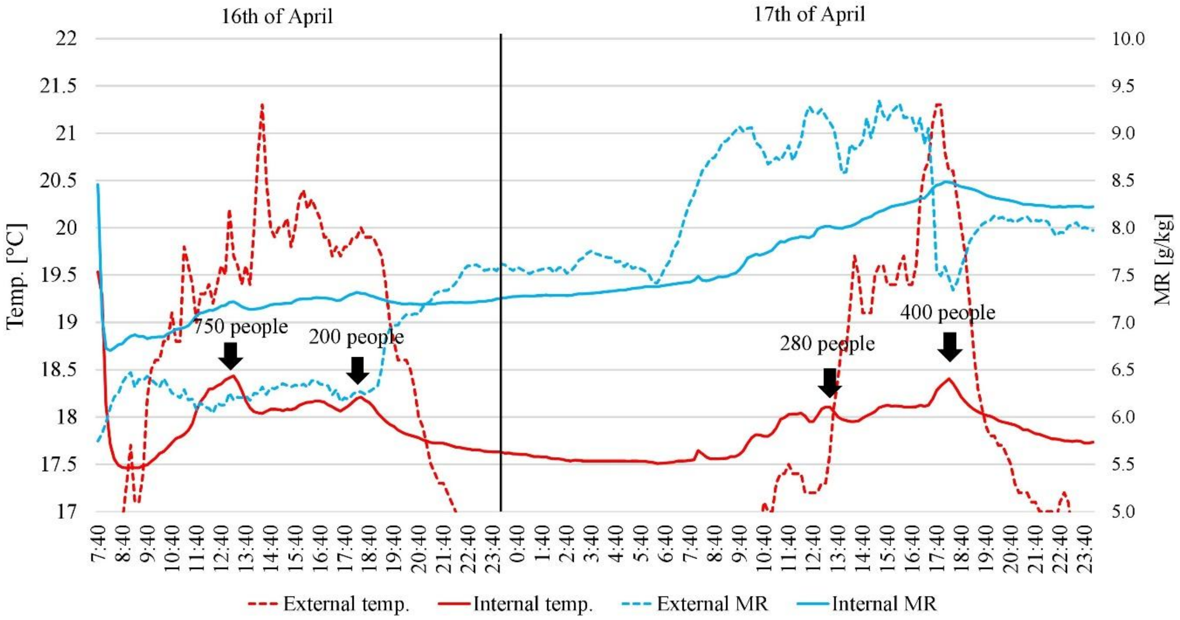

*Fig. 6 - Internal and external temperature and mixing ratio values during April 16th and 17th; the arrows indicate the number of people present when some temporary peaks of temperature and mixing ratio were recorded during the events.*

A similar behavior was observed for the mixing ratio. In particular, during the two monitored days, an increase in local values was recorded in relation to the ceremonies (Fig. 6).

From the analysis of the data collected, it can be observed that the presence of people, even if in substantial numbers, has a temporary effect on the local microclimate of the Duomo, mainly due to its large air volume, its huge thermal mass and to air change rate (see Section 3). Further analysis on this topic will be carried out in the prosecution of the research.

### 5.2 Analysis of the long-term monitored data

This section aims to discuss the obtained results of the long-term monitoring.

In order to increase the readability of the results, in the following paragraphs the data of a single sensor (sensor n. 3) placed close to the altar of the Cathedral have been reported and analysed. In fact, as stated in section 4, the differences in terms of temperature and relative humidity among the various measurement points are negligible, except for the sensor located close to the entrance in the North aisle (sensor n. 2). Accordingly, sensor n. 3 was selected since it is placed closer to many objects and artworks made of different materials, thus it was considered the most relevant for the present risk analysis. Nevertheless, the calculated average deviations between the sensor n. 3 compared to the average of the other measurements, during summer months when ventilation through opening are enhanced, are equal to 0.2°C for temperature and 3% for RH (values equal/lower than the instrument accuracy). Sensor n.2 has instead a calculated average deviation compared to the average of the measurements of 0.8°C and 3% for temperature and relative humidity respectively.

In Fig. 7 the band-gap showing the maximum deviation of the acquired parameters from the 6 sensors compared to sensor n.3 is reported.

