
*Photomontage of the CapsulART technological gateway at the entrance to the Hall of Tyrannicides, National Archaeological Museum of Naples - MANN, Italy.*

# Digital microclimate simulation models to support innovative management and preventive conservation processes in cultural sites

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Abstract: Among the least investigated aspects in historical architecture, one is the microclimatic behaviour linked to the preventive conservation of cultural heritage. This aspect should be studied intensively since it is closely related to any deterioration phenomenon of materials and can have a crucial role in updating management systems of cultural sites. Today the sensors that monitor environmental parameters can transfer data in real time into a continuous monitoring logic (cloud platforms) and this, in addition to the development of software capable of modelling the thermo-hygrometric behaviour of buildings, opens up new lines of research. The authors believe that it represents one of the most promising areas of investigation and capable of offering greater results in terms of preventive and planned measures. This contribution collects an experience recently conducted, financed by the Ministry of University and Research, in one of the most prestigious Italian museums, the National Archaeological Museum of Naples (MANN). The monitoring and modelling methodologies are illustrated, as well as the objectives of the intervention, with a view to a fruition that holds the psycho-physical well-being of staff and visitors and the conservation of heritage as close as possible. The results are closely linked to the pandemic experience, with the secondary objective of risk prevention for people and cultural heritage.

Keywords: cultural site management; microclimatic control; sustainability; preventive conservation; digital simulation; innovation.

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## 1. Introduction

The pandemic has highlighted the close relationship between the fruition of cultural heritage (and any other form of associated life) and the salubrity of the air we breathe. To this we should add that the quality of the air of indoor environment in cultural sites is a significant factor in material degradation processes and therefore a fundamental element in ensuring their preservation. The focus on the indoor environment of works of art has generated an interesting debate centred on the development of the concept of preventive conservation. Today, this idea requires the commitment not only of conservators, but also of architects, engineers, atmospheric physicists, chemists and all the other researchers and professionals who can contribute to overcoming this new post-pandemic challenge. In short, a multidisciplinary approach is needed, which once again from the Athens Charter (1931) draws our attention to the effectiveness of collaboration between disciplinary and scientific fields that care for our cultural heritage. Indeed, some studies have already been undertaken to investigate the impact of covid-19 on cultural heritage (Icom, 2020; Icomos, 2020; Cicerchia and Minuti, 2021).

The analysis of this phenomenon provided an opportunity for an overall rethinking of the ways of using cultural sites. In order to improve the safety and wellbeing of both staff and visitors, it was necessary to establish new connections with university research, which at the same time aims to develop ways of preserving, enhancing and using cultural heritage, with a focus on air quality monitoring and flow management and sustainability. Putting momentarily to one side the many serious problems that Covid has grieved, the pandemic has forced a modus operandi that is useful for a general rethinking of fruition. In the reorganisation of the activities of cultural venues due to pandemic, a fundamental part concerns the ways in which the public can enter them, connected to the growing importance of measurements, aimed at establishing air quality (presence of dust, other pollutants, $CO_2$ concentration, etc.), parameters that, in part, also affect the state of preservation of the works of art they contain. To this end, historical research moves in advance to recompose the historical-constructive framework useful to define the HIM, Historical Indoor Microclimate (Pretelli and Fabbri, 2018). Through the historical-critical investigation, the complex scenario of successive modifications over time is reconstructed, carried out within the different phases of the history of architecture in response to changing political, cultural and social needs, shedding new light on the articulated network of connections and evolutions between the places of art, the works inside them and the microclimate characteristics over time.

## 2. The cultural site environment. A microclimate and air quality affair

Preserving material evidence of the past coincides with ensuring their permanence in the best environmental conditions, indoors or outdoors. If this concept, i.e., that of preventive conservation, is by now well known, regulated and made binding in Italy by Legislative Decree 42/2004 (art.29, clause 2), less clear are the operative techniques to implement the best solutions for damage prevention. In the standard EN 15898:2019 (CEN, 2019) preventive conservation is defined as "measures and actions aimed at avoiding or minimizing future damage, deterioration, loss and consequently, any invasive intervention. […] In the field of movable cultural heritage, "preventive conservation" is generally indirect, i.e., such measures and actions are implemented on the immediate environment of the object. […] Strategies combining preventive actions and measures are outlined in a conservation plan".

Over the last twenty-five years, several standards have been published in Europe concerning the parameters of the indoor environment: UNI 10586:1997, UNI 10829:1999, EN 15757:2010, EN 16893:2018. In Italy, the legislation in force and in particular the Italian Ministerial Decree of 10 May 2001 applies to the museum heritage or generically pertaining to the Ministry of Culture.

In UNI 11897:2023 preventive and planned conservation is defined as a medium to long term strategy that places the integration of conservation and valorisation activities at the basis of effective cultural heritage management (Moioli and Baldioli 2018; Moioli 2023). It is oriented towards the prevention and constant care of cultural heritage and is an articulated process of producing new knowledge and layering information that requires planning and value management tools. It focuses on the application of general criteria of quality in interventions and states that the choice of preventive conservation action is generally made to reduce risk and is therefore easily verifiable with objective evidence. The same measures used to identify or estimate risk can provide an assessment of the quality of the intervention and verify the lack of secondary effects that could trigger other forms of alteration. The factors that are acted upon with a preventive intervention are the climatic-environmental parameters and in general all those that must be monitored. Monitoring is set up by preliminarily identifying the factors that may contribute to defining the risk threshold for the object.

