Cultural Heritage Resilience Against Climate Change and Natural Hazards

Methodologies, Procedures, Technologies and Policy improvements achieved by Horizon 2020 - 700191 STORM project

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It all began in the Summer of 2015... building up a strong idea on how to preserve our cultural heritage and identity threatened by climate change.
After four years we are proud to present this book with the main achievements reached throughout the effort of twenty Organisations and thirty-two European external stakeholders.
I would like to thank all the people involved in STORM for their total commitment and passion in carrying out the activities.

Silvia Boi
(Engineering Ingegneria Informatica)

Foreword

Vanni Resta, Andrei Borissovitch Utkin,
Filipa Mascarenhas Neto, Charalampos Z. Patrikakis

This volume is the result of three years of research and prototype activity performed in the framework of the Horizon 2020 STORM project. Together with twenty organisations comprising the final phase of the pilots, this book forms one of the last initiatives of the Consortium which is briefly presented in the poster reproduced in the last pages of this book which had been realised as project's propotional material once STORM started in 2016.

All the authors of the following Chapters are members of the STORM team and some of them are Member of the Executive Board thereof, and the four editors are the expression of different aspects of the complex research performed during the project lifecycle.

Authors of this book come from diverse backgrounds, and so do their Chapters. The works herein all evidence of climate change and therefore they allow us to understand the multifarious aspects its threats.

Coming back to the STORM project, it is the case to start giving evidence of its origin mentioning its framework and the H2020 'call for proposal' which it refer to. STORM born as a proposal in the summer of 2015 written to 'reply' to a call belonging to the 'Secure Societies' programme which is the seventh programme within the Horizon 2020 pillar called 'Societal Challenges'. In details, taking into consideration the four working area comprising 'Secure Societies' the project is related to the one called *Disaster-resilience: safeguarding and securing society, including adapting to climate change* and, more in detail to its third topic *DRS-11-2015: Mitigating the impacts of climate change and natural hazards on cultural heritage sites, structures and artefacts*. The Consortium is composed of twenty Partners across six European Countries plus an extra one: the Turkey. Further to the Partners there are also two so called 'associated Partners' which participate to the research without being funded.

The author of the foreword is a non-expert in the variety of competencies around the world of cultural heritage protection and preservation. For certain situations this is a disadvantage even though it enables us to consider the matter from a different perspective. From this angle, this book aims to give evidence of the various technologies and methodologies enhanced by years of research and experiments on the field to give cultural heritage sites 'resilience' to climate change. The sad reality is that the starting level for every kind of cultural heritage site is 'zero' and only with a lot of determination could this aim be achieved. Further evidence of difficulties faced is the lack of a proper manner to measure resilience both in qualitative and quantitative terms. This fact affirms it is no possible to define a "Resilient" cultural heritage site in a shared view. Empirical evidence demonstrates the non-uniformity in defining all the processes and measures adopted from a cultural heritage management to achieve this purpose. This consideration encourages the need of the creation of a proper 'resilience certification' like is happening in other emerging sectors also [see i.e. the ISO (International Organization for Standardization) which "covers almost every product, process or service imaginable, ISO makes standards used everywhere"]. As per the mentioned certification its potential of innovation lies in the principles from which it draws inspiration, that is the sharing of responsibility in the management of conservation issues, the control of activities generating impacts and the use of market mechanisms that seek in cultural heritage preservation excellence a source of competitive advantage. The strong point of this potential resilience record, beyond the creation of a solid structure capable of systematically controlling and managing climate change and environmental impacts on a cultural heritage site, lies in the pursuit for communication and transparency, or in improvement of the relations between cultural heritage site's manager and control bodies, institutions, citizens one of the pillars on which the STORM project is based on.

However, there are other vast obstacles before one should think about resilience certification. These relate to the fact that every site and each threat from climate change has its own peculiarities. In other word, it is the case to introduce a new relevant concept: the 'quantity of resilience' necessary in each site. This amount is another unknown element which should be studied. But this is another story which could form the subject of an *ad hoc* research with other multidisciplinary teams.

Chapter 1 presents several recommendations that resulted from the experience gained within STORM project, as well as thoughts from experts, in order to improve government policies on cultural heritage risk management.

