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The Scrovegni Chapel.

Multidisciplinary Research and Environmental Protection

Introduction

The restoration of the pictorial cycle of Giotto in the Scrovegni Chapel has meant for the Central Institute of Restoration (ICR) and former director at that time, Mr. Giovanni Urbani, the opportunity to put together a proposal and experiment a radically different approach to restoration from the traditional one, which is based on a few, but fundamental principles:

1. The first one consists in detecting, through a number of investigations, tests and scientific analyses appropriately tackling the issue, which were the causes of decay or damages that were visible on the paintings with the purpose of removing them or at least reducing their kinetics.
2. The second one consists in implementing target interventions ahead of time to reset the environment to suitable conditions, i.e. making it ideal for the work of art with which it interacts – making sure that any intervention on the same will have to be made only after the ambient has been tested proper and fit.
3. The third one consists in making sure that interventions will have to be made not only progressively, i.e. from the basic ones to the more complex ones, but also without any automatization or compulsory sequence: hence, adopting the more complex ones (which are also the most expensive in general, and the most risky ones) just when all the rest have seemed to be clearly insufficient.

These studies conducted on the Chapel are the result of a big commitment carried out since 1977 and throughout 2002, by a team basically represented by chemists, physicists, biologists, engineers, architects, art historians and restorers.

Keeping in mind the volume named "Il Restauro della Cappella degli Scrovegni: indagini, progetto, risultati"[2] for an essential, however, complete synopsis of the research, studies and interventions, both conducted on the environment, the building, the mural paintings and the other masterpieces of the Chapel, this paper mainly wants to summarize the chemical – physical evaluation relative to the study of the state of conservation and the causes of decay of the mural paintings and to the assessment of air quality and microclimate of their container, in addition to defining and realizing a number of interventions aiming at preventing the decay; the ultimate goal of the research has been creating a technological ambient (named in Italian Corpo Tecnologico Attrezzato, acronym CTA) equipped with a heating and chilling plant and an air filtering unit for the preventive conservation of the Chapel.

To better outline the development of the research and the interventions applied to the environment, the building and the mural paintings, a chronological order has been followed.

Research and interventions: Years running from 1977 through 1979

Two American researchers, Sayre and Majewski, have published in 1963 a first study on the state of conservation of the paintings, detecting a significant presence of calcium sulfate onto the surface.[3] In 1977, the Central Institute for Restoration, based upon an initiative of the director Mr. Giovanni Urbani, was the promoter of an interdisciplinary research consisting in a series of chemical, physical and biological researches.[4]

The analysis relative to the content of gypsum in the paintings confirmed in the broadest and systematic way the data of the two American researchers; the most interesting outcomes resulted from the measurements of air quality of which two significant points were stressed:

a) The Chapel was a space strictly linked with the external environment by a sensitive air exchange renewal at open door (during the day, in relation to the in & out of visitors); hence, there was an uncontrollable intake of polluting agents besides damaging thermo-hygrometric gradients inside the Scrovegni Chapel which have been evidenced by parallel measurements.
b) The sulphation of the paintings was due to the effects of dry deposits of sulphur dioxide and suspended particulate matter (s.p.m.) containing jointly gypsum and sulphuric acid.

In fig. 1 it has been indicated the flow of concentration of sulphur dioxide on March 21st, 1979, in opening (open door) and closing (closing door) the entrance door of the Chapel: we can clearly argue that the unregulated opening of the door determined an immediate diffusion of sulphur dioxide in the inside, that was subsequently (at the time of closing the doors) completely adsorbed by calcium carbonate of the walls in nearly 4 hours. Simultaneously, the calcium carbonate/gypsum ratio was measured (through X-ray diffraction) on samples of painted plaster taken at different levels of depth, outlining a clear sulphation relative to the dust deposited and to the first layer some tens of micron thick (see table 1).

[1] G. Basile, E. Mancinelli, P. Santopadre, M. Ioele: Central Institute for Restoration, Rome; V. Fassina: Superintendence to the Historical, Artistical and Demoetnoanthropological Heritage of Veneto, Venice; A. G. Stevan: SYNCRO, Padua; R. Cesareo: University of Sassari; A. Castellano: University of Lecce.

[2] Giuseppe Basile (Ed.), Il Restauro della Cappella degli Scrovegni: indagini, progetto, risultati, Milano 2003.

[3] Edward V. Sayre, Lawrence J. Majewski, Studies for the Preservation of Frescoes by Giotto in the Scrovegni Chapel at Padua. Technical investigation of the deterioration of the paintings, in: Studies in Conservation 8, 1963, pp. 42–54.

[4] The team was set up by ICR in cooperation with the CNR Laboratory of Chemistry and Technology of Radioactive Elements in Padua, the Universities of Padua, Venice and Rome, the CNR Centre of Rome "Works of Art", the CNR FISBAT Institute of Bologna and the Chemistry Laboratory of the BB.AA.SS. Superintendence of Venice.

Sample		*carbonate/sulphate*
Deposited dust		47/53
Last Judgment, grey background		
First surface layer		63/37
Same point	up to 1mm	89/11
Same point	from 1 to 6 mm	100/0
Same point	from 6 to 10 mm	100/0
Same area, other		
First surface layer		78/22
As above	up to 1 mm	94/6
As above	from 1 to 6 mm	100/0
As above	from 6 to 10 mm	100/0
Left side wall, green band		
First surface layer		61/39
Same point	up to 2 mm	100/0
Same point	from 2 to 6 mm	100/0
Same point	from 6 to 10 mm	100/0
Mary's birth, blue background		
First surface layer		43/57
Right side wall, green band		
Plaster	up to 2 mm	90/10
Same point	from 2 to 6 mm	100/0
Counterfaçade, beneath the vault		
Small area "testimony" of the background*		
First surface layer		87/13
Same point	up to 2 mm	100/0
Same point	from 2 to 6 mm	100/0
Same point	from 6 to 10 mm	100/0

*Left intentionally unfinished by Leonetto Tintori during the restoration performed in the years 1961 throughout 1963.

Table 1. Calcium carbonate/calcium sulphate weight ratio in painted plaster samples at various depths.

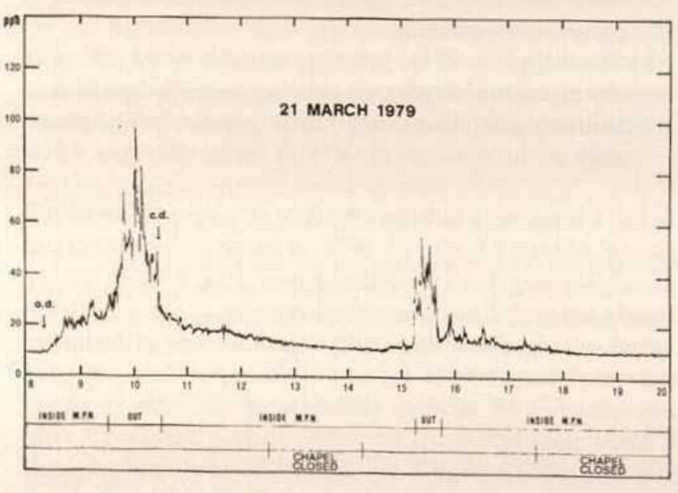


Fig. 1. Padua, Scrovegni-Chapel: Tred of concentration of sulphur dioxide (SO2) registered on March 21, 1979 at open door (o.d.), at closed door (c.d.), at half nave (mpm), at external location (out).