In order to achieve a quality preventive conservation project, it is therefore necessary to structure a path of knowledge of the built heritage that also involves

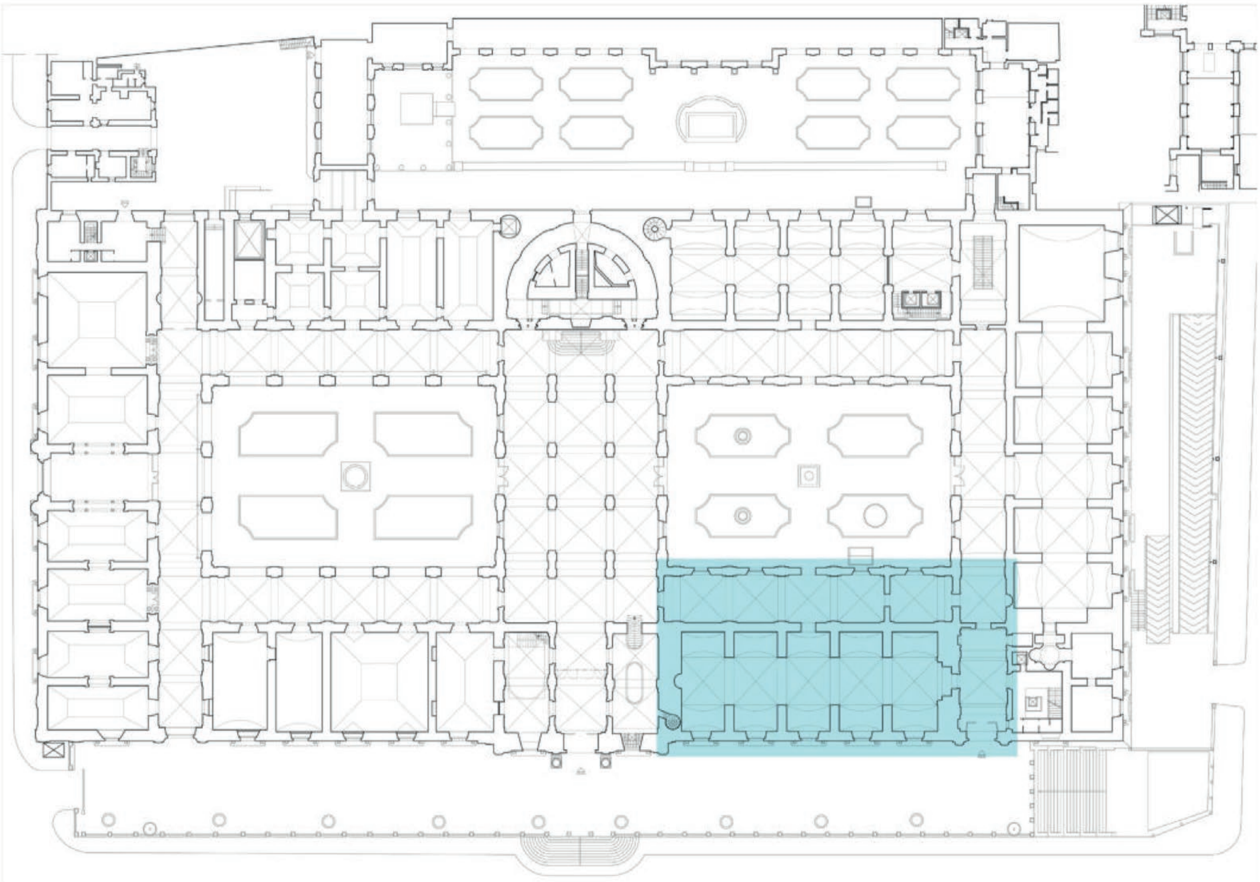

**Figure 1** | Plan of the ground floor with the identification of the Tyrannicides Hall and the Farnese corridor, MANN (Naples).

investigating the thermo-physical behaviour of the building, HVAC systems installed and the habits of the users.

Continuum microclimate monitoring must be preliminary to the definition of the interventions, continue during the building site and finally continue after the end of the intervention to verify the effectiveness of the microclimate modifications that have become necessary or to verify the maintenance of the historical microclimate. The values obtained from monitoring, or even from a prolonged measurement campaign, can provide indications of the object/environment system, but to be valid for conservation purposes they must be correlated with checks and controls of the surface or structural state of conservation of the material. There is therefore a need to structure a protocol for analysing the state of conservation of the cultural asset in relation to microclimatic parameters, exploring the correlation with the environmental mechanisms in place (thermo-hygrometric parameters and ambient air quality).