Starting from the main European and international frameworks, this chapter explores different areas that require some improvements in order to implement a Disaster Risk Management (DRM) approach in cultural heritage sites. More precisely, it introduces operative proposals regarding: heritage Conservation; Communication between climate researchers and heritage managers; Coping and Adaptive capacities approaches based on current conceptual models; Cooperation among the different actors involved in the DRM of cultural heritage; Capacity building of heritage professionals, communities, via training and education programmes (the STORM 5 'C's'). A STORM risk-oriented proposal to improve policies at governmental level focused on prevention (i.e. focused on reducing vulnerabilities and exposure of cultural heritage) are also envisioned, although in a broader scope in order to answer to the common constraints of the different STORM countries.

Chapter 2 presents an integrated methodology of risk assessment and management for cultural heritage properties in response to the adverse effects of natural hazards and climate change-related events. The proposed methodology is applied to the five STORM pilot sites to identify and analyse the potential hazards and their corresponding risks. Accordingly, relative risk maps are generated to share a common understanding of the risks with the site managers and stakeholders. The output of the risk assessment for the pilot sites will further support the decision-making process to determine risk treatment strategies, including risk mitigation, risk preparedness, and recovery plan.

Chapter 3 focusses on the specific sensors and supporting information technologies developed during the Project for timely artefact diagnosis and early detection of potential threats to the cultural heritage. Several technical solutions were chosen on the basis of the plethora of existing and emerging techniques in this field — discussed, analysed and benchmarked at the first stage of STORM. The selection was determined, first of all, by the peculiarities of hazards for each of the pilot sites where the technical solution was going to be deployed and, secondarily, by the cost-effectiveness and how safe the diagnostic procedure is for the artefact (in particular, at what extent the measurements are non-destructive and non-invasive. The reviewed sensing and information technologies cover all the five pilot sites of the Project and numerous measurement techniques and data processing algorithms dealing with assessing structural performance by vibration, crack monitoring, electrical resistivity tomography, ground penetrating and interferometry radar, fibre Bragg grating interrogation, induced fluorescence spectroscopy, multispectral aerial photography, as well as photogrammetry and terrestrial laser scanning.

Chapter 4 charts the use of the data streaming in from the tools and sensors used in the STORM project. Several aspects are discussed herein, the analysis of weather data collected from the UK pilot sites weather station, the analysis of earthquake damage on structures at the Turkish pilot site together with the analysis of the novel Twitter Event Extractor developed by Resil-Tech and cursory analysis of the wireless acoustic sensors currently deployed across the STORM pilot sites to detect hazards from noise. This chapter gives an overview of just a small selection of data analysis currently being tested across the consortium and within the scope of the STORM project in a bid to help site managers and stakeholders in the efficient monitoring and preservation of their Cultural Heritage sites.

Chapter 5 gives an overview of the tools and services developed in the STORM project that contribute to share knowledge and critical information to face critical events in Cultural Heritage sites. The STORM Collaborative Decision-Making Dashboard provides two environments, the collaborative and the operative, which are strongly interconnected with one other. The user interface and the services developed in the backend permits to collect, show, store and retrieve all the information related to existing knowledge about disastrous events and to new knowledge (e.g. from the situational picture, risk assessment) of the actual situation shared by team of experts in order to identify the best recovery actions. The STORM's surveying and diagnosis service and mobile application will make it simpler for sites to monitor their CH assets through the STORM Prevention and Mitigation Processes, allowing to report issues within the application while conducting surveying activities, while the STORM Risk Assessment and Management Tool aims at providing to the site managers and experts a tool to identify and analyse the natural hazards, assessing the level of risk in different areas of a site and giving a level of priority to the items contained in the areas. Finally, the STORM web-GIS infrastructure supports the visualization of geospatial data managed by several services such as the risk assessment and the situational awareness

Chapter 6 describes in detail the cloud-based infrastructure that supports the data management of the STORM platform. An overview of the modular STORM cloud architecture is presented, which consists of a Core cloud and several Edge cloud instances. Moreover, herein are introduced the STORM platform's authentication and registration mechanisms for establishing a secure communication between the sensors and the data analysis services. Finally, the chapter concludes by defining the interfaces between the Core cloud and the Edge clouds.