The relevant outcomes were published in a special volume in the "Art Bulletin of the Ministry of Fine Arts and Cultural Activities" entitled "Giotto in Padua"[5] and in which the Director of ICR indicated the preventive actions of simpler realization: application of screening window panels to protect the interior from IR and UV rays; replacement of incandescent lighting with cold lamps to prevent the vortex effect that was pushing dust and pollution agents onto the wall paintings; planting evergreen trees with a high trunk in order to screen windows from sun rays. The definition and the implementation of much more complex interventions had to be postponed to a subsequent time following the evaluation of the efficacy of the first provisions taken.

Years running from 1988 through 1996

Having evaluated positively the results from those first interventions (exception made for the trees that were never planted for screening), at the beginning of 1988 a new cycle of studies began, primarily aiming at better understanding the causes generating an extended whitening, located mainly on the wall of the counterfaçade and on the joint between the left wall and the vault upon the triumphant arch, together with much abundant flaking and pulverization of the pictorial layer.

During this phase, ionic chromatography has been utilized for the analysis of soluble salts and scanning electronic microscope with a micro-analytical X-ray device (SEM+EDS) for the elemental analysis of plaster with particular reference to the distribution of sulphur.

In fig. 3 results are shown relative to chlorides, sulphates, and nitrates, measured in watery extracts of cellulose pulp of pads used for the extraction of soluble salts, from which it is clear a significant presence of nitrates, which were not detected in the first phase of the study.

In fig. 4 an X-ray map is indicated (realized by SEM + EDS) relative to the distribution of sulphur and calcium in plaster samples taken from the counterfaçade: the map indicates a considerable adsorption of sulphur dioxide up to 50 microns. Based upon this analysis, sulphation resulted penetrating between 10 and 60 microns on average (reaching sometimes also 100 micron), starting from the external surface.[6]

Briefly, the causes determining whitening and/or yellowing of the pictorial layer are summarized in table 2.

Particularly, in the case of the Chapel, the causes determining the whitening of the wall of the counterfaçade are indicated in table 2 from 1 to 5 and 7. In fig. 5 it has been documented the damage caused by the crystallization of gypsum beneath the pictorial layer.

[5] Dario CAMUFFO, Patrizia SCHENAL, Microclima all'Interno della Cappella: Scambi Termodinamici tra gli Affreschi e l'Ambiente; Domenico ARTIOLI, Maurizio MARABELLI, Costantino MEUCCI, Fattori Ambientali e Stato di Conservazione dei Dipinti murali della Cappella degli Scrovegni; Guido BISCONTIN, Silvio DIANA, Vasco FASSINA, Maurizio MARABELLI, Indagine sugli Inquinanti Atmosferici all'Interno e all'Esterno della Cappella, in: Bollettino d'arte, 63, seconda serie speciale: Giotto a Padova, 1982, pp. 119–220; pp. 59–67; pp. 69–110.

[6] Ernesto BORRELLI, Maurizio MARABELLI, Paola SANTOPADRE, Studio dello Stato di Conservazione e Messa a Punto del Sistema di Pulitura, in: BASILE, Scrovegni (note 2), pp. 106–114.

Fig. 2. Padua, Scrovegni-Chapel, entrance wall: The Last Judgement, with the kneeling donor next to the Blessed (after the restoration).

1. Sulphation of calcium carbonate
2. Crystallization of soluble salts
3. Microcracking and/or pulverization of pictorial layer
4. Microcracking and/or pulverization of a protective/fixative product used for the pictorial layer
5. Chromatic alteration and fading of the superficial protective/fixative product
6. Re-crystallization of calcium carbonate on the surface
7. Oxalate patina formation
8. Microbiological attack

Table 2. Possible causes of whitening – yellowing phenomena of the surfaces.

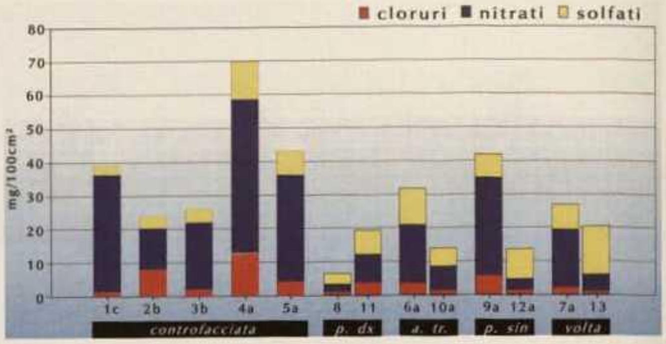


Fig. 3. Padua, Scrovegni-Chapel: Concentration of anion present in the extraction pads of soluble salts applied on the walls.

Following these researches, between the years 1995 and 1996 a campaign of measurements relative to the air quality comparable to the one performed in the years between 1977 and 1979 was conducted. It detected that the levels of internal s.p.m. were reaching higher levels in the summer time and during the day (up to 200 – 280 μg/m^3).

The maximum concentration of sulphur dioxide had fallen to 50 μg/m^3 from 100 μg/m^3, while concentration peaks of nitrogen dioxide reached during the winter levels of about 50 μg/m^3. Nitrogen dioxide was surely linked to external pollution due to diesel car traffic, with medium/high levels of the semi-hourly averages and peaks between 30 and 50 μg/m^3 (see fig. 6).

From these results it was possible to assume that the problems linked to pollution remained still in place whilst, in comparison with a decrease of sulphur dioxide, a significant amount of nitrogen dioxide was present.

At the end of the survey conducted on air pollution and microclimate, measurements of indoor/outdoor air exchanges were carried out via the so called sulphur hexafluoride methodology.[7] The latter confirmed the conclusions that were reached during the years 1977 – 1979, pointing out a daily maximum air exchange rate of 9 volumes (in the summer and at time of visitors' entry, see table 3).

From the number of these studies the need to find an adequate solution seemed to be emerging, with the aim of preserving the pictorial cycle of Giotto from the decay, together with the other works of art inside the Chapel, without drastically hindering or reducing the entry of visitors. Specifically, it was necessary that acidic s.p.m. and gases would diffuse inside the least possible and that thermo-hygrometric damaging gradients would be hindered. It seemed also clear that it was necessary to stop the infiltrations of rain water through a normal activity of ordinary management of the building – something that was made possible by renovating the roof, treating the outside walls with a water repellent formula and constantly monitoring the levels of water infiltrated in the underground area of the Chapel, in order to keep capillary raise front in the walls within a security level.

Fig. 4. Padua, Scrovegni-Chapel: X-Ray map at SEM + EDS of calcium (pink) and sulphur (green), 80x.

It was confirmed that the visitors played a negative role in producing water vapor from breathing; hence, it was concluded after long and accurate evaluation on behalf of the interdisciplinary Commission for the Restoration of the Scrovegni Chapel, which had been constituted in the meantime, to reach a solution which was without any doubt innovative, because founded on a "philosophy" of intervention that was "controlling" the ambient, i.e. which meant to ameliorate and improve the situation through a series of coordinated interventions circumscribed but

Table 3. Indoor – outdoor air exchange rate determined with the methodology of sulphur hexafluoride.

Operating conditions	*In visitors' absence (Closed door)*		*In visitors' presence (Open door)*	
	07-25/28-1995	01-16/19-1996	07- 25/28-1995	01-16/19-1996
Time of air renewal	33-34h.	31-32h	13-14h	23-24h
Number of air exchanges/hourly	0.224	0.203	0.378	0.310
Number of air exchanges/daily	5.4	4.9	9.1	7.4

Fig. 5a. Padua, Scrovegni-Chapel: Stratigraphic section observed at transmitted light, parallel nicols, ob. 2,5x. Gypsum crystallization is visible under the pictorial layer.