## 3. An innovative method applied to the MANN museum in Naples: meeting future challenges for Cultural Heritage

The present historical moment will probably go down in history as one of those turning points, on a par with the great Revolutions (agricultural, industrial, etc.) that have marked the life of Humanity. The expansion of the availability of increasingly sophisticated instruments for measuring various parameters; the operation of these instruments continuously and no longer by separate moments; the possibility of increasingly sophisticated and fast processing of measured data; the constant and continuous expansion of the quantity of data on any phenomenon; the growing possibility of their management by means of automatic cross-referencing systems; finally, the possibility of automatically executing variations in the management set-ups of some of those parameters, capable of compensating for the instantaneous variations detected, pose new challenges to those who have to deal with heritage management, new challenges also imposed by the presence of variation factors (just think

**Figure 2 |** View of the first north-west span of the Tyrannicides Hall. Above right are two environmental parameter monitoring systems, one of which was installed during the CapsulART research.

of macro-climatic changes) that put heritage even more at risk. The experience conducted in Naples, which will be described here, had, among others, this objective.

The aim of the inter-university project "Through Capsulart: improving conservation and health in artistic and cultural sites during pandemic events", funded by the Italian Ministry of University and Research (Competitive grant FISR2020IP_05553 - Special supplementary fund for research, 2020), was to reconcile the comfort and health of operators and visitors of cultural sites with the needs of cultural heritage conservation, combining the fight against the spread of pandemic risks with the improvement of the conditions of this heritage. These factors have been brought together in an original way, validating a research method investigating the indoor environment, which we go on to explain related the case study. Monitoring the microclimatic parameters and air quality of an exceptionally important museum site, the National Archaeological Museum of Naples (MANN), was the focus of the action. MANN hosts a unique collection that gathers together acquisition of finds from excavations in Campania and Southern Italy, as well as from private collections, for instance the Farnese collection, the most famous among Roman antiquities.

An attempt was made to consider the different 'faces' of a broad and diversified problem at the same time, so that the research areas - technical physics, history of architecture, restoration and building technology - could talk to each other and interface, in order to define solutions capable of offering effective answers both to the immediate stresses, represented by pandemic risks, and to those of a longer perspective aimed at making the environment "safer" also for the exhibits. With these aims in mind, a project was developed to create a simplified "technological chamber", which due to its characteristics can be likened to an entrance capsule to a specific space. It is a "technological gateway" capable of making access control easier, simpler and safer and, at the same time, of considerably reducing the contribution of pollutants that, under traditional conditions, are carried by visitors. The objective of passing through this gateway is not only to monitor the health of visitors, as was necessary during the pandemic, but also to 'cleanse' them of the pollutants of which they are unwitting vectors. In this completely innovative way, actions that have an impact both on people's health and on the preservation of cultural heritage are combined.