Chapter 7 presents the STORM System Architecture inspired by a layered architectural principle that includes six main logical layers (Source, Data, Information, Event, Service and Application Layer) implementing the STORM functional and non-functional requirements. Going through each layer, this chapter gives an overview of the main STORM Logical Architecture sources and modules, including their functionalities, dependencies and basic operations. Moreover, the STORM Interoperability Architecture is described to show the interactions and the control flow among the architectural modules. Finally, the chapter focuses on which technologies are used to implement such functionalities. The technical and implementation aspects of all STORM modules are described, and some technical guidelines and details match the requirements of the logical architecture are proposed

Chapter 8 gives a brief overview about advantages and possibilities offered to protection and enhancement of Cultural Heritage by the chance of always being connected by a net. In particular, all the advantages given by the technologies developed within the STORM Project and the usefulness of the STORM approach in remote monitoring are described, since all these help in having greater preparedness and effectiveness of interventions, in addition to the possibility of collecting and storing very huge number of data. in order to prevent damage or material loss. In a connected world, every specialist has the opportunity to acquire the necessary data and to know the work of art's situation in advance, having the time to plan the right intervention to be carried out and to organize the needed activities with the due attention. Particular attention is also given to the usefulness that apps and services created for recreational purposes (i.e. social networks) may have not only to enhance cultural heritage, but also to raise awareness among the population about this theme.

Chapter 9 provides an overview of the STORM strategy in the pilot sites, focusing on pilot practical experiences, with an initial assessment of the results achieved until now. Multiple experimental scenarios in five countries (the UK, Italy, Portugal, Greece, and Turkey), covering both slow- and sudden-onset hazards, validate the proposed solutions in relation to the three phases defined in the project: Risk Assessment, Situation Awareness and First Aid activities. STORM introduces a comprehensive approach that supports end users with transversal services as data analytics and knowledge sharing during all these phases.

The book is ending with an ‘epilogue’ in which there is a ‘recipe’ on how to proceed in making cultural heritage more resilient against climate change. Not only in term preservation, but in view of an aware use of this huge value which the Europe Union is a guardian, paladin as well as proud owner!

1.
Cultural Heritage Policies for Prevention, Preparedness and First Aid

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Introduction

Cultural heritage, as a fundamental manifestation of individual and collective identity and memory, represents an unquestionable value for the sustainable development and the quality of life of present societies. Recently, a significant mind shift regarding the perception of heritage and cultural activities has been influenced by the impact of cultural heritage in the European GDP. Archaeological sites, museums, monuments, people's stories and historical environments hold enormous potential to regenerate and renew communities, through their contribution for economic growth, jobs creation, social cohesion and environmental sustainability (Busquin, Thurley 2015).

Following this recognition, the world has witnessed the integration of cultural heritage protection measures in the main international documents, especially from 2015 until the present moment, intending to mainstream cul-

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tural heritage in risk management policies and climate change strategies, as a call for action for governments and communities.

Below, this chapter explores the international frameworks and approaches currently in practice to influence the implementation of conservation and cultural heritage protection policies introduces the STORM risk-oriented proposals to improve governmental policies, mainly focused on prevention, allow a possible adaption to national legal systems of the STORM partner countries, as well as for their appropriation by different communities.

1. The international framework for cultural heritage protection from natural disasters and climate change

According to the United Nations document *Transforming our world: the 2030 Agenda for Sustainable Development*, cultural heritage is a valuable asset that contributes for several of its goals – *Goal 4 Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all; Goal 11 Make cities and human settlements inclusive, safe, resilient and sustainable; Goal 12 Ensure sustainable consumption and production patterns* – which clearly reiterate the importance of reinforcing the protection and safeguard of cultural and natural heritage. This document, calling on the strong commitment of governments, public and private organisations and citizens, highlights a three-dimensional course of action: the economic, social and environmental aspects being fundamental components for the transformation of societies and the creation of a fairer and more resilient and enjoyable world (United Nations 2016).

This new vision, based in the idea that the sustainability of the world and of human civilization are dependent on inclusive, adaptive and flexible solutions, is bound to introduce cultural heritage as a key element, since this appears to be the essential "value of all values" (Oliveira Martins 2016). History and culture alone allow for a better understanding of individual and collective identities, i.e., humankind and its place in the surrounding world, granting humans a sense of belonging and the adaptability that is fundamental for the development of innovation and creative processes.