Fig. 5b. Padua, Scrovegni-Chapel: Stratigraphic section observed at transmitted light, crossed nicols, ob. 10x. Gypsum crystallization is visible under the pictorial layer.

targeting. This appeared to be much better than modifying the microclimate drastically with an intervention of a radical and "forceful" type (shortly what is called, synthetically, environmental regulation through the installation of an air conditioning unit forcing the indoor microclimate). Hence it was decided to close the main entrance (at that time the only one) of the façade and to create at the same time an ambient-entrance (CTA) by the North side of the Chapel just in conjunction with the ancient entrance door of the Scrovegni Palace, that was bricked up for security reasons after the demolition of the same structure, but that could possibly be re-opened. This was suggested in order to better manage the number of visitors and for higher protection of the Chapel from thermo-hygrometric gradients and from pollution agents coming from the outside.

Years running from 1999 through 2000

The CTA was realized between 1999 and 2000; it consists of a steel and glass structure and is meant to prevent that the external air might reach the inside of the Chapel during the phases of visitors' entrance and exit, thanks to how it's divided into compartments, that is into 3 rooms: an entrance area/waiting room, a filter area which consists of the tunnel entrance/exit from the Chapel and an area leading towards the outside, with automatic sliding doors interlocked. The CTA has an air conditioning unit of its own (fig. 7).

The use of a mechanical ventilation system with thermo-hygrometric control of the air inside the Chapel is linked to the presence of the CTA; the latter, as a matter of fact, by eliminating the air exchange between outside and inside, assures the replenishing of air and compensates the sensitive latent loads due to visitors, especially during the summer time.

The need to plan and implement a unit of air-conditioning plant for the CTA has required a first phase of studies necessary to define all the features of the unit itself, which had to have the goal to be usable and beneficial for a small number of visitors, preserving the wall paintings from pollution agents and from

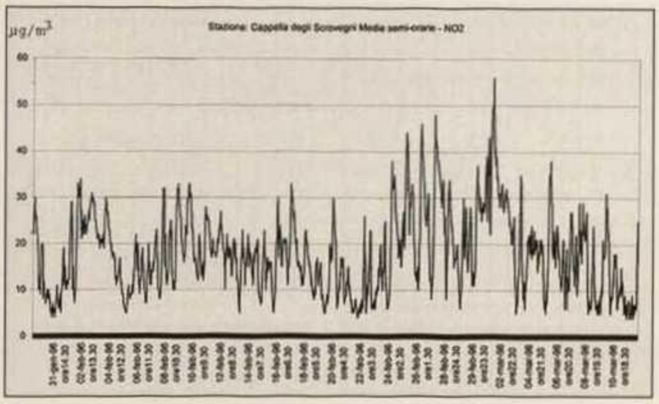
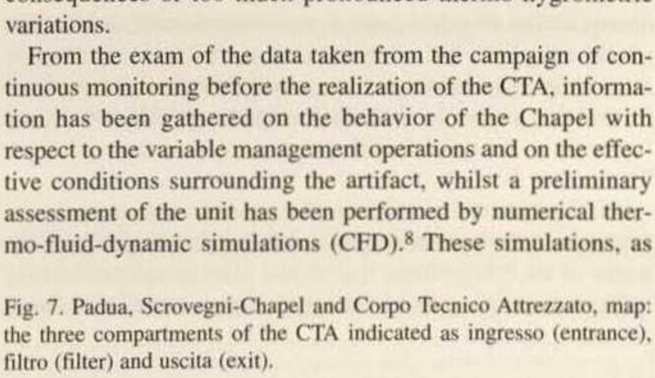


Fig. 6. Padua, Scrovegni-Chapel: Trend of semi-hourly average values of nitrogen dioxide (NO2) registered during the period between January 31, 1996 – March 10, 1996.

consequences of too much pronounced thermo-hygrometric variations.

From the exam of the data taken from the campaign of continuous monitoring before the realization of the CTA, information has been gathered on the behavior of the Chapel with respect to the variable management operations and on the effective conditions surrounding the artifact, whilst a preliminary assessment of the unit has been performed by numerical thermo-fluid-dynamic simulations (CFD).[8] These simulations, as

Fig. 7. Padua, Scrovegni-Chapel and Corpo Tecnico Attrezzato, map: the three compartments of the CTA indicated as ingresso (entrance), filtro (filter) and uscita (exit).



[7] Measurements registered by A. Ventura (IMIT Co. – Novara).

[8] Cesare Bonacina, Alessio Gastaldello, Piercarlo Romagnoni, Antonio G. Stevan, Modellistica di Previsione per il Controllo del Microclima: l'Uso della CFD, in: Basile, Scrovegni (note 2), pp. 39–44.

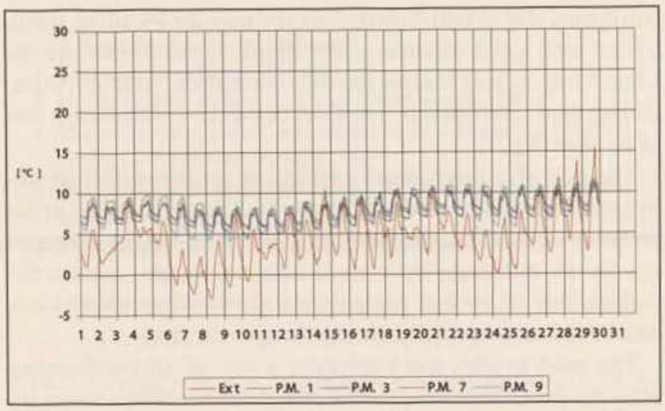


Fig. 8a. Padua, Scrovegni-Chapel: Diagrams of temperature and humidity levels relative to air registered by the monitoring system before the installation – February 1996, right wall.

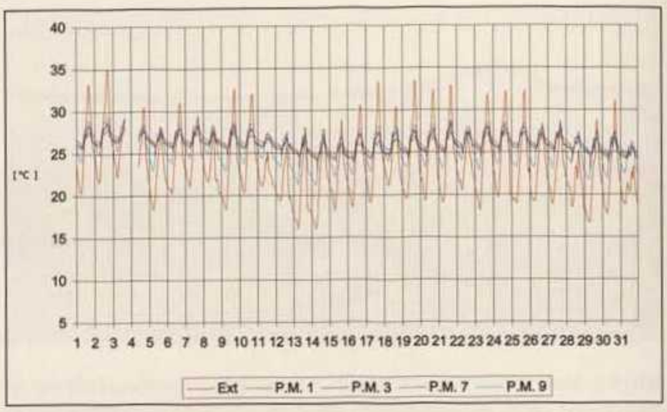


Fig. 10a. Padua, Scrovegni-Chapel: Diagrams of temperature and humidity levels relative to air registered by the monitoring system before the installation – August 1996, right wall.

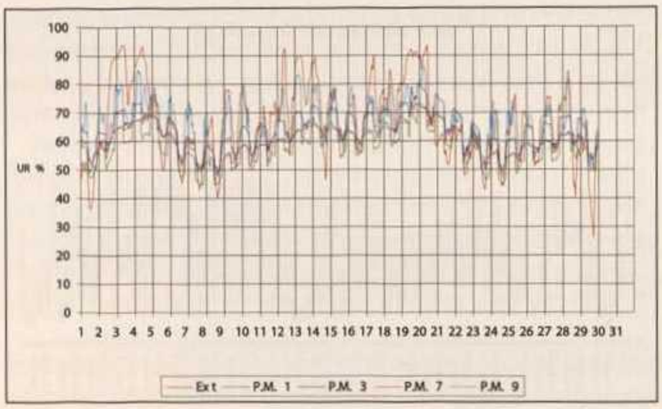


Fig. 8b. Padua, Scrovegni-Chapel: Diagrams of temperature and humidity levels relative to air registered by the monitoring system before the installation – February 1996, left wall.