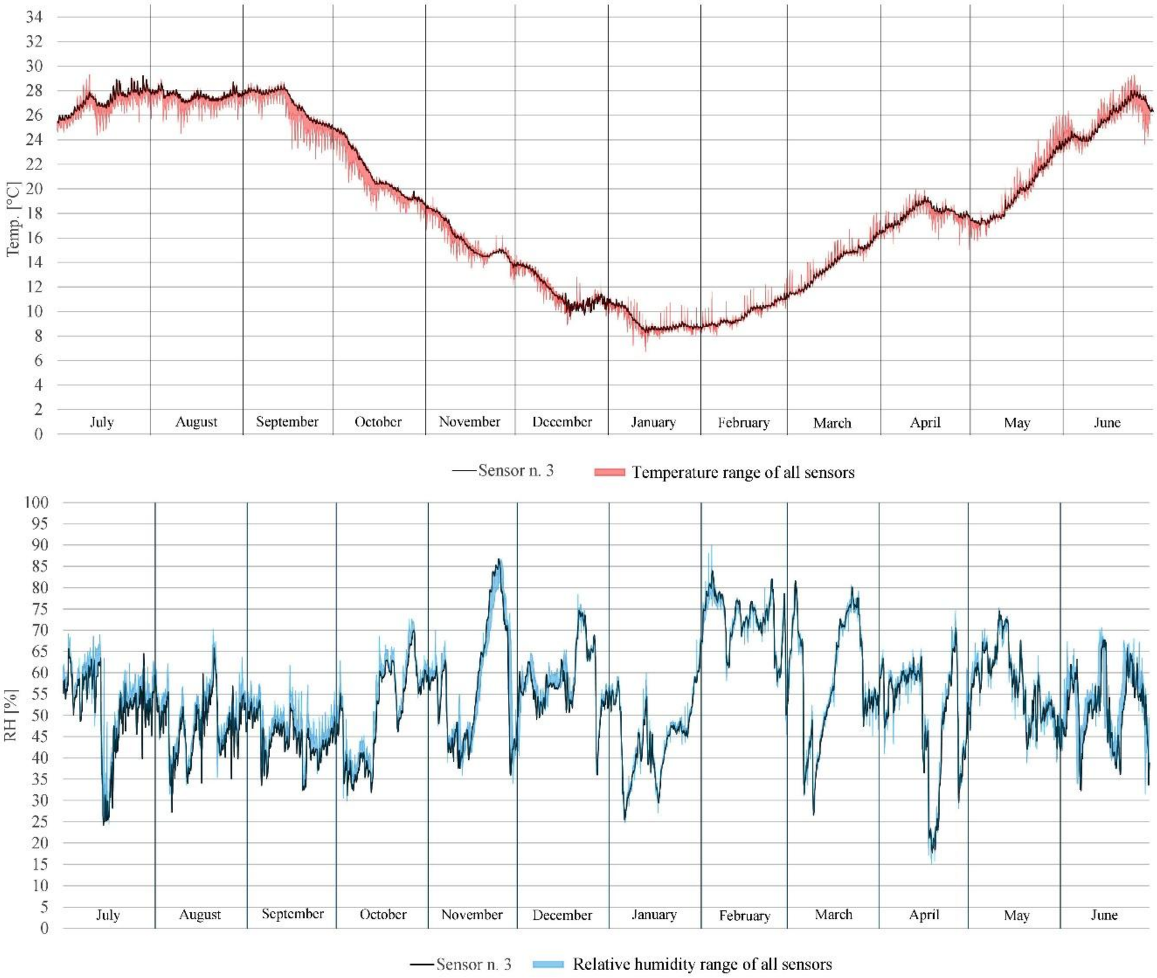


*Fig. 7 - Indoor temperature and mixing ratio range of all the sensors used for the long-term monitoring, the black lines represents the sensor n. 3 considered for the analysis.*

The graphs shows the trend of the microclimatic parameters (temperature, relative humidity and mixing ratio of water vapour in air) during the period July 2016-June 2017.

The internal temperature during the year ranges between a minimum value of 8.3°C in winter and a maximum value of 29.2°C in summer, against external ones that reached minimum and maximum values equal to -2.6°C and 35.4°C (Fig. 8), respectively. In the months of July and August, the internal temperature is quite stable, with a variation of only a few degrees. From September to January, as a result of a rapid decrement of the outside temperatures, also internal temperatures decrease; however, thanks to the huge thermal inertia of the envelope, these are attenuated, and do not fall below 8°C (in January), while externally peaks are found to be below 0°C. In the following months, the internal temperature returns to rise, following the tendency of the external one.

During the monitoring period, relative humidity reached a minimum value of 18% in the month of April, and a maximum of 87% in November. Contrary to the temperature, as can be seen in Fig. 9, relative humidity does not follow a particular trend, but may be subject to considerable variations in the course of each individual day, mainly due to the external climatic conditions.

The mixing ratio reached its peak of 15.3 g/kg in June and its minimum value of 2 g/kg in January. During the entire monitoring period the indoor mixing ratio had a trend similar to the outdoor one.