The European Commission and international organisations such as UNESCO and the Council of Europe have been recommending the creation of policies to reinforce the relationship between cultural assets and citizens, encouraging new forms and models for the management and promotion of cultural heritage.

The adoption of the *European Heritage Strategy for the 21st Century* aims to contribute towards a novel concept of protection and valuation of cultural heritage, stressing its value for education and knowledge, territorial and economic development and social context. It is an innovative document, resulting from a broad debate, carried over more than 40 years, on heritage conservation and protection reflected in European and international charters and conventions (Council of Europe 2018b). Its conception and implementation are mostly based in the principles of the Council of Europe's *Framework Convention on the Value of Cultural Heritage for Society*, signed on 27th October 2005 in Faro, Portugal, intended to transform the course of history of heritage management policies by placing the spotlight on the role and function of cultural heritage for human development (Council of Europe 2005). The former materialistic view, focused in the protection of objects and materials, is replaced by a humanistic vision. As stated by Guilherme d'Oliveira Martins, "it is about going from the "how to preserve heritage and by what procedures" to "why and to whom" (Oliveira Martins 2016). Based on this concept, the 32 recommendations proposed by *Strategy 21*, to be implanted at national, regional and local levels, are meant to promote the development of knowledge and the sharing of know-how, highlighting the recovery of traditional skills and its articulation with scientific research, in a spirit of a shared social responsibility with cultural heritage management.

Thereby, cultural heritage as a source of information and primary knowledge is an essential resource for enhancing community resilience, especially for those most stricken by natural disasters and phenomena potentiated by climate change. Local populations have been forced, throughout history, to adapt and devise solutions to face climate instability. Ancestral knowledge and traditions are testimonies to such resilience strategies, and both its preservation and valuation have been recognized as priorities in the development of new approaches for the sustainable management of cultural and natural heritage (Freitas *et al.* 2018).

The *Sendai Framework for Disaster Risk Reduction 2015-2030*, being a voluntary international agreement signed by 112 member states of the United Nations, represents a significant advance towards the implementation of a culture of prevention. This document sets as a priority the role of governments in the implementation of disaster risk reduction policies, forcibly implying the involvement of all sectors of society, including Culture. In its practical component, this important instrument to global scale mobilisation is represented, at national level, via risk reduction platforms functioning as spaces for collaborating and sharing of good practices that are essential for the elaboration and revision of sectorial programs, policies, strategies and standards (United Nations 2015).

Within the European territory, the implementation of the *Sendai framework* is supported by an *Action Plan 2015*-2030 (European Commission 2015a), which reflects the concerns of the European Commission regarding the building of resilience and translates the *Sendai* priorities into European policies.

The agenda defined by the European Commission for the cultural sector in the *Work Plan for Culture (2015-2018)*, which aims to contribute for the exchange of knowledge, improvement of creativity and innovation, and definition of priorities in the policy-making process, foresees a topic on risk assessment and prevention for safeguarding cultural heritage from the effects of natural disasters and threats caused by human action (Council of the European Union 2014). This assignment, in line with the European Commission's Sendai Action Plan, was accomplished through a study to identify and map risk assessment and prevention strategies and procedures at national levels. The study was developed on 28 European countries and provides evidence-based recommendations to improve the integration of cultural heritage in national platforms for Disaster Risk Reduction, as well as to promote cooperation between all the players involved. The study functions thus as an important survey of the current state of risk management tools and strategies for cultural heritage in Europe, with the aim to propose measures of prevention and preparedness (Vintzileou *et al.* 2018).

The *Work Plan for Culture 2019-2022*, goes even further, by including a topic regarding the adaptation to climate change. The conduct of a study destined to identify and share good practices and innovative measures for heritage sites under the menace of climate change impacts is also to be expected (Council of the European Union 2018). Such arrangement follows the work developed by the Council of Europe, mirrored in the recommendations published over the last decade (Sabbioni et al 2008) and by other international agencies such as UNESCO (Markham *et al.* 2016), ICOMOS (ICOMOS 2007) and ICCROM (*https://www.iccrom.org/news/climate-change-heritage-has-role-play*).

The use of emerging technologies for the management of information about heritage at risk is one of the main challenges regarding the improvement of the protection of cultural assets, assisting with data organization and the definition of strategies and priorities of intervention in all stages of the Disaster Risk Management (DRM) process.