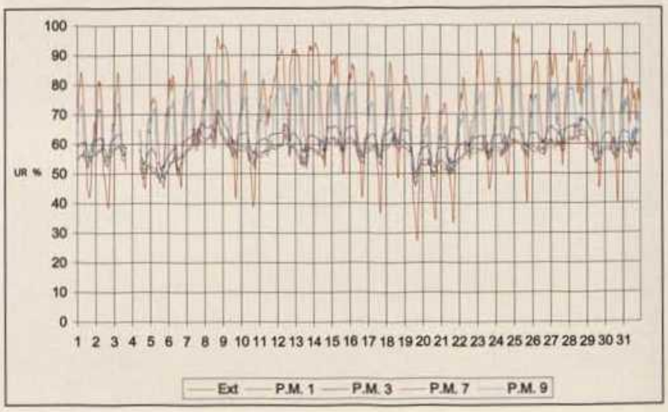


Fig. 10b. Padua, Scrovegni-Chapel: Diagrams of temperature and humidity levels relative to air registered by the monitoring system before the installation – August 1996, left wall.

demonstrated in other cases,[9] constitute a valid instrument which completes the information acquired from the experimental campaign; through this method, phenomena have been studied that cannot be described uniquely with discrete measurements, as for example with the air displacement map in confined areas.

It is fundamentally important for preventive conservation to know about the environmental conditions in proximity of the works of art,[10] knowledge that should refer to a period of time sufficiently ample. It is necessary, as a matter of fact, to detect all variations at medium and long term, indispensable to build up a microclimatic behavior reliable for the works of art, apt to describe the gradients of surrounding environmental conditions and suggesting ways of managing the environment. Therefore, together with continuous monitoring of the temperature and relative humidity of the air and of the superficial temperatures of the walls, it was also necessary to carry out measurements of the number of air exchanges in conditions near to those after the intervention, that is with windows and entrance door closed. These measures, based on the decay of the concentration of an

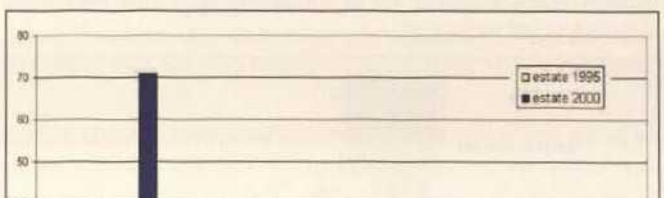


Fig. 9. Padua, Scrovegni-Chapel: Distribution of relative frequency of daily concentrations of s.p.m. inside the Chapel: comparison of summer 1995 with summer 2000.

9 L. AGNOLETTO, Paolo BAGGIO, Piercarlo ROMAGNONI, D. ROSSI e Antonio G. STEVAN, Studio Numerico del Comportamento Termico e Fluidodinamico dell'Aria Ambiente all'Interno della Basilica di S. Francesco in Arezzo per la Conservazione degli Affreschi di Piero della Francesca, in: Atti della 3° Conferenza Internazionale sulle Prove non Distruttive, Metodi Microanalitici e Indagini Ambientali per lo Studio e la Conservazione delle Opere d'Arte, Viterbo, 4–8 ottobre 1992, pp. 1117–1129; Charles E. BULLOCK, Frank PHILLIP, Walter PENNATI, The Sistine Chapel: HVAC Design for Special-Use Buildings, in: ASHRAE Journal, 38, 1996, n. 4, pp. 49–58.

10 Vasco FASSINA, Antonio G. STEVAN, Influenza dell'Ambiente sui Fenomeni di Alterazione dei Dipinti Murali, in: Le Pitture Murali (edited by Opificio delle Pietre Dure e Laboratori di Restauro), Centro Di, Firenze 1990, pp. 203–216; SYNCRO Advanced Engineering Consulting, La Cappella degli Scrovegni–Misura dei Parametri Fisici Ambientali, Rapporti al Comune di Padova, marzo 1997 e gennaio 2002.

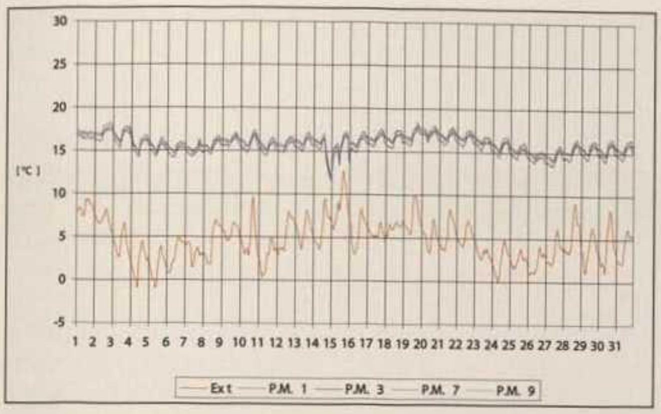


Fig. 11a. Padua, Scrovegni-Chapel: Diagrams of the air temperature and humidity values registered by the monitoring system after the CTA has been installed – January 2003, right wall.

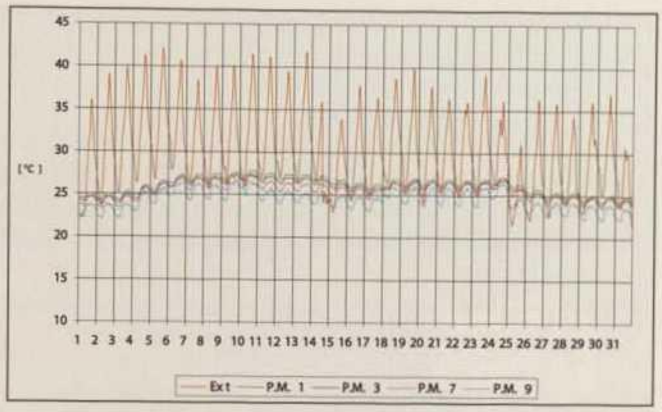


Fig. 12a. Padua, Scrovegni-Chapel: Diagrams of the temperature and humidity values relative to the air registered by the monitoring system after the CTA has been installed – August 2003, right wall.

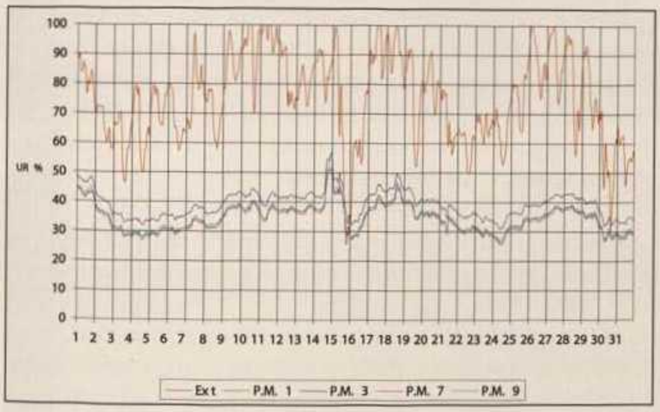


Fig. 11b. Padua, Scrovegni-Chapel: Diagrams of the air temperature and humidity values registered by the monitoring system after the CTA has been installed – January 2003, left wall.