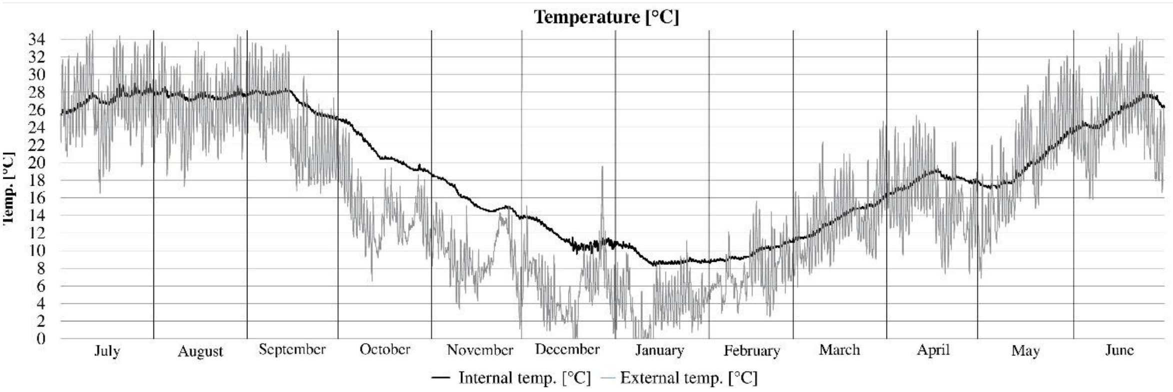


*Fig. 8 - Indoor and outdoor temperature data from July 2016 to June 2017.*

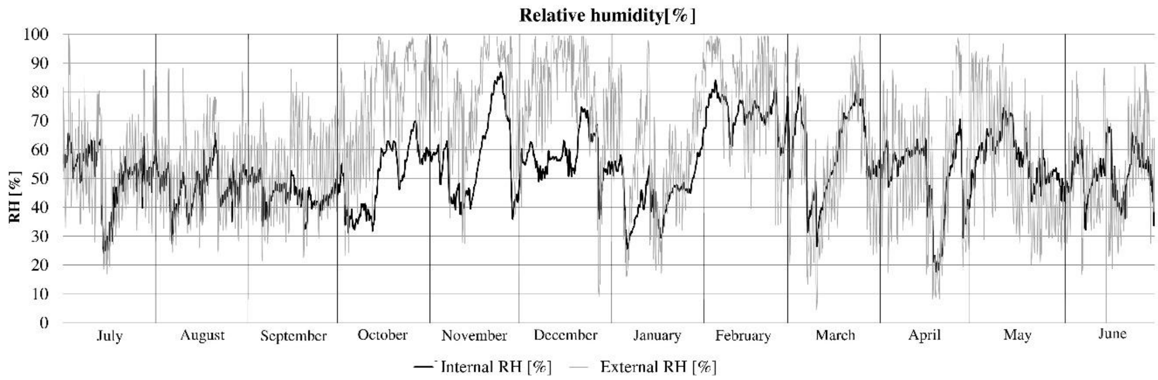


*Fig. 9 - Indoor and outdoor relative humidity data, and rainfall from July 2016 to June 2017.*

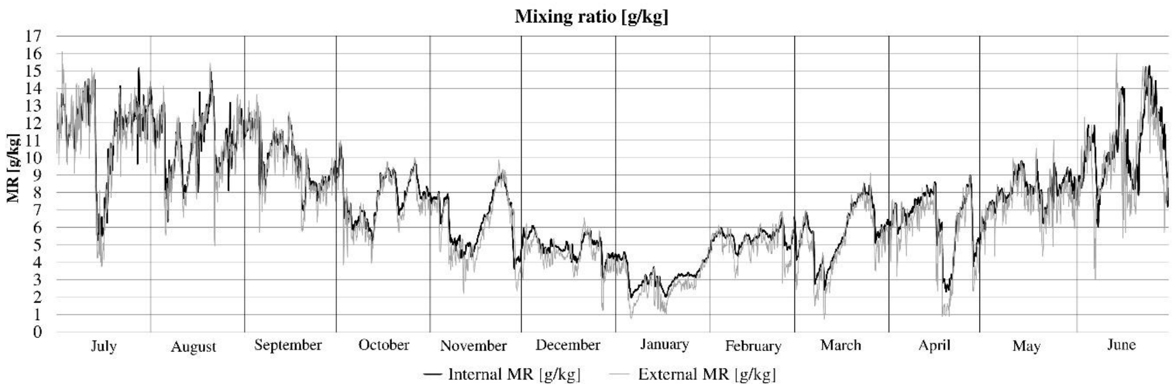


*Fig. 10 - Indoor and outdoor mixing ratio data, and rainfall from July 2016 to June 2017.*

Based on the data collected during the monitoring, a few graphs were drawn, to describe and quantify the interdependence of the internal hygro-thermometric parameters with the external ones. From the data, it is possible to draw a straight line (linear correlation line) that best interpolates the population of each variable. From this straight line, a $R^2$ index can then be calculated, which allows to quantify the quality of the interpolation. This index can have values between 0 and 1; a value close to 0 means that there is no dependence between the data, while a value close to 1 indicates that there is a strong dependence.

The dependence between outdoor and indoor air temperature, as well as that between the outdoor and indoor mixing ratios, are shown in Fig. 11 and Fig. 14; it should be noted that relative humidity is not taken into consideration, because it depends on temperature, and therefore the information is not particularly relevant.

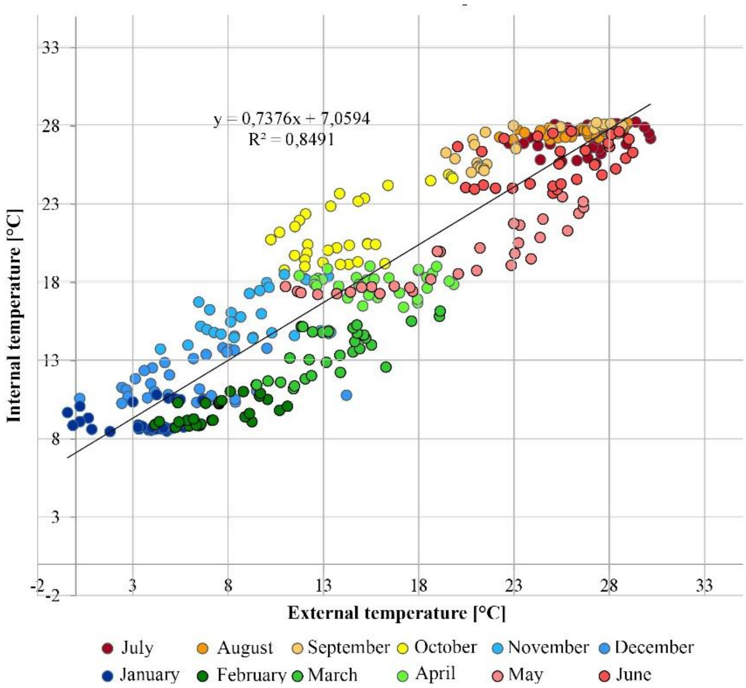


*Fig. 11 - Comparison between the average indoor and outdoor daily temperature recorded from July 2016 to June 2017: the linear correlation line obtained from the data and the corresponding $R^2$ index are shown.*

With regard to temperature, Fig. 11 shows that there is a moderate interdependence between the internal and external average daily values. In fact, the $R^2$ index is about 0.85, mainly because of the high thermal inertia of the envelope, that dampens the temperatures inside the building. In particular, it is possible to observe that, in the summer months, internal temperatures remain close to 28°C, while external ones vary between 20 and 30°C. The same behavior is evident in the months of January and February, when internal temperatures stabilize at values close to 9°C, while outside temperatures vary between -1 and +11°C.