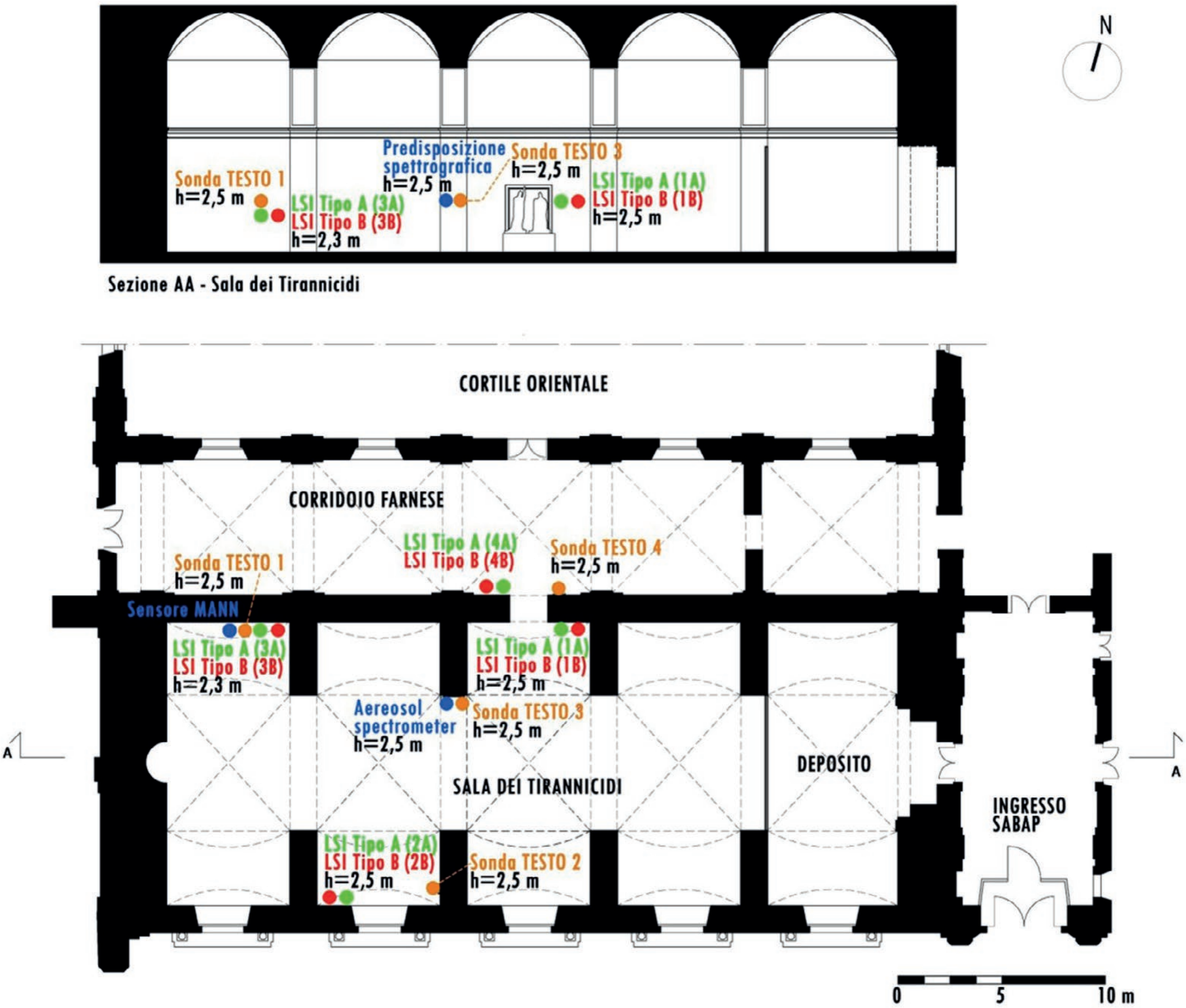


**Figure 3 |** Vertical section and floor plan of the Tyrannicides Room and adjoining rooms on the ground floor, showing the different types of instruments installed.

The project was based, as will be explained in the following pages, on the now extensive possibilities offered by sensor technology, which puts the researcher in a position to monitor the indoor microclimate of environments in real time, and subsequently to carry out simulation and modelling through the use of specific software for digital microclimate simulation. These tools make it possible to study the variations induced by the use of HVAC systems, but also to evaluate the effects on the microclimate deriving from the simple management of doors and windows or from the presence of visitors, which, especially in museum environments such as the one monitored, where dozens of visitors pass through every hour, involves non-insignificant changes in terms of temperature, relative humidity and dust. The 'traditional' microclimate monitoring, i.e., parameters of temperature and relative humidity, was combined with the monitoring of the presence of particulate matter, volatile organic compounds and carbon dioxide.

The data collected following the relevant standards allowed us to investigate the interaction between the presence/passage of visitors and changes in microclimatic parameters associated with the content and size distribution of pollutants in the environment, already making assumptions about their interaction useful in conceiving the operation of our technological gateway, CapsulART. The name recalls the technological sphere, playing with the word 'capsule', linked to space exploration, with the suffix -art, precisely because it is dedicated to care and prevention applied to cultural heritage. "Capsule" is a concept that represents the desire to work

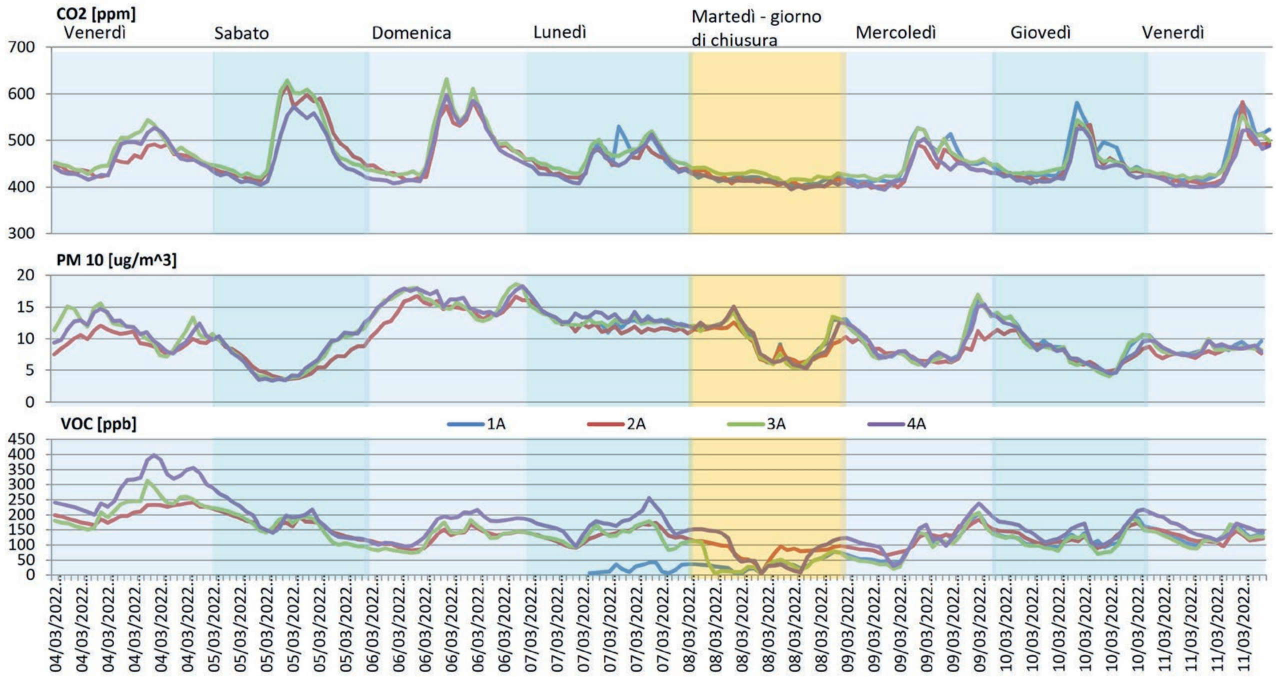


**Figure 4** | Trend of indoor air quality parameters ($CO_2$ - PM10 - VOCs) monitored with Sphensor LSI sensors during the week 04/03/2022-11/03/2022.

on a device that has the possibility of being replicated and transported with a certain ease, that has a "skin" compatible with the environments of high historical and artistic value where it can be inserted.