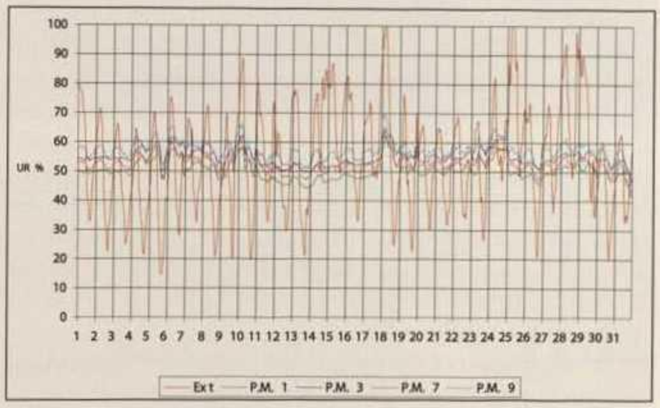


Fig. 12b. Padua, Scrovegni-Chapel: Diagrams of the temperature and humidity values relative to the air registered by the monitoring system after the CTA has been installed – August 2003, left wall.

inactive gas tracer (SF_6), have shown, as mentioned before, that the number of air exchanges is more or less equal to 9 daily air exchanges when the door is periodically opened and decreases to about 5 when the door is kept closed (see table 3).

The need to limit the diffusion of pollution agents from the outside and at the same time to maintain ideal conditions for the visitors was determining in finding a way of managing the Chapel.

Under these circumstances, that means with a reduced number of visitors, we can reasonably assume that the conditions that take place seem to be substantially similar to those detected at closed door.

The rate of air renewal that can be expected (estimating the volume of the Chapel to be 2500 m^3) results being equal to: Air Mass Flow =2500X5/24=521 m^3/h.

We can now consider that, if on the one hand the external air flow necessary to ensure the comfort of a person in quiet and good conditions is 30 m^3/h, the total air required to remove the heat generated and the water vapor from a visitor breathing, without introducing high thermal gradients, is about 75 m^3/h. Hence, without a mechanical ventilation system, the number of people that can stay in the Chapel at the same time results being very limited (7–8 persons). Considering people stopping in for about 15 minutes in the Chapel, there would be an hourly flow of about 30 persons, which is absolutely insufficient to satisfy the request of getting in.

Therefore, a mechanical ventilation plant with a filter system providing thermo-hygrometrically treated and filtered air, seems wholly justified and carries the following advantages:

- Allows a bigger number of visitors
- Controls the air quality inside the Chapel (which would otherwise be determined by air exchange with the exterior resulting from natural ventilation)
- Removes part of the thermal radiation load during the summer time
- Stabilizes water vapor content indoors.

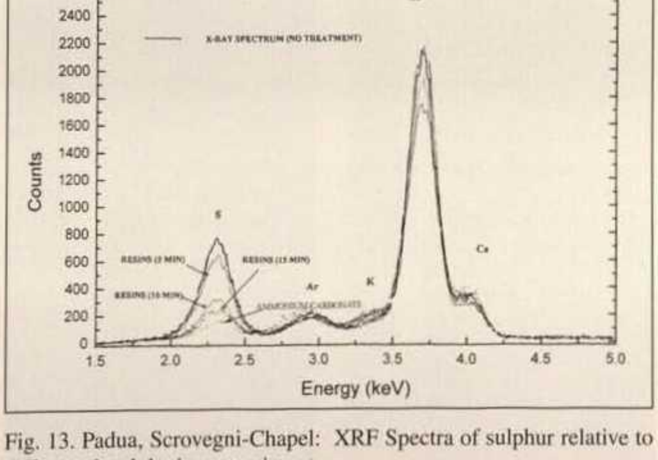


Fig. 13. Padua, Scrovegni-Chapel: XRF Spectra of sulphur relative to different desulphating experiments.

There haven't been any contra-indications by installing a ventilation plant (a problem solving already successfully experimented in monumental buildings), as long as its adoption would appear to be completely reversible and several precautions can be taken – dictated by forethought and considering the special features of the building, that is:

- Indoor conditions should not be substantially altered
- Excessive air velocities should not take place as these could modify the thermo-hygrometric stability of the painted surfaces and should not cause movement and scavenging of s.p.m. on the painted surfaces.

The first feature aimed at preventing that the air injected would result in being too different from the average one in the inside.

The second one wanted to prevent the inlet of air by mechanical ventilation from causing an air velocity near the frescoed surfaces that could significantly alter the thermal and mass exchange coefficients.

In addition, considering the difficulty of uniformly distributing the emitted air while on the meantime respecting the architectural constraints, it was thought to be cautious not to exceed an air flow of 1 volume/hour.[11] Thus, even if the distribution was not uniformly taking place, the air velocity would have remained nonetheless very contained (<0,1 m/s), except for obviously close to the feed vents. By limiting the number of air exchanges, there was also the reasonable certainty that the emission of treated air would not cause sudden alterations of environmental conditions.

The temperature of the air injected inside the Chapel would not have to vary too much from the average seasonal temperature detected inside the Chapel; a difference of more or less 4–5°C respectively during the summer and winter season was allowed.

As seen before, a duly cautious approach to the effects the installation might produce on the indoor micro-climate has suggested, at least in an initial phase, to reduce the temperature difference between the injected air and the average seasonal conditions existing inside the Chapel.

Taking into consideration, on the basis of the current available data, that during the summer season the temperature within the Chapel varied between 27 and 30°C and during the winter period between 6 and 9°C (temperature destined to rise when due to the different methods of managing opening and closure of the door would not have been frequent), temperature of air introduced had to vary between 23 and 26°C during the summer time and between 10 and 13°C during the winter season. This is an indicative evaluation and susceptible to changes based on information obtained from samplings now under way.

Fig. 14a-b. Padua, Scrovegni-Chapel, The Betrothal of the Virgin, Detail: the light blue background before (a) and after the cleaning (b).

The relative humidity values measured inside the Chapel before the installation were between 40% and 70% with peaks of 80%. (see fig. 8 and 10).

The air-conditioning system of the CTA would also had to reduce these peaks and stabilize values inside the Chapel within a range slightly narrower than that taken into examination.

Based on what was mentioned previously, it was deemed necessary to limit to 25 the number of visitors into the Chapel, with a maximum number of 35 persons.

Thus, it allowed not to go beyond 1 air exchange per hour, equal to 2.500 m^3/h during visitor's peak hours and keep it to about 0,75 air exchanges per hour with 25 admissions into the Chapel. Please check the annex with all the technicalities regarding specific plants adopted for the CTA, and the installation put in for treatment, filtration (in order to eliminate s.p.m. and acidic gases) and air circulation.

Following the realization of this structure in the year 2000, an additional campaign of supervision of pollution agents underwent. Particularly, comparing the values of frequency distribution relative to the daily concentrations of s.p.m. into the Chapel in the summer season with those of the preceeding years, it can be seen that there is a strong decrease of such pollution agent (see fig. 9).[12]

As for the installation, its management during the first year of working had to evaluate how responsive it was to the environment, in relation to the parameters of regulation of the installation itself.

In collaboration with the Department of Technical Physics of Padua, air velocity was detected at different air mass flows and also temperature and relative humidity of the environment for different air mass flows.

It was conceivably regarded that the main required feature of operation was successfully satisfying, that is reaching a balance of temperature and humidity of the air between the CTA and the Chapel, though slightly modifying the regulating parameters. A more accurate assessment of the functioning of the installation was conducted utilizing the continuous monitoring system of environmental conditions.

By comparing the new data with the information taken before the CTA was installed, it can be pointed out that it is possible to control effectively the thermo-hygrometric parameters inside the Chapel even during the summer period that presents critical conditions, reaching at the same time a significant improvement of the well-being of the visitors (see fig. 11 and 12).

[11] Garry THOMSON, The Museum Environment, London 1986.