Risk assessment charts are an essential instrument for such management, but the complexity of their preparation, resulting from the need to articulate data from various scientific and technical areas and to allocate specialized human resources, has been holding back its implementation nationally.

An exemplary case is the Italian *Carta del Rischio del Patrimonio Culturale*, developed over several decades and still operational (at *www.cartadelrischio.it/*), based in an integrated vision of cultural heritage, highlighting the relationship between the cultural dimension and the understanding of the surrounding territory. The registration files of architectural, archaeological and museum assets arise from the systematic inventory and listing of cultural goods, georeferenced with a Geographic Information System (GIS). Similar approaches have been developed in other European countries, most of them as part of a specific project, but were not followed by an effort to adapt its results and include them in the current practices of integrated heritage management. Such reality is in fact identified in the aforementioned European Commission study *Safeguarding Cultural Heritage from Natural and Man-made Disasters. A Comparative Analysis of Risk Management in the EU*, as an issue that needs to be addressed, as stated:

> [...] there is a need to develop maps of the European cultural heritage stock at risk which must be related to existing maps of natural and man-made hazards and potential risks. This will enhance the assessments of the risks, and can help to predict the extent of catastrophic events. Such information is lacking over most of the European territory, though it is a fundamental need for establishing risk management strategies and activities. (Vintzileou *et al.* 2018)

As a way to invest in the development of more informed cultural risk polices, the European Commission has been encouraging, through the Structural and Investment Funds, the execution of projects developing innovative and sustainable solutions to better support decision-makers in managing and protecting cultural heritage at risk, such as the STORM project, or its preceding projects *Noah's Ark* (European Commission 2015b) and *Climate for Culture Ark* (European Commission 2015c). The current H2020 Framework Programme, also aims to encourage, the sharing of information gathered from the projects already completed, thus contributing for the application of acquired skills and the qualification of professionals and institutions involved in heritage safeguard.

Every year, cultural heritage all over the world is lost or damaged under the devastating impact of climate change and natural hazards. Damage, too many times irreversible, also results from insufficient and disjointed preparedness systems, unable to cope with such threats. Awareness of this situation, and of the urgent need to find solutions for it, has been a motivational call to taking actions towards the raising of awareness of all involved, the incentive to training and the sharing of good practices.

Since 2015 the number of measures promoting risk reduction in cultural and natural heritage has grown continuously, resulting from the effort of the main international agencies by means of the publishing of good practice manuals and guidelines (Pedersoli *et al.* 2016; Michalski, Pedersoli 2016; Tandon 2016; Tandon 2018) and the organisation of training courses. We would like to point out the great contribution of ICCROM in these areas, specially through its training programs on *Disaster Risk Management of Cultural Heritage*, with the objective of enhancing national capacities on risk prevention and mitigation (*https://www.iccrom.org/courses/disaster-risk-management-cultural-heritage-2*); and *The First Aid to Cultural Heritage in times of crisis*, developed in cooperation with the Prince Claus Fund and other partners, aiming to train professionals working on cultural heritage on the procedures of assessment, safety and stabilisation of cultural assets endangered by extreme events. The training is multidisciplinary, with a practical component, including simulated emergency events, role-plays and group discussions *(https://www.iccrom.org/courses/first-aid-cultural-heritage-times-crisis-2018*).

ICOMOS has also been promoting several technical meetings to encourage further multidisciplinary research for the improvement of the assessment of climate change impacts and the promotion of best practices on prevention, mitigation and recovery of cultural heritage. The recent Working Group on Climate Change and Cultural Heritage, established in the *ICOMOS 19th General Assembly and Scientific Symposium*, held in India in 2017, has been joining efforts within the research community and the cultural heritage managers to propose updates on the UNESCO *Policy Document on the Impacts of Climate Change on World Heritage Properties*, issued in 2007, aiming in the long term to develop an ICOMOS charter on climate change and heritage. This charter will include information to support prevention, adaptation and mitigation actions on all types of cultural heritage (ICOMOS 2017).