## 4. Indoor microclimate and air quality. Monitoring campaign and assessment

The Tyrannicides Hall and the Farnese corridor, located on the ground floor of the east wing of the MANN, were subjected to microclimatic analysis and thermo-physical simulation. The Tyrannicides Hall is characterized by a weave of arches, cross vaults and barrel vaults that divide the room into five bays. The maximum height of the rooms in the hall is 11.7 m, the floor area is 490 $m^2$ and the total volume is 5730 $m^3$. Access to the room is possible through an opening on the northern side, through the Farnese corridor. This corridor is characterized by a covering of cross vaults set on large arches, which divide the corridor into five bays, corresponding to those of the hall. The environment is characterized by five large windows surmounted by lunettes. The maximum height of the room is the same as the Tyrannicides Hall and the floor area is about 250 $m^2$, for a volume of 2930 $m^3$. Within the halls there are no HVAC.

The analysis of the indoor environment parameters was conducted with the aid of three types of monitoring systems:

- Monitoring provided by MANN, Hanwell Pro sensor, and made available for analysis as part of the project. A single sensor positioned inside the Hall records the microclimate parameters of temperature, relative humidity and carbon dioxide. The period analysed runs from 15/02/2021 to 09/12/2021. The sensor is installed 2.70 m above the floor.

- Monitoring obtained with the use of four TESTO 174 H temperature and relative air humidity sensors: no.3 TESTO sensors in the Tyrannicides Hall; no.1 TESTO sensor in the Farnese Corridor. The period analysed runs from 03/01/2022 to 27/05/2022. The sensors are installed 2.50 m above the floor.

- Monitoring obtained with the use of eight Sphensor LSI LASTEM sensors. Temperature, relative humidity, atmospheric pressure, lux, carbon dioxide, fine dust (PM1; PM 2.5; PM 4; PM10) and volatile organic compounds (VOCs) were measured. The period analysed runs from 27/01/2022 to 22/02/2023. The sensors are installed 2.50 m above the floor.