[12] Maurizio MARABELLI, Paola SANTOPADRE, Vasco FASSINA, Rilevazioni degli Inquinanti Atmosferici prima e dopo l'Istallazione del Corpo Tecnologico Attrezzato, in: Basile, Scrovegni (note 2), pp. 45–51.

[13] Maurizio MARABELLI, Marcella IOELE, Domenico ARTIOLI, Alfredo CASTELLANO, Roberto CESAREO, Giovanni BUCCOLIERI, Stefano QUARTA, Cesare CAPPIO BORLINO, La Distribuzione dei Solfati prima e dopo l'Intervento di Restauro, in: Il Restauro della Cappella degli Scrovegni, Milano 2003, pp. 141–150.

Fig. 15a. Padua, Scrovegni-Chapel, The Angel at the Tomb and the Noli me tangere: after the cleaning.

Fig. 15b. Padua, Scrovegni-Chapel, The Angel at the Tomb and the Noli me tangere: before the cleaning.

Moreover, in the previous years, and most of all at time of restoration of the wall paintings (June 2001 – March 2002), a series of analyses and researches have been promoted bearing in mind two goals: conservation and study of pictorial techniques.

In particular, two XRF portable equipments have been utilized, calibrated to measure sulphur and chlorine on wall paintings: this technique has allowed to map the distribution of the two pollutants on many panels before and after the cleaning.

It was hence possible to determine in a not destructive way quantities of sulphur on the surface respectively before and after the application of pads of a saturated solution of ammonium carbonate and respectively of a strong anionic resin (Akeogel –Syremont), with different times of application. From the spectra reported in fig. 13, it is evident the extracting capacity of the two treatments.[13]

The contemporary extraction with organic solvents and the subsequent analysis by infrared spectrophotometry (FTIR) and pyrolysis plus gas-mass, regarding areas treated before in previous restorations, have pointed out the presence of acrylic resins, polystyrene, and polyvinyl acetate as fixatives, whose microcracking has brought to the development of superficial whitening.

At the same time it has been pointed out by X-ray diffraction that gypsum had been utilized as a consolidating agent in previous restorations.[14] At last, it was applied the spectrocolorimetric technique (spectrocolorimeter X-Rite) both in studies of the pictorial technique and to characterize the surfaces before and after the cleaning phase.

In fig. 14 it is shown a detail of the sky in the painting *The marriage of Mary and Joseph* before and after cleaning and in table 4 the trichromatic values measured on different types of blue are reported. By comparison we could come to the conclusion that this color has gained saturation after cleaning, by taking off a dark layer brushed on and juxtaposed, so increasing the blue component of the reflected light (decrease of *b*).[15] It remains only to be added that the Chapel is still undergoing permanent monitoring relative to the microclimate and to the quality of the air and that with an annual deadline a systematic close-up assessment is being performed (by the restorers) with regards to the state of conservation of the wall paintings in addition to the colorimetric control of the surfaces.

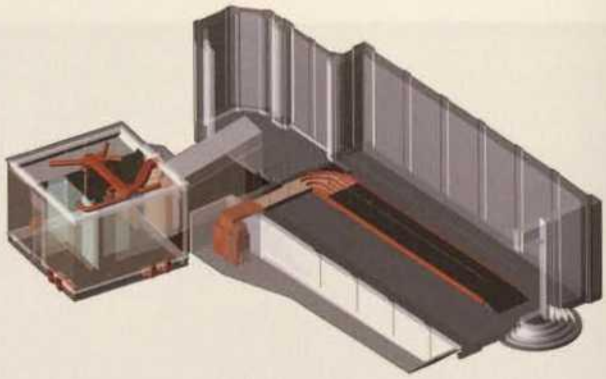


Fig. 16. Padua, Scrovegni-Chapel: Scheme of the air distribution system inside the Corpo Tecnico Attrezzato and the Chapel.

Conclusions

The overview that emerges from the information reported highlights some fundamental basic points and guidelines relative to the environmental research for the realization of an installation of this nature:

- The need to characterize the environment from a chemical and physical point of view
- The need to monitor the state of conservation by non-destructive surveys, so as to allow checking and comparisons in the long run
- The utility to study issues of restoration through a comparison and the integration between the non-destructive surveys and the micro-destructive ones
- The need to implement a project that would protect the environment before proceeding to the real restoration per se
- The opportunity to check and optimize in a long term installations that have been realized.

14 Maurizio MARABELLI, Paola SANTOPADRE, Marcella IOELE, Giuseppe CHIAVARI, Silvia PRATI, Studio dei Materiali di Restauro e dei Prodotti di Alterazione tramite Analisi Microdistruttive, in: BASILE, Scrovegni (note 2), pp. 132–140.

15 Marcella IOELE, Maurizio MARABELLI, Misure Colorimetriche sui Dipinti Murali prima e dopo l'Intervento di Restauro, in: BASILE, Scrovegni (note 2), pp. 151–155.

16 Antonio G. STEVAN, Progetto Esecutivo degli Impianti Meccanici, Elettrici e Speciali della Cappella degli Scrovegni e del Corpo Tecnico Attrezzato, Padova 1998.

17 Installation project data. *Outside conditions for reference:* Lowest winter outdoor temperature -5°C, Average outdoor winter relative humidity 80%, Highest summer outdoor temperature +33°C, Average outdoor summer relative humidity 50% – *Indoor CTA project data:* Indoor winter temperature (15 ±1)°C, Indoor winter relative humidity (50 ±5)%, Indoor summer temperature (26 ±1)°C, Indoor summer relative humidity (50 ±5)% – Injected air flow 50 m^3/ (h · person). Other information: Highest number of concurrent visitors' attendance in the CTA = 50 people; Highest number of concurrent visitors' attendance in the Chapel = 25 people; Thermal load due to lighting = 10W/m^2 floor; CTA plant operating time = 12 h/day; Chapel plant operating time = 24 h/day.

Measurement area	color	before cleaning			after cleaning		
		L	a	b	L	a	b
Mary and Joseph Wedding azurite of the sky with a tendency to purple	Dark blue	30.61	0.55	-23.40	32.07	2.22	-29.89
Lazarus' Resurrection azurite of the sky	Dark blue	33.83	-2.01	-17.92	35.82	-1.43	-25.66
Arrival at Jerusalem azurite of the sky	Blue	40.73	-3.13	-16.92	38.63	-2.71	-22.15
Last Judgment 1st section, left side azurite of the sky between the torch and the angel's banner	faded blue	42.52	-3.15	-7.97	41.67	-4.05	-14.79

Table 4: Color coordinates of the system CIELab; Lightness (L), red-green component (a) and yellow-blue one (b) of the blue sky before and after cleaning.

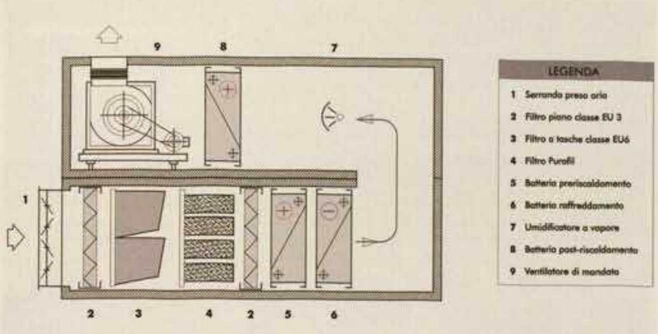


Fig. 17. Padua, Scrovegni-Chapel: Scheme of the air treatment unit, showing the intaking air shutter (1), the filtering air system (2,3,4), the pre-heating battery (5), the cooling battery (6), the dehumidifier (7), the post-heating battery (8), the inflow fan (9).