From the observations and the analysis of the data, it can be assumed that the hourly variations of the internal temperature depend on the thermal mass of the building envelope that contributes to maintain the indoor temperature stability [50], reducing the amplitude of the hourly variations due to the air exchange rate with the outside, which occurs through the openings.

Going into details, the temperature values for four representative days of the month of December (Fig. 12) and four days of July (Fig. 13) are shown below. It can be observed that, although outside temperatures oscillate between 10°C and 1°C during the day, internal temperatures remain almost constant, between 13.5°C and 12.5°C (with daily variations not exceeding 0.5°C). This phenomenon, as previously mentioned, is mainly due to the reduced amount of external air coming from the entrance doors. In contrast, when analyzing the days of July (Fig. 13), internal temperatures undergo higher variations in the course of the single day (between 1°C and 1.5°C), due to the windows and doors being open for longer period during the summer months and to higher differences between external and internal temperatures.

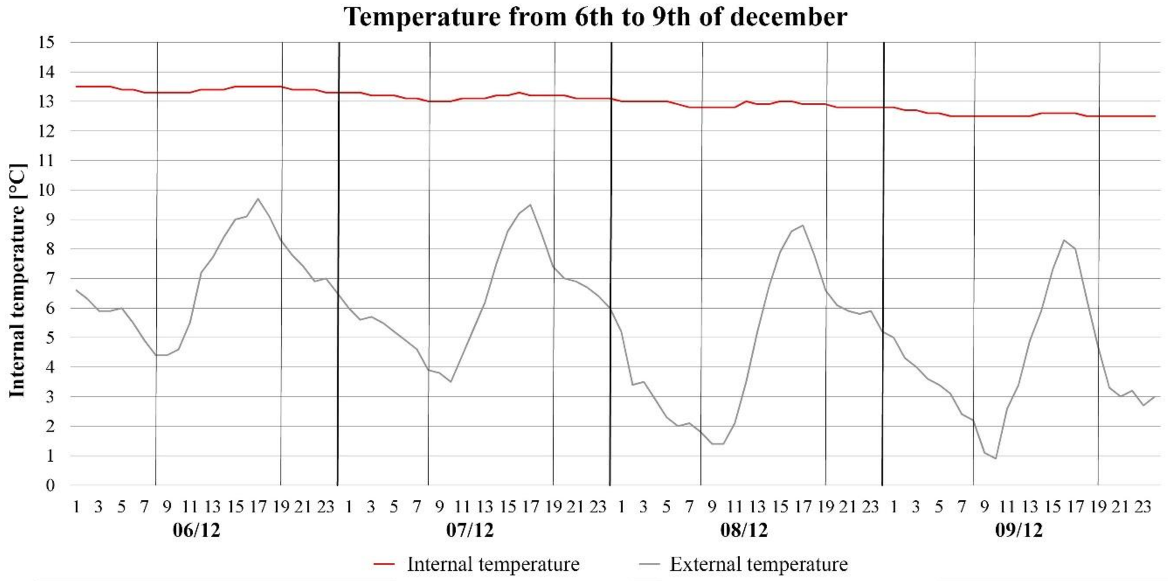


*Fig. 12 - Comparison between internal and external temperatures during selected December days.*

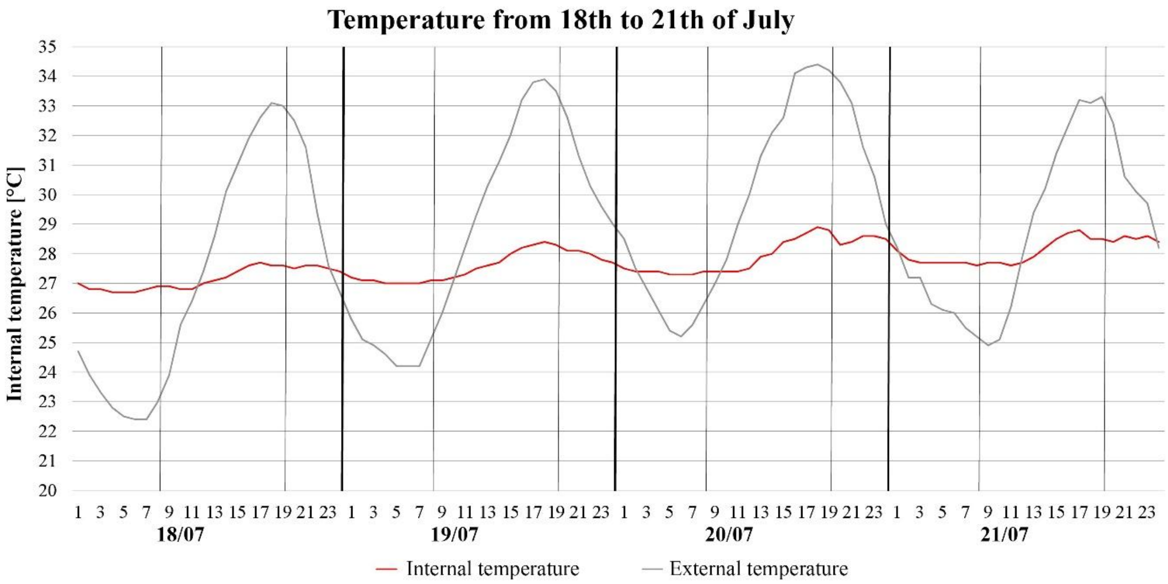

*Fig. 13 - Comparison between internal and external temperatures during selected July days.*

To complete the analysis, the dependence of the internal mixing ratio on the external one is shown in the following graph.