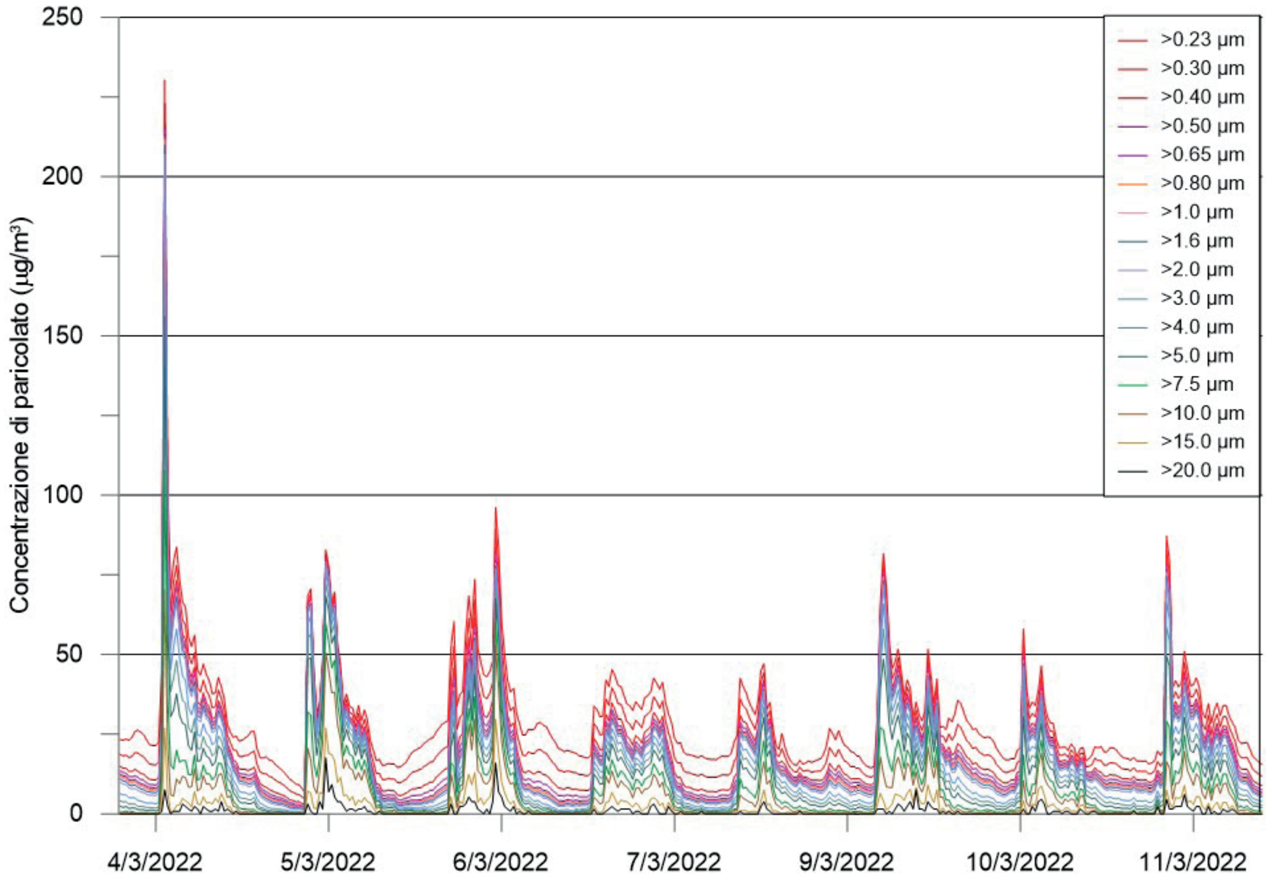


**Figure 5 |** Size distribution of airborne particulate matter particles detected by Grimm's Dual -Technology spectrometer in the week 04/03/2022-11/03/2022.

The latter system installed uses the Thread protocol (IoT): the monitored data is sent via radio signal to a getaway connected via Wi-Fi or 4G that sends the data to a cloud system platform, which can be accessed remotely.

Particulate matter was also analysed using a portable spectrometer, Grimm's Dual -Technology (model 1.108) designed to monitor dust aerosols.

The instrument is equipped with an internal pump that sucks in the dust from the environment, which is immediately intercepted by a light beam consisting of a laser beam, which, depending on the amplification of the recorded signal, classifies the dimensions. Both the concentration and the size distribution of airborne particles are thus detected. The instrument has 15 size channels, so it is possible to measure the size distribution of particulate matter in the following detection ranges, from 0.23 µm to 20 µm.

Relative surface humidity measurements were also conducted in the vicinity of the access opening to the Tyrannicides Hall using the TESTO 616 "Material moisture" instrument, as well as air velocity measurements using a TESTO 410-2 "Air velocity" portable anemometer. Considering the $CO_2$, particulate matter and VOCs trends in the Tyrannicides room and the Farnese corridor, it can be seen that the amount of $CO_2$ is indicative of the ventilation rate and the amount of people in the environment. As can be seen from the graph in Figure 4, on Tuesdays (highlighted band) when the museum is closed to the public and no visitors are present in the places under analysis, the amount of $CO_2$ is around 500 ppm, which can be considered to be the "background $CO_2$", i.e., that which is normally present in any environment. As far as the trend in fine dust is concerned, there is a phase shift between the peak of people in the environment and the peak of dust.

That is, when the number of visitors decreases (and $CO_2$ drops), the amount of dust and particulate matter present does not decrease at the same time. One possible interpretation is that particulate matter is raised by people and when the influx of visitors falls, dust is deposited according to type, mass and size distribution.

Figure 6 | View of the south windowed wall towards Piazza Museo: the LSI sensors installed for the CapsulART research are visible at the top right. In the wall thickness there is a radio repeater that allows easier interconnection of the monitoring system, which is also connected to the wi-fi network. The system was designed and set up to allow data to be consulted remotely.

## 5. Modelling and simulation: innovative management for heritage preservation

The monitoring and measurements described above were aimed at constructing an "evolved" microclimatic model of the spaces, in order to define technological solutions to control indoor air quality and reduce risks to the health of visitors and the conservation of works of art. All this is done through the use of technologies that, to a large extent, exploit the possibilities offered by the digitisation of micro-environmental data and the transmission of these data in real time. Therefore, the use of digital tools is necessary for the prevention of damage to collections and for the safe use of museum and tourism systems.

The construction of the virtual model was carried out with the IES.VE software with which the Tyrannicides Hall, the Farnese Corridor, the adjacent rooms and a fictitious room located at the entrance to the Tyrannicides Hall were modelled in order to simulate the presence of CapsulART. The thermophysical data considered for the characterisation of the components were taken from historical research and the reference bibliography.

A virtual model of the indoor microclimate of the rooms under study was constructed to analyse how the technological capsule for access to the Hall of Tyrannicides was designed. This model was useful for defining its mode of operation, providing design, construction and site parameters, and for verifying its effectiveness. The objective of the simulation is to integrate the information acquired from monitoring by predicting the microclimatic phenomena that might be established in the interior environment as a result of the insertion of the visitor control device. Monitoring data was essential to validate and characterize the simulation tool, starting from a 3D representation of the actual state and arriving through simplifications at the microclimate model, treated with dynamic simulation software.