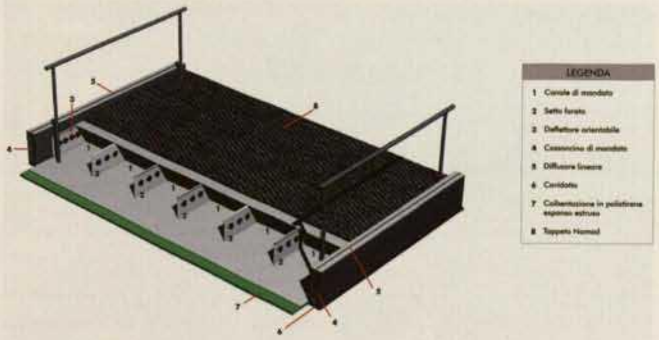


Fig. 19. Padua, Scrovegni-Chapel: Axonometric cutaway of the air distribution platform, showing the inflow channel (1), the pierced partitions (2), the steerable deflectors (3), the discharge ducts (4), the linear diffusors (5), the cables of the electrical plant (6), the lagging (7), and the 3M Nomad carpet (8) are indicated.

Technical annex

Description of the installation

The air conditioning installation and air filtering unit of the CTA and the system of ventilation of the Chapel have been realized between the years 1999 and 2000 before the restoration of the pictorial cycle, following the above mentioned guidelines.[16] The features of the installation project are herewith indicated.[17]

The type of installation adopted is an external air type; the unit treating air for the CTA is located externally adjacent to the structure, protected by an appropriate closet. The treating unit at disposal of the Chapel is positioned in the area beneath the entrance tunnel of the Chapel itself, in the underground space accessing to the crypt (fig. 16).

The two air handling units (fig. 17) each have a maximum air flow of 2500 m^3/h and are equipped with a variable air flow fan that can be adjusted to the effective conditions presently in state.

Before the thermo-hygrometric treatment, the air goes through a filtering section consisting of panel filters, high efficiency bag filters and special *Purafil* filters with active charcoal and activated alumina plus potassium permanganate to remove gaseous pollutants at high and low molecular weight. The filtering section is provided of manostatic control to signal out possible obstruction.

The treatment section is made of a heating cell fed by hot water, a cooling one fed by chilled water, a vapor humidifying section produced by a flooded electrodes generator, and a post-heating cell fed by hot water.

The air distribution in the CTA takes place via a micro-perforated false ceiling, and the chamber enclosed by the covered and false ceiling has the function of air inlet.

To prevent uncontrolled air flows from one area to another when the doors are opened, pressure gradients amongst the various areas are created through the air extraction system, controlled by the opening and closing switches of the sliding doors separating the areas.

Renewal and subsequent expulsion of air take place through the raised floor sections by means of walkable grids.

The underfloor space is divided into compartments next to the three areas into which the CTA is divided, forming three distinct extraction areas, each equipped with two variable-speed fans so that, by automatically excluding two of the fans, it is possible to obtain a pressure gradient between two areas put in connection when opening the doors.

Air distribution inside the Chapel is led by means of a low platform, with slot diffusers along both sides. Fig. 19 shows a cutaway view of the platform, where the main elements are

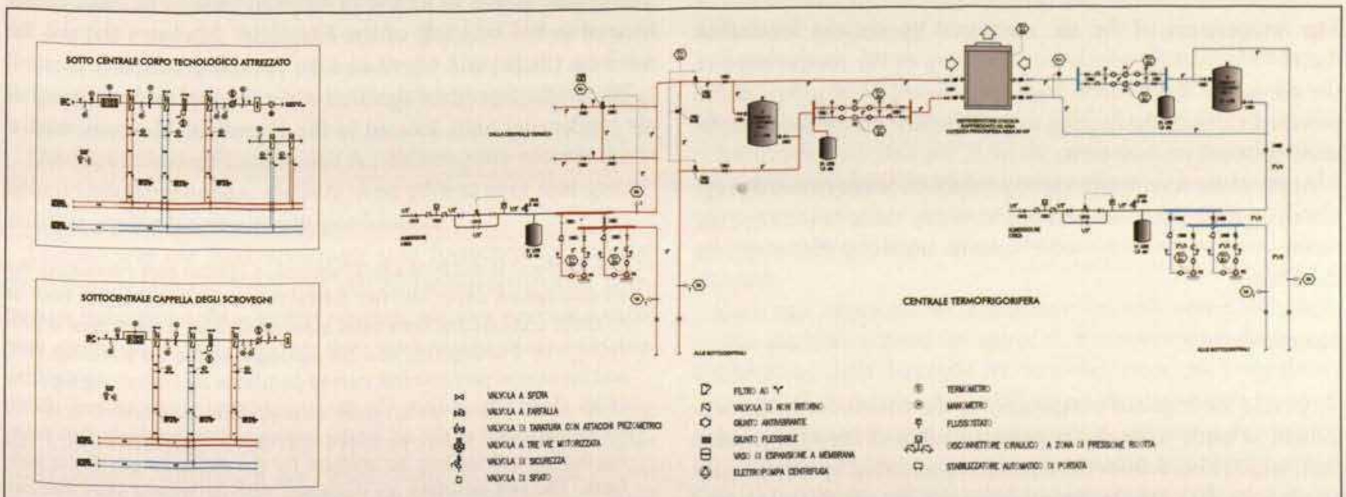


Fig. 18. Padua, Scrovegni-Chapel: Functional scheme of the mechanical plants.

Fig. 20a. Padua, Scrovegni-Chapel, The Virgin's Return Home: before the cleaning.

Fig. 20b. Padua, Scrovegni-Chapel, The Virgin's Return Home: after the cleaning.

located. Specific areas of the platform are described in the note below.[18]

Due to the fairly small air flow injected in relation to the volume of the Chapel there is no need to perform a mechanical extraction. The air goes out through the doors and window slots thanks to a slight over pressure to which the environment is kept, avoiding external air penetration.

Regulating the installation

Installation is regulated by direct digital control (DDC), which makes it easy to operate the equipments.

The control system is interfaced with the management system of the technological plants and is equipped with a local terminal.

The CTA thermo-hygrometric treatment of the air is regulated in the following way.

Winter season

The temperature of the air, measured by sensors located in the environment, is regulated according to the temperature of the air inside the Chapel. This is achieved leveraging on the powered valve of the heating unit to balance the climatic conditions between the two areas.

At the same way, water vapor production is continuously regulated on the basis of the relative humidity value of the environment, so as to reach the same specific humidity that runs into the Chapel.

Summer season

To ensure the required temperature in the environment, the regulation is made through the powered valve of the refrigeration unit, which also dehumidifies, and is controlled by the humidity sensors. In case the temperature of the air flow injected seems to be lower than the required one due to the dehumidification, the post-heating unit will start working.

Regulation of the air treatment unit takes place by handling in advance the temperature conditions inside the Chapel, corresponding to the conditions observed when there are no visitors inside.

The thermo-hygrometric features of the air flow are regulated in a cascade sequence, on the basis of the values measured by the temperature and humidity sensors inside the Chapel. Regulation of the air treatment unit takes place by handling in advance the temperature up to the minimum acceptable value and then by increasing the fan air flow.

The control system of the mechanical installation provides to detect the inflow and outflow temperatures of water and air, incoming and outgoing air humidity values, differential pressures existing in the filters, the functioning state of the variable air flow fan, and also the operational state of the air extraction fans.

Heating and chilling plant

The heating power of 95 kW is supplied by the electrical cables located in the building of the Eremitani Museum not too far from the Chapel and where also the pumping station is located.