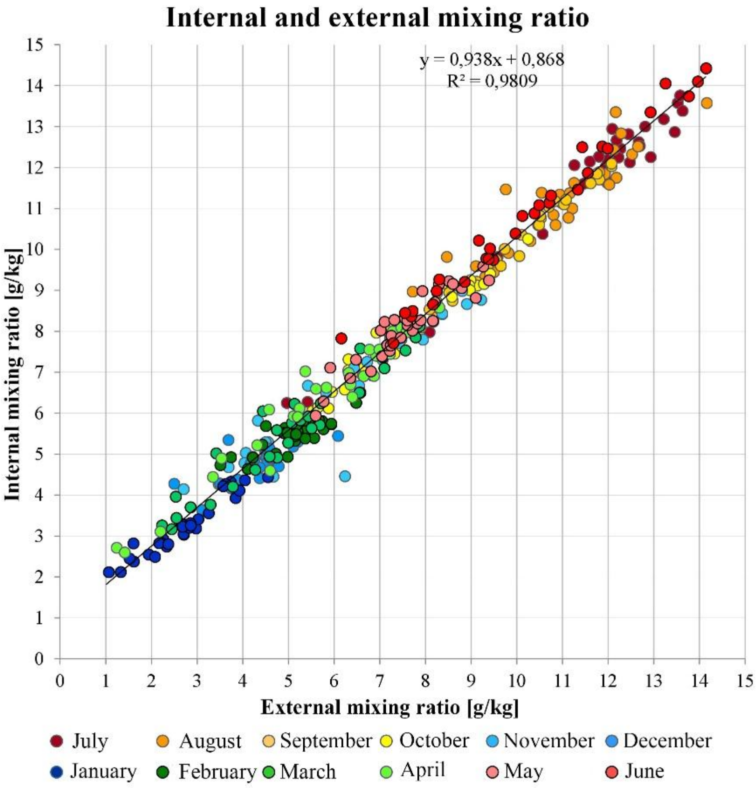


*Fig. 14 - Comparison between daily average internal and external mixing ratio values recorded from July 2016 to June 2017: the linear correlation line obtained from the data and the corresponding $R^2$ index are shown.*

As it can be observed, the $R^2$ coefficient, very near to 1, highlights that the natural ventilation inside the Duomo allows an air-change rate with the outside that sufficient to balance the internal and external daily average mixing ratio values (Fig. 14), without any evident differences between summer and winter. Unlike the internal temperature, which is subject to the effect of the thermal inertia of the envelope, the mixing ratio is mainly influenced by the exchange of air with the outside, while the water vapor produced by people compared to the volume of the building turns out to have little influence.

The microclimatic data collected can be used for different purposes, such as:

- analyze the possible risks to materials caused by specific environmental temperature and relative humidity conditions;

- estimate some parameters that cannot be easily evaluated, for example, air-change rate and infiltration, verification of surface condensation, etc.;
- create a simulation model capable of estimating different intervention scenarios according to different boundary conditions.

In particular, the following section analyzes the possible risks for each type of material used for the artifacts present inside the Duomo.

## 6. Risk-based analysis on the conservation of materials

From the data and information previously collected, it is possible to establish temperature and relative humidity ranges for the correct conservation of the artifacts present in the Duomo, taking into consideration the different causes of the degradation processes. These intervals were derived from regulations [39,40] and from the analysis and comparison of different sources of technical literature [22–24,28–38] (Table 1).

This section summarizes the problems and risks linked to the conservation of certain materials, caused by unfavorable environmental conditions inside the Duomo.

In detail three families of materials, among the main ones the majority of the artifacts inside the Duomo are made of: wood, stone and metal, have been analyzed.

According to the technical literature consulted and reported in Table 1, the most recurrent and commonly accepted conservation ranges for the three main materials analyzed were chosen.

More in detail, the optimal range for the material conservation proposed in this research are the following.

- For wooden materials: temperature between 19°C and 24°C and relative humidity between 45% and 65%, with a maximum daily fluctuation of 6%;
- For stone materials: temperature between 5°C and 25°C and relative humidity lower than 45%, with a maximum daily fluctuation of 10%;
- For metallic materials: temperature range is not considered relevant and relative humidity must to be lower than 50%.

Fig. 15 compares temperature and relative humidity to identify the riskiest periods, during which both factors exceed the suggested limits for the correct conservation of materials. The green areas represent the optimal conditions, both for temperature and relative humidity, for the conservation of the material (the clearer ones both from regulations and literature, while the darker ones only from one source), the yellow areas are where one of the two factors is beyond the conservation limits (dark yellow both from regulations and literature and light yellow only from one source), the red areas are where both microclimatic factors are beyond the conservation limits (dark red both from regulations and literature and light red only from one source): these areas represent the riskiest situations.

