Inquinamento atmosferico e patrimonio culturale: impatti, metodi di indagine e strategie di conservazione preventiva
ENVIRONMENT – CULTURAL HERITAGE

- Changes in climate/pollution
- Accumulation
- Synergy
<table>
<thead>
<tr>
<th>SENSITIVITY</th>
<th>RESILIENCE</th>
<th>VULNERABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cultural Heritage</td>
<td>Adaptation</td>
<td>Critical elements</td>
</tr>
<tr>
<td>materials</td>
<td></td>
<td>Physical/Managerial</td>
</tr>
</tbody>
</table>

**ENVIRONMENT/POLLUTION – CULTURAL HERITAGE**

**EXPOSURE**
Climate/geographical conditions

**SENSITIVITY**
Cultural Heritage materials

**RESILIENCE**
Adaptation

**VULNERABILITY**
Critical elements

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<table>
<thead>
<tr>
<th>Rank</th>
<th>Type</th>
<th>Vulnerability</th>
<th>Examples</th>
<th>Preventive measures and priorities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inf0</td>
<td>Complete description of CH asset explain and its availability to stakeholders involved</td>
<td>No major vulnerability issues. Comprehensive risk management plans can be developed and appropriately shared</td>
<td>Data concerning CH assets are complete (maps, condition assessment of objects and records of contents), accessible to all relevant stakeholders and up-to-date</td>
<td>Regular inspection of CH assets is required on periodic basis to keep risk-management plans up-to-date. Regular maintenance is also necessary to ensure conditions of the asset.</td>
</tr>
<tr>
<td>Inf1</td>
<td>Partial or complete data existing but not available to stakeholders</td>
<td>Loss might be expected particularly during rescue activities when handling, transportation and storage requirements are not accessible</td>
<td>Examples include information concerning movable heritage such as collections and artefacts in a museum not available to rescue units</td>
<td>Regular inspection of CH assets in buildings with data on their location and description for evacuation purposes; Digitalization of CH related data; Integration of existing databases.</td>
</tr>
<tr>
<td>Inf2</td>
<td>Only partial, not up-to-date or incomplete information exists</td>
<td>Damage is expected to the CH object and its contents. Failure of structural components and loss of movable objects can occur due to incorrect, missing or not valid information</td>
<td>Maps and databases related to CH assets present in a specific area exist however significant information is missing or invalid due to changes in time of asset vulnerability or hazard level</td>
<td>Regular inspection identifying and marking stock at risk through mapping; Damage assessment and evaluation; Records of movable heritage stored in buildings.</td>
</tr>
<tr>
<td>Inf3</td>
<td>No information about heritage in one of the following locations: conditions, contents</td>
<td>Different levels of damage from minor to collapse can occur even if the use of actions of minor intensity. Lack of information can seriously affect the proper determination of security assessment. Natural disasters or weather effects (e.g., in case of weather-induced degradation of mechanical properties of material load-bearing capacity might be overstated)</td>
<td>No mapping of CH assets present in a risk-prone area is available. Structural and material condition of assets. No data concerning valuable contents of buildings are known</td>
<td>Regular inspection and repair of faults deficiencies; Identifying and marking stock at risk through mapping; Damage assessment and evaluation; Records of movable heritage stored in buildings; Digitalization of CH related data; Integration of existing databases.</td>
</tr>
</tbody>
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**Central Europe**

**ProteCCh2save**

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**Interreg**

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**ISAC**

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METHODOLOGICAL APPROACH

ANALYSIS OF SAMPLES COLLECTED FROM HISTORIC BUILDINGS

TESTS IN SIMULATION CHAMBER

ATMOSPHERIC MONITORING CAMPAIGNS CLOSE TO CULTURAL HERITAGE

FIELD EXPOSURE TESTS
POLLUTION IMPACT ON CULTURAL HERITAGE

- Soiling and black crust formation
- Chemical dissolution (surface recession)
- Salt crystallisation (decohesion, powdering)
- Biodeterioration
SOILING AND BLACK CRUSTS FORMATION

- Sulfation of marble and limestones due to dry and wet \( \text{SO}_2 \) deposition (calcite into gypsum)
- Particles deposition from stationary and mobile combustion sources
SURFACE RECESSION

Rainwashed areas

- Chemical dissolution/Material loss
- Erosion

ANALYSIS OF SAMPLES COLLECTED FROM HISTORIC BUILDINGS
Vulnerability of building materials is different depending on chemical composition and porosity.

