HYPERION – A Decision Support System for Improved Resilience and Sustainable Reconstruction of historic areas


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Abstract – *We introduce a research framework for downscaling the predicted/simulated climate and atmospheric conditions as well as associated risk maps down to the 1x1 km (historic area) scale, merging them with geohazard maps and integrating them with site and structure specific multi-hazard vulnerability functions to determine the time-varying risk for historical cities. Applying atmospheric modelling for specific Climate Change (CC) scenarios at such refined spatial and time scales allows for an accurate quantitative impact assessment of the estimated micro-climatic and atmospheric stressors. The ambition of this work, performed under the framework of the HYPERION EU-funded project, is to produce a comprehensive tool to assess the threats of CC in tandem with other natural hazards, visualize the built heritage and cultural landscape under future climate scenarios, model the effects of different adaptation strategies, and ultimately prioritize any rehabilitation actions to best allocate funds in both pre- and post-event environments.*

Keywords – Climate Change; Cultural Heritage, Risk Assessment

1. INTRODUCTION

Recent studies [1] highlight the potential impact of Climate Change (CC) and geo-hazards (such as landslides and earthquakes) on historic areas hosting Cultural Heritage (CH) sites and monuments, which in turn yield significant adverse impacts on economies, politics and societies. The deterioration of CH sites is one of the biggest challenges in conservation; aspects such as building technologies/materials, structural responses, preventive measures and restoration strategies, resilience and adaptation methodologies must be considered. Currently there is no specific process towards understanding and quantifying CC effects on historic areas; combined with the limited strategies on CC-related issues, it becomes difficult to assess quantitatively and qualitatively the impact of various climatic and other parameters on the CH sites [2]. These issues form an integral part of the necessary support that should be provided to governmental bodies and cultural authorities to properly adapt their policies, in the short and long term, towards deploying sustainable mitigation plans and providing efficient reconstruction of the CH parts that have been damaged. Finally, the absence of social and communities' participatory aspects to the overall resilience and reconstruction planning of the historic areas is a main challenge to tackle.

In this paper we present a novel research framework, which aims to leverage existing tools and services (e.g., climate/extreme events models, and their impacts, decay models of building materials, Copernicus services, etc.), novel technologies (terrestrial and satellite imaging for wide-area inspection, advanced machine learning, etc.) to deliver an integrated resilience assessment platform, addressing multi-hazard risk understanding, better preparedness, faster, adapted and efficient response, and sustainable reconstruction of historic areas. This work, conducted under the framework of the HYPERION EU-funded project, which involves 18 different academic, industrial and local authority entities from 8 European countries, will take into account the local eco-systems in the CH areas, mapping out their interactions and following a truly integrated/sustainable reconstruction approach (technical, social, institutional, environmental and economic level), by incorporating active communities participation (using the PLUGGY social platform [3]) and by supporting new business models based on the concept of a "load-balancing" economy, (using an algorithm that acts like a "reverse proxy", distributing client traffic across different companies within the same sector) and offering financial risk-transfer tools (insurance, Catastrophe-CAT-bonds) that can ensure the immediate funds availability to fuel timely build-back-better efforts. In the following paragraphs we give an overview of the concept behind the research framework, the envisioned system components and methodology.

2. METHODOLOGY

The proposed framework offers an overarching strategy that includes risk management, protection, and preparedness as complementary strategies to prevent damages to CH sites, identify and ward off additional threats and promote adaptation, reconstruction and other post-disruption strategies to restore normal conditions to the historic area, as well as long-term strategic approaches to adapt to