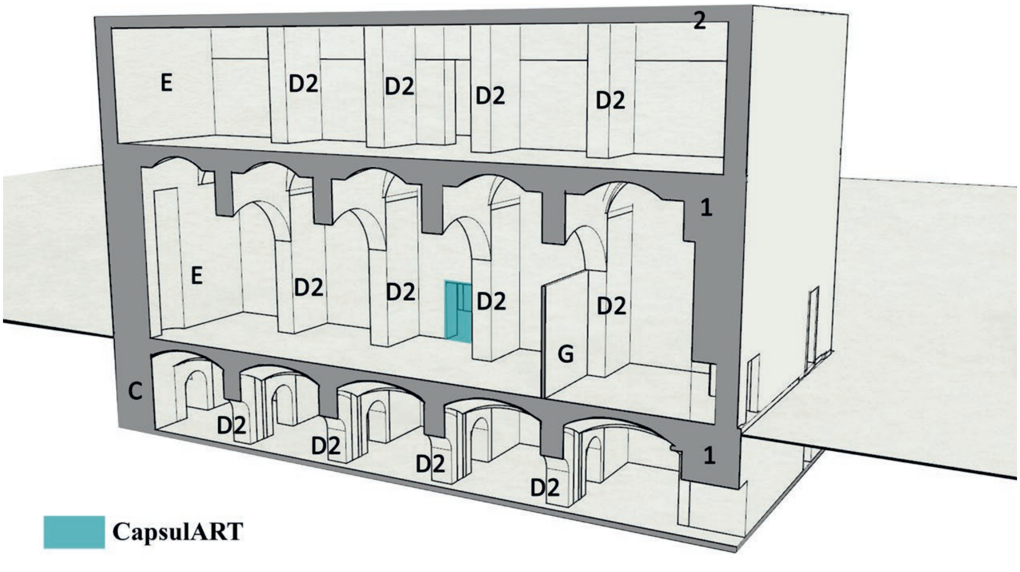


Figure 7 | Virtual modelling of the Tyrannicides Hall and the Farnese corridor used for microclimatic simulations. The alphanumeric codes refer to the classification of the different components of the building structure (opaque and transparent envelope, and internal partitions).

The virtual model includes:

- Tyrannicides Hall and Farnese Corridor (subject of study and monitoring).
- A faux room located at the access to the Tyrannicides Hall that simulates the future presence of the "micro-climate capsule".
- Rooms adjacent to the Hall of Tyrannicides and the Farnese corridor, including on the lower and upper floors.

By evaluating the transmittance of individual materials in the stratigraphies and manually entering it into the software, the model was characterized by:

- No. 8 types of masonry stratigraphies.
- No. 2 types of inter-floor floor and the counter-floor floor.
- No. 10 different types of fixtures.

The model also included data on:

- Latitude and longitude of the museum.
- Orientation of the rooms with respect to north.
- No. 6 distinct types of light fixtures, characterized to include lighting data in the simulation.

Meteorological data provided by the Superior Institute for Environmental Protection and Research (ISPRA), which refer to a meteorological station located in the port of Naples, were considered as outdoor environmental parameters.

Also calculated using the software were:

- Air changes.
- Natural ventilation and infiltration into the rooms.

From the data provided by the museum, the average occupancy values of the rooms by visitors were also entered into the energy model.

The software simulation of the actual state of the microclimate of the rooms under study produced results that were compared, for the corresponding periods, with the monitoring carried out with TESTO probes. Data recorded by the TESTO probe located in the corridor were used to validate the energy model of the Farnese corridor.

The validation was carried out by referring to the ASHRAE 14-2002 guidelines for energy software. This standard refers to energy consumption and not to microclimate performance, but the method it uses is still applicable considering indoor temperature as the variable. This was in fact considered to be the most robust with respect to simulation characteristics since it

**Table 1** | Results of simulation model validation according to ASHRAE Guideline 14: MBE (Mean Bias Error), CV of RMSE (Coefficient of Variation of Root Mean Square Error), PEARSON.

| | Farnese Corridor | Tyrannicides Hall | |
|---|---|---|---|
| MBE (%) | 3,91% | 7,57% | fall if MBE > 10% |
| CV of RMSE (%) | 4,32% | 7,76% | fall if CV (RMSE) > 30% |
| PEARSON | 0,84 | 0,62 | if > 0.7 strong correlation<br>if 0.3 - 0,7 correlation<br>if < 0.3 weak correlation |

is not affected by sources inside the room related to, for example, the influx of people (as is the case for relative humidity or CO2) or other factors.

According to ASHRAE guidelines, model calibration was evaluated based on the MBE, CV and Pearson parameters. MBE allows evaluation of the trend of the simulated variables over the entire period, CV evaluates the fluctuations in the data, and Pearson evaluates the linearity relationship between the simulated and real variables, for each reference time.

The three parameters must be below the thresholds in the standard: it must occur simultaneously that MBE < 10%; CV < 30%; Pearson > 0.3. If Pearson > 0.7 there is a "strong correlation" between the model and reality. The calculation of the three parameters, for the above reasons, was conducted based on the measured and simulated indoor temperature for the same period (Table 1).

Thus, it is confirmed that the model is validated, that is, it is demonstrated that it is possible to simulate, through the constructed microclimate model, the temperature inside the rooms. It can therefore be used to predict the effects of different design scenarios for the "microclimate capsule".

During the monitoring and construction phases of the virtual model, a discussion was initiated with the MANN Management about the most appropriate solutions for defining the formal and technical aspects of the device CapsulART. In the light of the security and visitor flow management requirements, two hypotheses for the design of the technological gateway were defined: the first consists of a "technological passage", without closures, through which the visitor is obliged to pass, without encountering any physical block; the second, on the other hand, consists of a closed chamber in which the visitor must stay for very short times. In both cases, the capsule is equipped with a ventilation system and filters to intercept dust.

The objective of the simulation is to verify that the software recognizes the effects of the capsule on the room's microclimate; since the variable used to characterize the microclimate in the simulation model is temperature, the simulated scenarios are evaluated according to their effect on the temperature inside the Tyrannicides Hall and the Farnese Corridor. Based on the temperature difference, it is possible to determine the effect of various design configurations on the interior microclimate of the rooms.