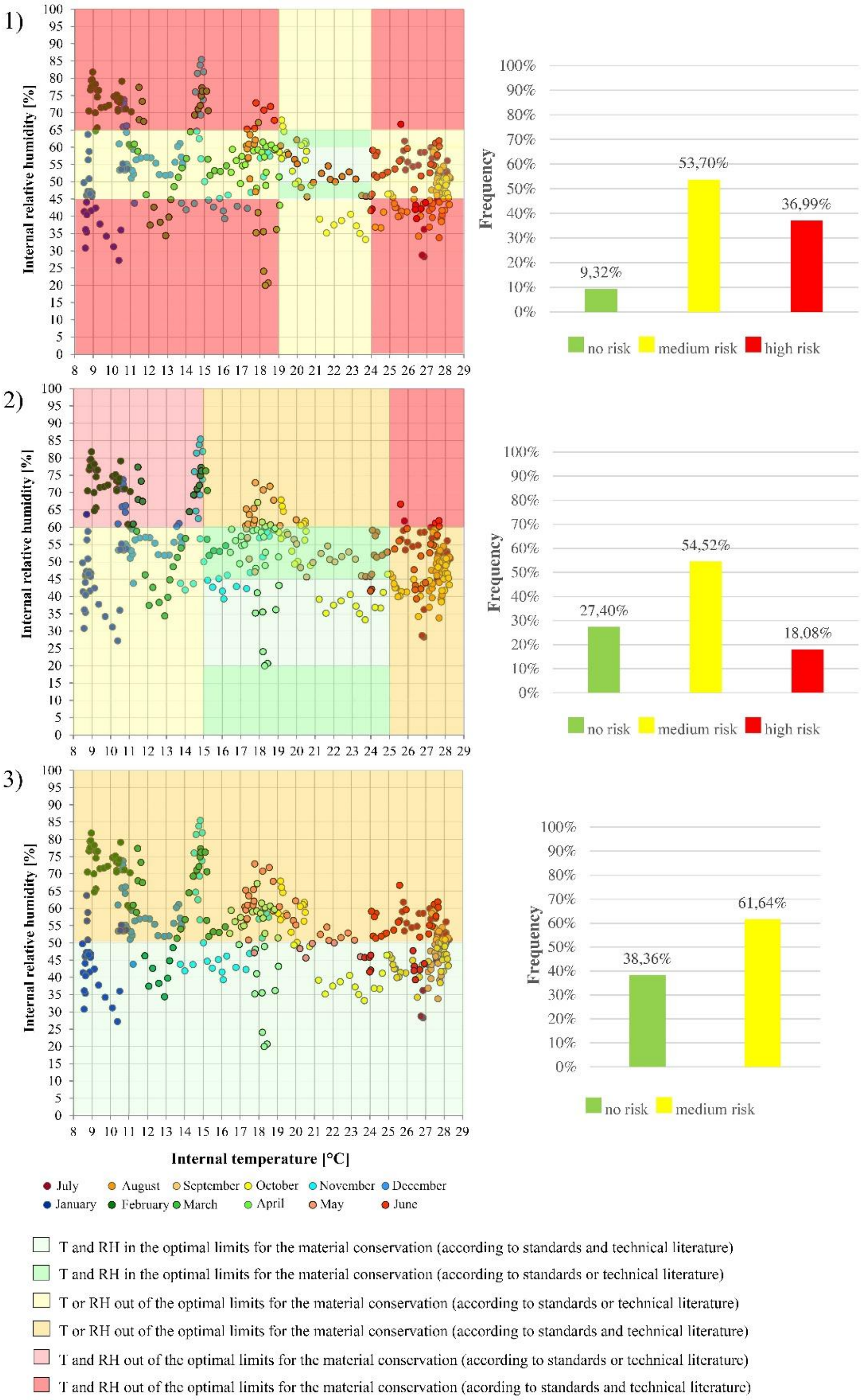


*Fig. 15 – On the right, a comparison between temperature and relative humidity through the identification of the riskiest periods during the months in which both microlimatic factors exceed*

*the intervals for the correct conservation of the material. On the left, frequency and risk level for the materials in the monitoring year (1, 2 and 3 are wooden, stone and metal materials, respectively).*

In detail, wooden materials have more restrictive conservation limits than the other materials analyzed. In the specific case, taking as reference painted wood, standards [39,40] suggest favorable temperatures between 19°C and 24°C, with maximum daily variations of 1.5°C. According to the same regulation, relative humidity must be kept between 50% and 60%, with daily variations of up to 4%. However, as briefly stated above, some literature sources [22–24,28–38] suggest a wider interval.

According to Fig. 15, it can be seen that in the summer temperatures are almost always higher than the recommended values, relative humidity often remains within the upper limit suggested by regulations and technical literature. Under these conditions, biodeteriogens, if present on the surfaces of the materials, can continue to grow, however, a higher relative humidity is required to develop a new attack of mold or fungus. During the months of February, March and December, the relative humidity inside the Duomo remains above the recommended threshold, allowing the biodeteriogens to continue to develop; however, even in this case the chances of a new attack are low, since temperatures are not high.

During some days of April, March, July, August and October, relative humidity reached values below the recommended threshold (45%); this condition, if maintained for a sufficiently long time, can make organic materials less flexible. In particular, in the months with a temperature lower than 19°C this situation can become further risky for the paintings on wooden support, due to the low temperatures that weaken the surface layer, making it subject to the formation of cracks [22].