CC and to wield policy tools for economic resilience. To achieve that, HYPERION introduces a research framework for downscaling the created climate and atmospheric composition as well as associated risk maps down to the 1x1 km (CH site) scale. Applying atmospheric modelling for specific CC scenarios at such refined spatial and time scales allows for an accurate quantitative and qualitative impact assessment of the estimated micro-climatic and atmospheric stressors. The system performs combined hygrothermal (HT) and structural/geotechnical (SG) analysis of the CH structures (indoor climate, HVAC, moisture and air transfer through walls, roofs and foundations, and related strains and stresses) and damage assessment under normal (past) and changed (future) conditions (anthropogenic or/and natural disasters), based on the climatic zone, the micro-climate conditions, the petrographic and physical-mechanical features of building materials, historic data for the structures, the effect of previous restoration processes and the environmental/physical characteristics of the surrounding environment. The data coming from the deployed sensors are coupled with (and utilised also to update) simulated data over the wider CH area (under HRAP) and are further analysed through our data management system and support communities' participation and public awareness. The data from the sensors feed the DSS to provide appropriate adaptation and mitigation strategies, and support sustainable reconstruction plans for the CH damages to the vulnerable assets. The HYPERION system ends up to an enhanced visualization tool with improved 4D capabilities (3D plus time) that can provide a simple and easy way for all relevant stakeholders to assess damage and risk. The produced vulnerability map (based on the produced climate risk regional models) will be used by the local authorities to assess the threats of CC (and other natural hazards), visualize the built heritage and cultural landscape under future climate scenarios, model the effects of different adaptation strategies, and ultimately prioritize any rehabilitation actions to best allocate funds in both pre- and post-event environments. The overall results will inform the employment of appropriate physical, organizational and financial tools to support resilience, including (a) structural rehabilitation interventions and associated policies (b) load-balancing reciprocal agreements between local businesses of the same type and (c) financial risk transfer tools (community/municipality insurance plans, single/multi-hazard insurance-linked securities) that can offer low-cost financing within hours of any extreme event, to jumpstart an immediate reconstruction effort. The aforementioned system will be evaluated in CH sites in Greece, Italy, Norway and Spain, representing different climatic zones. Table 1 provides a list of hazards to be considered per case study.

3. SYSTEM GOALS

In order to achieve the delivery of an integrated resilience assessment platform, addressing multi-hazard risk understanding, better preparedness, faster, adapted and efficient response, and sustainable reconstruction of historic areas, a number of system goals have already been identified, as these are described in the next paragraphs.

Table 1. Potential Impacts of CC, geo-hazards and man-made threats on the selected demo-cases [5]

Hazard	**Case Study**			
	Granada	*Venice*	*Tonsberg*	*Rhodes*
Sea Level rise/ Flooding	Very Low	High	Very High	High
Temperature Increase (ºC)	Very High (>4.1)	Very High (2 – 5.5)	Medium (3.1 – 3.5)	Medium (3.1 – 3.5)
Mean Precipitation – Summer (%)	-39.9 up to -20	-39.9 up to -20	⁻19.9 up to 0	≤ -40.0
Drought (%)	Very High > 18.0	High:16,1% - 18.0	Very Low: < 12,1 Very	Very High > 18.0
Landslide (L), Earthquake (E)	High (L)	High (E)	High (L)	Very High (E)
Atmospheric composition change	Very High	Very High	High	Medium

3.1 RELIABLE QUANTIFICATION OF CLIMATIC, HYDROLOGICAL AND ATMOSPHERIC STRESSORS

The system employs quality assessed numerical modelling results for selected CC scenarios in the historic areas under consideration, covering processes and interactions from the short-term to the long-term (10-60 years). These data will be used to estimate quantitative indicators for the potential impacts of CC on historic areas from the individual building to a regional level, including also aspects related to their aesthetics due to long-term exposure of the structures to air pollution and microclimatic conditions. Changes of both the average climate and the increase of the intensity and frequency of extreme climatic/weather events will be considered. A Land Surface model has been identified to account for the impact of climate and atmospheric composition on soil surface parameters (e.g., the presence of liquid water), thereby quantifying the structural and thermo-physical impacts on the structural elements [4]. The high-resolution modelling effort will exploit existing sources of climate and air pollution data enriched with sensor data (on site) and enhance their added value through risk indicators for selected risk hot-spots (e.g., foundations, facades of buildings), introducing a risk modelling interface with our resilience assessment platform.

3.2 MULTI-HAZARD MODELLING

This covers single, cotemporaneous (e.g., extreme temperature, humidity, wind, air pollutants) and cascading (mudflow/landslide after rain, etc.) hazards. Inundation maps will be provided for specific catchments by using hydrological modelling for various precipitation capacities, while seismic hazard will be quantified in terms of seismic intensity levels (peak ground acceleration, spectral acceleration estimates, and surface faulting deformations) and their spatial/temporal distribution for the historic area, by using stochastic modelling approaches (probabilistic seismic hazard analysis). HYPERION aims to provide input for the relevant regulatory framework, (e.g. Eurocode 1), on the load models for climatic actions. Data-based calibration of these models will be done at case-study level, and methodologies for evolution of these load models to take into account CC will be proposed.

3.3 ANALYSIS OF BUILDING MATERIALS AND DETERIORATION PROCESSES

Deterioration patterns and dose-response functions of building materials to be integrated in Heat, Air & Moisture (HAM) simulations are being developed for (a) classification of various building materials and damage assessment at demonstration sites, physical/mechanical characterisation of fresh, unaltered samples; (b) identification of critical first order factors that are not currently considered in the available recession models, and their measurement at CH-scale; (c) deterioration analysis of physical-mechanical properties of materials; (d) refinement of damage and dose-response functions; (e) effect of extreme events & environmental aging processes on deterioration of building materials.