Another variable that was considered in the design is the possible presence of an air conditioning system in the capsule. In fact, it is possible to include a cooling system, which is useful in lowering the temperature of the microenvironment, and thus inducing a decrease in the sweating of visitors as they pass through. This is an ancillary performance that would require a set up capable of considering the ambient temperatures, so as to avoid a feeling of discomfort for people.

## 6. Results

As a result of these studies, six operational scenarios were subsequently developed, four of type A and two of type B.

Type A: open capsule with dust interception as visitors pass through:

- Scenario 1: ventilation system air flow rate 30 l/s.
- Scenario 2: cooling system (1 kW), ventilation system air flow rate 30 l/s.
- Scenario 3: 1 self-closing door to the Tyrannicide room, ventilation system air flow rate 30 l/s.
- Scenario 4: 1 self-closing door to the Tyrannicides Hall, cooling system (1 kW), ventilation system air flow rate 30 l/s.


**Figure 8 |** Two possible configurations of the CapsulART technological gateway at the entrance to the Hall of Tyrannicides: an open gateway (left) a gateway closed by one or two doors (right).

Type B: capsule enclosed by two self-closing doors. Visitors wait 10 seconds in the confined environment:

- Scenario 5 - ventilation system air flow rate 30 l/s.
- Scenario 6 - with cooling system (1 kW), ventilation system air flow rate 30 l/s.

From a temperature point of view, the simulation results show that in scenarios with one or two doors there is a greater difference between the simulated and actual room temperature.

Scenario 5 for instance shows a difference of 0.25°C from the actual state, while, without doors the difference is only 0.15°C and 0.10°C (scenarios 1 and 2).

This analysis allows us to understand the effects of the presence of the capsule with respect to the historical microclimate of the Tyrannicides Hall: the investigation concerns, for the moment, only the temperature since it is the most controllable variable within the energy simulation software used. The continuation of the research aims to investigate its effects on relative humidity as well.

## 7. Conclusion

The project's impact on cultural sites concerns the way in which activities and visitor processes are managed and reorganised, addressing the new needs and issues raised by the spread of the SARS-Cov-2 virus and the Covid-19 infection (or other virus). The device CapsulART, during the passage of visitors, reduces the amount of pollutants they carry, thus decreasing the possibility of viruses and bacteria, whose movement is facilitated by the presence of dust, circulating in the environment. In this way, the enjoyment of cultural sites is improved by bringing together, in a completely new way, actions that have an impact both on people's health and on the preservation of cultural heritage.

In the medium term, it is believed that the designed technological system can be used in different cultural sites, with simple variations, thus defining a new approach to the use of Cultural Heritage, with replicable tools, monitoring methods and evaluation indexes, with a positive impact on the industrial sector not only of the "technological gate" studied in this project, but also of related ones, such as environmental monitoring systems.

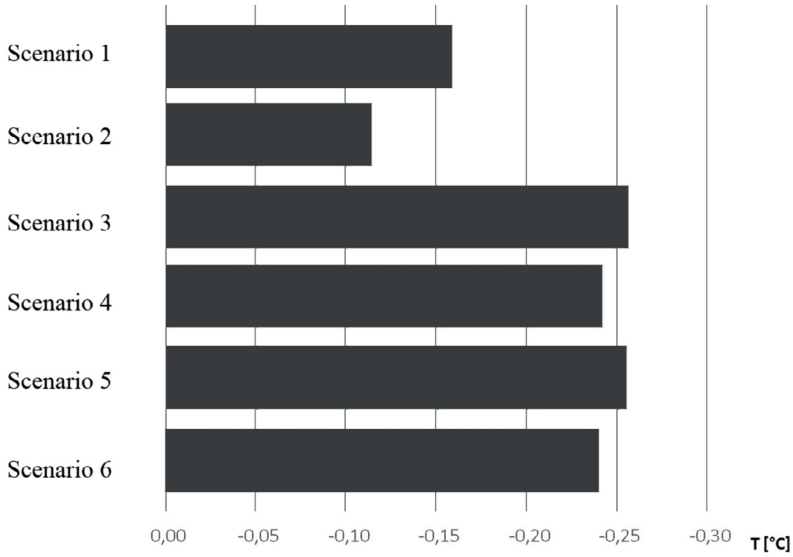


**Figure 9 |** The graph represents the effects of different CapsulART configurations on the temperature of the Tyrannicides Hall. The smaller the difference between the monitored and simulated temperature, the greater the guarantee of protection of the historical indoor microclimate to which the stone works have acclimatised over time.

Moreover, this type of application makes it possible to establish a stronger link between research and industrial production (of small and medium-sized enterprises in particular), but also to bring research institutions closer to the conception of innovative approaches, where the resources of academia and business become necessary and complementary.

In conclusion, it is believed that the research methodology adopted allows to give indications about the management issues of sites constituting the cultural heritage, also favouring the collection of useful information to simulate what benefits in terms of conservation policies - in this case preventive - can be obtained, also thanks to the use of digital software for modelling virtual environments and their microclimate. In the future, the monitoring of microclimate and air quality parameters after the capsule prototype has been inserted will enable its verification in situ. The results achieved by the present research will be used by the MANN Museum to implement the management and use of the rooms under analysis.

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