Reactivity towards $SO_2$
ROLE OF CARBONACEOUS PARTICLES

LABORATORY TESTS

CARRARA MARBLE

Carbonaceous particles give rise not only to aesthetic damage, being responsible of the black colour of the damage layers, but they play an active role in the formation of the gypsum layers, as catalysts of SO$_2$ oxidation at the stone surface.
SULPHATION PROCESS

Shift in modern urban atmospheres from a $\text{SO}_2$ dominated situation to a $\text{NO}_x$ – organic compounds dominated situation
Damage layers on European Monuments

Organic Carbon
- Atmospheric deposition
- Biological weathering
- Surface treatments

Elemental Carbon
- Particles emitted by combustion processes

OC prevails on monuments in European towns due to urban traffic

ANALYSIS OF SAMPLES COLLECTED FROM HISTORIC BUILDINGS

[Bonazza et al. Atmos. Env. (2005); Ghedini et al., EST (2006)]
GEOCHEMICAL CHARACTERISATION

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

ANALYSIS OF SAMPLES COLLECTED FROM HISTORIC BUILDINGS

AESTHETIC IMPACT ON SURFACE BUILDINGS

- Modern urban atmospheres deposit
  - less sulfur (phytotoxic)
  - more nitrate (nutrient)
  - more organic (nutrient)

- Surface yellowing
- Warmer conditions
- Encourage biological damage (green, grey and black)

Grossi et al., 2006; Bonazza et al., 2007; Grossi et al., 2008, Smith et al., 2010
Biomass accumulation on monuments

[Bolea et al., JCH (2012)]
Salt crystallisation/Relative humidity cycles = 75.5%

Western Europe. Temperate fully humid climates: highest potential for salt damage and possible higher number of transitions in summer. Climates with dry summers: lesser frequency of transitions in summer [Grossi et al., STOTEN (2011)]
ENVIRONMENTAL MONITORING

Traffic (till 2009)

Pedestrian area

• Gas ($SO_2$, $NO_x$, $O_3$)
• Total suspended particulate (TSP): soluble and carbon fraction

[Ghedini et al., Atmos. Environ. (2011)]
The Florence Baptistry

Monthly mean atmospheric concentrations of total suspended particulate at ND (entrance), SD (exit) and MR during 2003:

The crucial importance of performing aerosol monitoring in the proximity of monuments is evidenced by specific campaigns.

TRAFFIC

PEDESTRIAN

Non carbonate carbon concentration (NCC) at ND and SD during 2004.
# Soiling and blackening: models and damage functions

<table>
<thead>
<tr>
<th>Function</th>
<th>Variables involved</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R=R_0-k(\text{PM})^{1/2}$</td>
<td>$R =$ reflectance after time $t$; $t =$ time; $R_0 =$ initial value of reflectance; $k =$ constant; PM = particulate matter concentration ($\mu g \text{ m}^{-3}$).</td>
<td>Beloin and Haynie (1975)</td>
</tr>
<tr>
<td>$R=R_0 \cdot \exp (-kt)$</td>
<td>$R =$ reflectance after time $t$; $t =$ time; $R_0 =$ initial value of reflectance; $k =$ constant</td>
<td>Watt and Hamilton (2003)</td>
</tr>
<tr>
<td>$R=R_0 \cdot (R_0 - R_p) [1-\exp (-kt)]$</td>
<td>$R =$ reflectance after time $t$; $t =$ time; $R_0 =$ initial value of reflectance; $R_p =$ reflectance of surface covered by particles, $k =$ constant.</td>
<td>Brimblecombe and Grossi (2004)</td>
</tr>
<tr>
<td>$R=R_0 \cdot \exp (-k,\text{PM}_{10}t))$</td>
<td>$R =$ reflectance after time $t$; $t =$ time; $R_0 =$ initial value of reflectance; $k_s =$ rate constant for blackening and $\text{PM}_{10} =$ particulate matter concentration = 10 ($\mu g \text{ m}^{-3}$).</td>
<td>Kucera (2005)</td>
</tr>
<tr>
<td>$-dR/dt = (R_0 - R_p) \cdot \text{Vd}_{\text{EC}} \cdot \text{EC}/\tau$</td>
<td>$dR =$ rate of change in reflectance of the material (clean stone); $t =$ time; $R_0 =$ reflectivity of the clean stone; $R_p =$ final reflectance of the crust; $\text{Vd}_{\text{EC}} =$ deposition velocity of elemental carbon; $\text{EC} =$ elemental carbon concentration ($\mu g \text{ m}^{-3}$); $\tau =$ folding density (surface concentration of elemental carbon required to reduce the reflectivity by a factor e).</td>
<td>Brimblecombe and Grossi (2009)</td>
</tr>
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</table>
SOILING/BLACKENING DISTRIBUTION ON BUILDING