3.4 IMPLEMENTATION OF A HYGRO-THERMAL (HT) SIMULATION TOOL

The tool considers the coupled HAM transport phenomena through structure's elements under specific scenarios. It characterizes the microclimate, both exterior and interior, using Computational Fluid Dynamics (CFD), models the hygrothermal performance of building materials that integrates boundary conditions obtained through transient CFD models, it validates these models using time-series experimental data, it quantifies the pace and magnitude of the change of material properties through comparative analysis between modern local materials and in-site materials, it analyses the CC risk scenarios in 1D, 2D and 3D spatial resolution and assesses CC impacts on acceleration of materials and elements degradation, and enriches the validated databases of hygric and thermal building material properties to be used simulations.

3.5 IMPROVED PREDICTION OF STRUCTURAL AND GEOTECHNICAL (SG) SAFETY RISK

Using simulators that exploit monitoring data from various sensors, we are able to predict the SG safety risk. HYPERION will assess the current condition of structural, non-structural and content components of characteristic archetype buildings in the historic area. These detailed models will be leveraged to validate simplified surrogate numerical models or reduced-order physical models, achieve accurate pre-event and near-real-time (n-RT) post-event assessment of the impact of the climate pressure and geo-hazards, define related damage/vulnerability functions and capacity thresholds of the aging structure, optimise any reconstruction or retrofitting actions and finally evaluate the response of the structure in the future, for a large number of hazards scenarios with/without the proposed adaptation and mitigation measures.

3.6 ENVIRONMENTAL AND MATERIAL MONITORING INCLUDING STATE IDENTIFICATION AND DAMAGE DIAGNOSIS:

Novel Computer Vision (CV) and Machine Learning (ML) algorithms will be implemented to exploit sensors, such as visible spectrum cameras, hyper-/multi-spectral cameras, thermal/infrared/Ultra-Violet sensors, mounted on vehicles and drones to get a precise inspection of CH sites.

3.7 DESIGN OF A HOLISTIC RESILIENCE ASSESSMENT PLATFORM (HRAP) AND A DECISION-SUPPORT-SYSTEM (DSS), ENABLING COMMUNITIES' PARTICIPATION.

HRAP will allow the integration of various analysis, modelling tools and damage/vulnerability functions, hence incorporating information from various sources (literature, surveys, satellite, etc.) with different levels of granularity (building/block/regional level) together with the associated uncertainties. All these tools will be built on a Geographic Information System (GIS), interfaced with existing open-source hazard assessment software and network simulators, and chained to socioeconomic impact analysis tools to produce both quantitative and qualitative loss estimates (e.g. financial loss estimate, reputation impact, morale impact etc.) in order to develop an end-to-end simulation platform enabling the running of any number of different “what-if” scenarios.

The platform will also support the community-based participatory environment through the PLUGGY social platform, for increased CH site participation and awareness. HRAP aims to integrate all the hazard and impact assessment tools and modelling data (climatic, SG and HT) in order to support decisions at strategic, tactical and operational level.

4. CONCLUSION

A novel research framework is proposed for downscaling the assessed climate and atmospheric conditions down to the 1x1 km (historic area) scale, merge them with geohazard maps and combine them with vulnerability data to determine the resilience of Cultural Heritage (CH) sites and associated cities. Applying atmospheric modelling for specific Climate Change (CC) scenarios at such refined spatial and time scales allows for an accurate quantitative and qualitative impact assessment of the estimated micro-climatic and atmospheric stressors. HYPERION will perform combined hygrothermal and structural/geotechnical analysis of the CH sites (indoor climate, HVAC, related strains and stresses, etc.) and damage assessment under normal and changed conditions, based on the climatic zone, the micro-climate conditions, the petrographic and textural features of building materials, historic data for the structures, the effect of previous restoration processes and the environmental/physical characteristics of the surrounding environment. The data coming from the integrated monitoring system will be coupled with simulated data (under our holistic resilience assessment platform-HRAP) and will be further analysed through our data management system, while supporting communities' participation and public awareness. The data from the monitoring system will feed the DSS so as to provide proper adaptation and mitigation strategies, and support sustainable reconstruction plans for the CH damages. The produced risk map will be used by the local authorities to assess the threats of CC (and other natural hazards), visualize the built heritage and cultural landscape under future climate scenarios, model the effects of different adaptation strategies, and ultimately prioritize any rehabilitation actions to best allocate funds in both pre- and post-event environments. The project outcomes will be demonstrated to four European historic areas in Norway, Spain, Italy and Greece (representing different climatic zones).

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