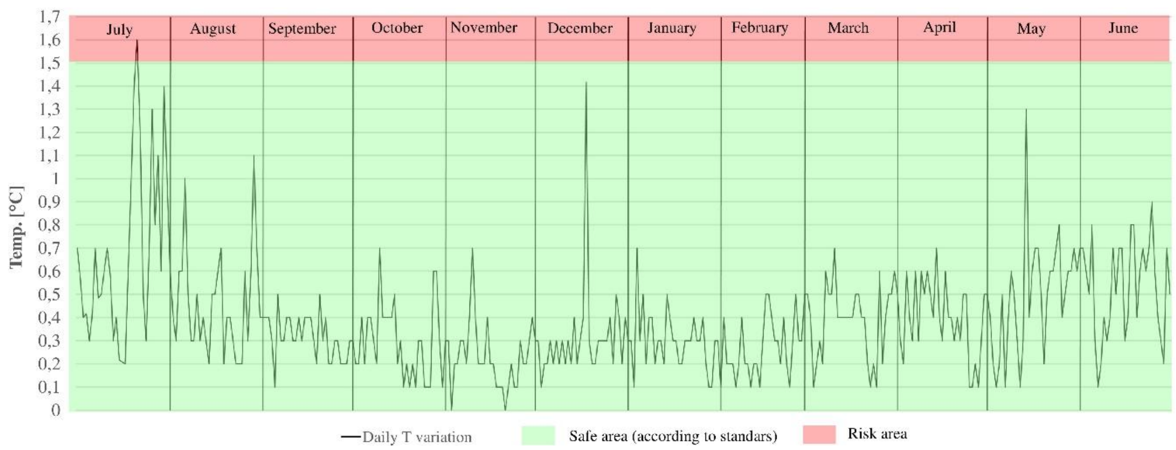


*Fig. 16 - Daily temperature variations within the Duomo in relation to the maximum daily temperature variation permitted by regulations (1.5°C).*

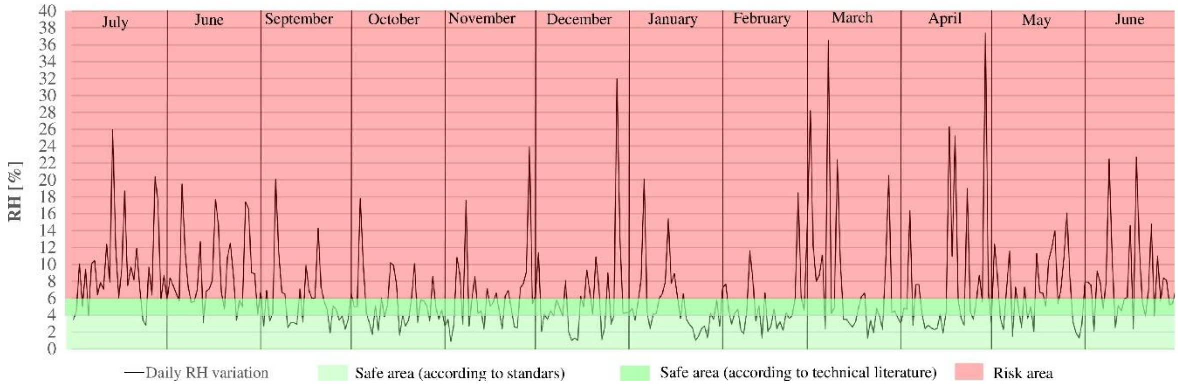


*Fig. 17 - Daily variations in relative humidity within the Duomo in relation to the maximum daily variation allowed by regulations for the correct conservation of wooden materials (4%).*

With regard to fluctuations over the short term, referring to the limits proposed by [39,40] and the technical literature, temperatures inside the Duomo do not constitute any risk for wooden materials, because the variations are always lower than 1.5°C (Fig. 16). Relative humidity (Fig. 17), on the contrary, undergoes repeated and large daily variations, often exceeding the 4% limit suggested by standards (about the 69% of the time) and the wider limits of 6% suggested by technical literature (about the 44% of the time). These continuous oscillations can cause compression-expansion stresses in the wood, which in turn can cause internal and superficial mechanical damage, with the consequent formation of cracks or detachments. This risk increases in the case of paintings on wooden support, due to the different moisture response of the different layers.

According to the acquired data, it can be stated that relative humidity is the main cause of deterioration, since it often exceeds the limits both in the short and long term. In particular, the continuous and wide fluctuation of the daily RH (Fig. 17) produces a stress on the wooden material that, over time, causes the formation of cracks on the surfaces of the objects. As far as the artifacts inside the Duomo are concerned, the presence of cracks and fissures in the choir stalls and numerous confessionals is evident (Fig. 19).

For stone materials, according to [39,40] the correct temperature and relative humidity intervals for a proper conservation are 15-25°C and 20-60%, respectively, with maximum daily variation suggested for relative humidity of 10% (referring to non-porous rocks, such as marble), while for temperature, in contrast, no daily variation limit is indicated. The technical literature consulted [22–24,28–38], on the other hand, provides less restrictive indications as shown in the above summary.

From the available data, it appears that relative humidity exceeds the limit of 60% during the months of February, December, March and May, allowing the growth of bio-organisms and increasing the risk of corrosion of some minerals present in stone materials, such as, for example, the pyrite present in Candoglia marble, with the consequent formation of stains on the material itself. The optimal conditions for the development and rapid growth of bio-organisms, however, occur when temperature and relative humidity are simultaneously above 25°C and 60%, respectively. This condition has rarely occurred, therefore the risks of rapid growth and biological diffusion on stone materials are limited.