- MATERIAL
- GEOMETRY OF BUILDING
- TIME OF EXPOSURE
- LOCAL CLIMATE AND POLLUTION
  (concentration of pollutants/\(\text{SO}_2\) and particles, wind driven rain, particulate composition)
- PROXIMITY OF POLLUTION SOURCES
Field exposure tests

Museo di San Marco, Firenze
[Vidorni et al., EPJ Plus 2019; Fermo et al., STOTEN 2020]
RESULTS and DISCUSSIONS

from stone samples

C fractions & related isotopes

Carrara Marble samples

TC = CC + EC + OC

EC = TC - CC - OC

• Soil dust
• Stone substrate

EC

• Incomplete combustion of organic material

OC

• Biomass burning and fuel emissions
• Plant debris and biological particles

\[ \text{TC} = \text{CC} + \text{EC} + \text{OC} \]

950° C

550° C

12h + 950° C

430° C

Carbon fraction / %

H

Related to NCC

NCC > CC always in all sites

OC > EC: 9% < EC < 29% and 71 < OC < 91% respect to NCC

OC: FE > FI > BO

CC\text{surface} slightly > in FI

OC\text{surface} and EC\text{surface} increased over time in FE and FI

[Ghedini et al., 2006; Natali and Bianchini, 2015; Natali et al., 2018]
RESULTS and DISCUSSIONS from stone samples

### Carrara Marble samples

<table>
<thead>
<tr>
<th>Process</th>
<th>Most distinctive change</th>
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<tbody>
<tr>
<td>Blackening</td>
<td>L* (field test/in situ analysis) – whitish limestone</td>
</tr>
<tr>
<td>SO₂ dry deposition</td>
<td>b* (simulation chamber) – yellowish limestone</td>
</tr>
<tr>
<td>Organic pollutants deposition</td>
<td>b* - whitish limestone</td>
</tr>
<tr>
<td>Biodeterioration</td>
<td>L*, a*, b* (in situ analysis) - calcarenite</td>
</tr>
</tbody>
</table>

[Durante-Suarez et al., 1995; Urzi and Realini, 1998; Benavente et al., 2003; Bonazza et al., 2007, Grossi et al. 2007]

Legend:
- Horizontal (rhombus) and oblique (squares) samples exposed in Ferrara over time: orange dot represents mean values of marble before exposure while grey, red and light-blue markers stand for samples exposed respectively for 6, 12 and 18 months.
Research on safeguarding Cultural Heritage in Europe

- Need of **damage functions** for quantitative evaluation of the impact
- Lack in **multi-risk scenarios for complex systems**, i.e. urban centres, archaeological sites
- Need of **early warning system** for disasters specifically addressed to CH safeguard
- Need of focusing on **preparedness**, measures are mainly based on response to emergency situations
- Definition of **air quality threshold levels** for the protection of cultural heritage
Resilience strengthening and risk management

National/Local level

FRANCE


ITALY

In 2014 three technical-scientific documents were published supporting the “Strategia Nazionale di Adattamento ai Cambiamenti Climatici (SNAC)” adopted by the Ministry of Environment and including cultural heritage as one of the priority sectors.

Stones/Bricks/Mortars (Out)
- Surface Recession
- Blackening/Soiling
- Thermal Stress
- Frost Weathering
- Salt Crystallization
- Biodegradation

Wood (In/Out)
- Mechanical Damage
- Fungal Growth

Metals (Out)
- Corrosion (T+SO₂, Steel/Bronze)
- Corrosion (T+Cl⁻, Zinc/Lead/Cupper)
CAMS EU Regional SO₂ surface concentration (average 09/09/2020)

Matching the requirements CH community with current Copernicus capacity

Blackening function

\[ R = R_0 \cdot \exp (-k_s \cdot PM_{10} t) \] [Kucera 2005]
RECOMMENDATIONS FOR PREVENTIVE CONSERVATION

- **Identify and prioritize climate parameters and pollutants causing deterioration**, depending also on the sensitivity of materials and the environmental context in which monuments are located.

- **Define risks** of cultural heritage by adopting *continuous environmental monitoring close to monuments* as a valuable tool. Definition of risks allows heritage managers to single out the priorities for greater investment in preservation and funding of actions to reduce the cause.

- **Promote actions** aimed at reducing exposure of cultural heritage to harmful agents

- **Mitigate the negative causes** by regulation at regional and local levels aimed at the reduction of pollutants, especially in developing urban plans for a sustainable mobility.