The production of refrigerated water is supplied by a group of air condensing units located in the Eremitani Museum, with a

[18] The platform is made of a head section, a central part containing the air distribution ducts, and two lateral discharge ducts and is built of modular sections that have been assembled. The head section is provided with a connecting end for joining it to the air handling unit, and the central part contains curved partitions for conveying the flow of air to the lateral duct. Via the steerable deflectors we can obtain the equalization of the air intake introduced in the ducts thus making the flow of feeding air uniform for the entire length of the platform. The slot diffusers are equipped with deflecting slats that can be adjusted as to individually direct and regulate the flow of air. The entire structure sits on expanded extrusive polystyrene panels that also thermally insulate the platform from the floor.

refrigeration capacity of 64 kW. This group contains a section for the recovery of condensation heat and consists of a pre-assembled unit that also contains the storage tanks and the primary cold and hot circuits pumps.

The thermo-conductor fluid consists of a mixture of water and glycol in a way that, if necessary, it dehumidifies efficiently, also at relative low dew point temperature values. For this purpose, the set point of the chiller is remotely adjustable, according to weather conditions of the seasons.

The hydraulic network that feeds the installation, connecting the Eremitani Museum with the Scrovegni Chapel, is built with insulated polyethylene tubing running underground through a covered trench. Fig. 18 shows the functional diagram of the mechanical installation.

Zusammenfassung

Die Scrovegni-Kapelle.
Interdisziplinäre Untersuchungen und Maßnahmen zum Schutz vor Umwelteinflüssen

Nur 8 Jahre nach Beendigung der letzten Restaurierung zeigten die Malereien in der Kapelle im Jahr 1971 bereits makroskopische Verfallserscheinungen.

Bei der ausgeführten Restaurierung handelte es sich aber nicht etwa um eine mangelhafte Restaurierung, sondern die Notwendigkeit regelmäßiger Kontrollen und Wartungsarbeiten am Gebäude und der Umgebung außer und vor den konservierenden Eingriffen an den Malereien wurden damals und seither immer unterbewertet. Insbesondere wäre es für die Ziele der Konservierung von Bedeutung gewesen, sich die Folgen der Umweltverschmutzung auf den Erhaltungszustand der Fresken zu vergegenwärtigen, wenn man beachtet, dass seit der Restaurierung durch Leonetto Tintori und der vorausgegangenen Restaurierung mehr als 60 Jahre vergangen waren.

Die Schäden an der Kapelle nach dem Erdbeben in Friaul 1976 bewegten die verantwortlichen Denkmalschützer beim ICR (Zentralinstitut für Restaurierung Rom) um Hilfe für den Malereizyklus von Giotto anzufragen, um eine korrekte Restaurierung zu gewährleisten. Und tatsächlich gab das Institut dem Problem der Konservierung ein völlig innovativen Ansatz, indem es die bisherige traditionelle Praxis veränderte, die Eingriffe auf das Artefakt vorsah, ohne die Umgebung zu berücksichtigen, während jetzt auch die Umgebung und die Anpassung des Gebäudes bei der Restaurierung berücksichtigt werden.

Die Methode der Planung und Ausführung der wissenschaftlichen Untersuchungen, die sehr weit gefasst aber sehr gezielt erfolgte, ist bis heute ein gültiges Modell.

Ebenso war die Konservierung sehr fortschrittlich, indem die Arbeitsschritte in Einheiten von einfachen bis zu sehr komplexen Schritten aufgegliedert wurden und der nächste Schritt erst nach der Verifizierung des vorhergehenden Schrittes erfolgte.

Nach den etwas einfacheren Eingriffen in die Verbesserung der Umweltbedingungen der Fresken (abgeblendete Schutzverglasungen, Austausch der Beleuchtung etc.) folgten Arbeiten zur Gebäudesanierung und zuletzt die Installation eines Filters (CTA – Corpo Tecnologico Attrezzato) zwischen Gebäudeinnerem und Außenwelt. Dies war der umfangreichste und innovativste Eingriff. Zum ersten Mal wurde dieses System hier für die Kapelle konzipiert, die Realisierung / Umsetzung folgte dann tatsächlich erst nachdem es für das „Letzte Abendmahl" von Leonardo da Vinci in Mailand bereits installiert war.

Nach circa einem Jahr der Inbetriebnahme dieses Filters konnte die neue klimatische Situation innerhalb des Gebäudes, die einer kontinuierlichen messtechnischen Überwachung unterlag, als ideal bewertet werden. Nach ungefähr 20 Jahren waren somit endlich die Voraussetzungen dafür geschaffen, durch direkte Eingriffe am Malereizyklus den sich gravierend verschlechternden Erhaltungszustand zu bremsen, der aus der Umwandlung des bemalten Kalkputzes in Gips mit der Folge einer Zersetzung der Malschicht bestand.

Sommario

La Cappella Scrovegni.
Ricerche interdisciplinari e protezione ambientale

Nel 1971, a soli 8 anni dalla fine dell'ultimo restauro, i dipinti mostravano già macroscopici segni di degrado.

Quello allora effettuato non era stato un cattivo restauro, ma la sottovalutazione della necessità di effettuare ciclici interventi di controllo e manutenzione sull'edificio e sull'ambiente, oltre e prima che sul manufatto, e soprattutto l'affermarsi di un fenomeno dirompente – ai fini conservativi – quale l'inquinamento atmosferico avevano fatto in modo che il deterioramento degli affreschi riprendesse e anzi subisse una inaspettata accelerazione, se si considera che tra il restauro Tintori e il precedente erano trascorsi più di 60 anni.

I danni subiti dalla Cappella a seguito del terremoto che nel 1976 sconvolse il Friuli indusse i responsabili della tutela del monumento a chiedere all'ICR di prendersi cura del ciclo giottesco affinché l'intervento di restauro fosse condotto nel modo più corretto. E, in effetti, l'Istituto diede al problema della conservazione dei dipinti di Giotto una impostazione profondamente innovativa, capovolgendo la prassi tradizionale che prevedeva l'intervento sul manufatto indipendentemente dallo studio e dall'eventuale intervento di adeguamento dell'ambiente e di conservazione dell'edificio, che invece debbono precedere.

Il metodo di programmazione ed esecuzione delle indagini scientifiche, ad ampio raggio ma strettamente mirate, costituisce un modello tuttora valido.

La stessa cosa vale per il modo, articolato e progressivo, in cui sono stati messi in opera i provvedimenti conservativi, dai più elementari fino ai più complessi, ma passando dall'uno all'altro soltanto dopo avere verificato la bontà dei risultati ottenuti.

Così agli interventi di miglioramento ambientale più facilmente attuabili (messa in opera di controvetrate schermanti, sostituzione delle lampade ad incandescenza, etc.) seguirono quelli di risanamento dell'edificio e infine la messa in opera del CTA (Corpo tecnologico attrezzato), una sorta di filtro tra interno del monumento ed ambiente esterno, che rappresenta il tipo di intervento più complesso e innovativo (messo a punto per la prima volta proprio per la Cappella, anche se poi la realizzazione segue a quella del Cenacolo di Leonardo a Milano).

Trascorso circa un anno dalla messa in funzione del CTA, alla fine della quale la nuova situazione ambientale interna dell'edificio, sottoposta a monitoraggio strumentale per verificare l'efficacia dei provvedimenti realizzati, era risultata idonea, si giudicò finalmente possibile, dopo circa 20 anni, intervenire sul ciclo pittorico, interrompendo così il gravissimo processo di deterioramento consistente nella trasformazione dell'intonaco dipinto in gesso con conseguente polverizzazione del colore.

Fig. 21. Padua, entrance to the Scrovegni-Chapel: Corpo Tecnico Attrezzato (2003).

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