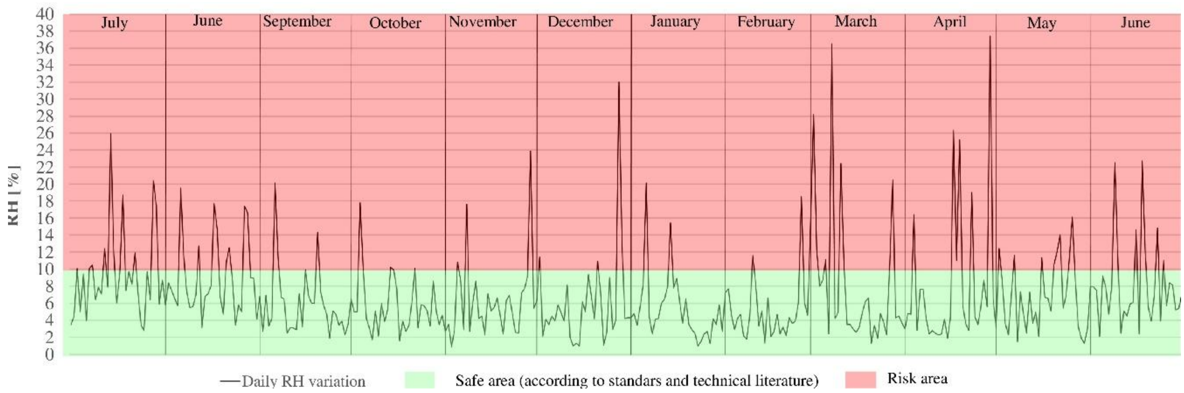


*Fig. 18 - Daily changes in relative humidity within the Duomo in relation to the maximum daily variation permitted by the stone materials regulations (10%).*

According to the analysis carried out, it appears that relative humidity often exceeds the proposed limits, both in the short and long term. In particular, a continuous and excessive fluctuation of relative humidity (Fig. 18) can cause condensation-evaporation cycles on the surface of the material, which favours the transport and accumulation of the salts contained in the stone materials (about the 18% of the time the RH exceeds the limit of 10%), with the consequent formation of efflorescence. Furthermore, if it comes into contact with the pollutants deposited on the material, water could trigger some chemical processes, such as carbonation or sulfation. Specifically, the presence of efflorescence was found in some points on the walls of the side aisles, as can be seen in Fig. 19. However, it should be noted that the rising dump and other phenomena that could cause efflorescence are not investigated in this study.

With regard to metallic materials, the standards [39,40] do not provide information regarding the optimal temperature range to be maintained for their conservation. For relative humidity, on the other hand, only the maximum value of 50% is provided, although no information is given as for the daily variations. According to the technical literature, the maximum relative humidity suggested is indicatively set at 50%, while for the minimum value no reference is provided.
During most of the months of the year, relative humidity was seen to maintain itself for several days above the recommended limit of 50%, favoring the occurrence of corrosion in the materials.
The phenomenon of corrosion in the vault chain of Duomo has been identified, as can be seen in Fig. 19.


*Fig. 19 – On the left, fissures and cracks found in the wooden stalls 1). In the middle, efflorescence found on the internal surfaces of the southern exposed walls 2). On the right, corrosion in the vault chains inside the Duomo 3). Below a map with the locations of the artefacts contained in the Cathedral*

## 7. Conclusions

This study was aimed first of all to identify a proper, non-intrusive monitoring campaign for the Duomo (Milan Cathedral), based on a preliminary acquisition of microclimatic parameters and on a subsequent long-term monitoring.

Based on the analysis of the microclimatic data collected during such monitoring, some specific considerations related to the microclimatic behavior of the Duomo were derived.

In detail, it was possible to state that the high inertia of the Cathedral envelope allows to keep temperature values almost constant during the daily cycles (with variations lower than 2°C) and causes gradual and dampened changes with respect to external conditions in the course of the seasons.

Furthermore, there were no high temperature stratifications with height (temperature differences are lower than 0.5°C) as well as on the horizontal plane, with the exception of the areas near the openings, which are more affected by the variation of the external parameters.

The average daily internal mixing ratio has values very similar to the external ones; this means that the internal air is continuously exchanged with external air through the different openings in the envelope (doors, windows, holes in the roof). Relative humidity has highly variable values over time, due to the external weather conditions; in fact, it can have large fluctuations over a single day, sometimes even higher than 30%.

With respect to the analysis carried out on the risks for the conservation of the main classes of materials present in the Duomo, by consulting the regulation sources and the technical literature, it appears that the most important microclimatic parameter constituting a danger for the conservation of the artifacts is relative humidity, due to its significant and repeated variations in the short term and the peaks reached during some months. During the monitoring year, values of temperature and relative humidity exceeding the limits suggested for the correct conservation of the materials were observed on different occasions, depending on the external climatic conditions. The development of degradation phenomena is mainly caused by the repetition of unfavorable environmental situations and therefore this condition represents a risk for the artifacts present inside the Duomo. From the on-site verification of the objects and the interior finishes, it appears that degradation phenomena are currently taking place. More in detail, in the wooden materials the presence of cracks and fissures is widespread, in the stone materials there is localized efflorescence and the metallic materials are instead subject to corrosion phenomena. In order to improve the environmental conditions inside the Duomo, it is possible to intervene, after a dedicated study, through the implementation of strategies, aimed at improving both the visitors' comfort and reducing the risk of deterioration of objects and interior finishes. These interventions should be planned according to criteria of energy saving, sustainability and conservation. Their design can be supported by the use of simulation models, realized according to the data acquired from the microclimatic monitoring. Such virtual models allow to evaluate different scenarios, depending on the different boundary conditions, in order to predict the building behavior, with the aim to identify the best interventions and solutions.

The methodology adopted in this work allowed to perform a fast, but sufficiently accurate characterization of the microclimate of the Milan Cathedral, using few instruments in comparison to the volume analyzed. The monitoring data collected is the main source of information for carrying out a risk analysis, and for the future implementation of a virtual model supporting further studies.

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