Resolutions issued within the framework of international conferences and workshops held with experts in the scientific fields of cultural heritage, environment and risk management have also been crucial for the sensitisation of the public and of governments. The workshop promoted by the Council of Europe - Cultural heritage facing climate change: experiences and ideas for resilience and adaptation, held in Ravello, Italy, May 2017 (Council of Europe 2018a), or the international conference *Cultural Heritage: Disaster Prevention, Response and Recovery*, held at the Calouste Gulbenkian Foundation in Lisboa, November 2016 (*https://gulbenkian.pt/museu/en/evento/international-*

conference-cultural-heritage-disaster-preparedness-response-and-recovery/), are good examples of how the public and the private sectors can work in the behalf of more informed and participative action-taking.

Starting with the international and European guidelines, the STORM project has also been promoting a discussion on the improvement of procedures and public policies for endangered cultural heritage through the organization of awareness-raising activities, whether among the key stakeholders or the general public.

Despite the multiplication of initiatives and the creation of knowledge that has happened in recent years in the European context, the process of implementation of concrete measures for risk reduction in cultural heritage has been slow and happening at different speeds. The reason for this is, above all, the lack of funding. Regardless of the political and economic circumstances within the various European states, there is a clear absence of investment in the creation of monitoring and conservation programs for heritage sites, the development of risk assessment methodologies effective in supporting decision processes, and the continuous training of professionals and the carrying out of awareness-raising activities among the civil society. Solving the issues afflicting cultural heritage will necessarily demand the creation of public financing instruments suitable to guarantee the safeguard of national heritages, a task unanimously assigned to governments. However, the role of the private players should not be underestimated, since they represent an important resource for the financing of preventive and restorative actions on cultural heritage.

Some researchers stress the role of insurance companies as fundamental, pointing to the fact that they can be important allies in several aspects, namely through the creation of insurance products stimulating more dynamism in preventive behaviour. Cultural risk management policies can benefit from the insurance companies' strategies since they "[…] can condition their policies on compliance with laws, such as building codes, thus playing a role in enforcing laws that promote catastrophe resilience". According to the same authors a mixed public-private system could be a future solution (Gizzi, Porrini 2017).

The development and access to funding instruments is also a concern of the *New European Agenda for Culture* of the European Commission, stressing the importance of its implementation in a transversal approach to the various political sectors, with an emphasis on the articulation between Culture, Education and Technology as fundamental supports for the evolution and transformation of mentalities (European Commission 2018).

In conclusion, a new paradigm is arising in cultural heritage policies that seeks to place heritage as a main feature to promote integrated approaches and collaborative strategies, where everyone is invited to participate. Risk management and climate change adaptation policies must also address these challenges in order to effectively contribute for the conservation of our historical legacy and European identity, and thus to enhance mutual understanding and enjoyment of cultural heritage for present and future generations.

1.1. From disaster management to risk management in cultural heritage policies

The 1972 World Heritage Convention, adopted November 16th UNESCO General Conference held in Paris, identifies a set of factors constituting a threat to the assets that are part of the cultural heritage of humankind, including "calamities and cataclysms; serious fires, earthquakes, landslides; volcanic eruptions; changes in water level, floods and tidal waves"[1] (UNESCO 1972). The same General Conference adopted a recommendation for each Member State to formulate, develop and apply, in accordance with its specific legislation, a policy to coordinate and use all available resources in order to ensure the effective protection, conservation and public fruition of the cultural and natural heritage in their territories.

The safeguard policies thus developed should consider the five strategic objectives of 1972 UNESCO Convention, also known as the five C[2]: 1) the Credibility of the World Heritage List "as a representative and geographically balanced testimony of cultural and natural properties of outstanding universal value" (Budapest Declaration 2002: nr.4a); 2) the effective Conservation of World Heritage properties, i.e., those inscribed in the World Heritage List; 3) the Capacitation in what relates to the identification of heritage properties,

[1] See article 11 (4) *in fine*, of the 1972 UNESCO Convention. To this list of risks for cultural heritage "threats posed by climate change" were latter added following, in 2014, the Intergovernmental Panel on Climate Change (IPCC) reports. Actually, in March 2006, UNESCO issued a recommendation to the intergovernmental committee responsible for heritage policies regarding research on the consequences of climate change in all cultural heritage aspects (physical, social and cultural). This committee now assesses the vulnerability of World heritage properties in what regards to exposure, sensitivity and adaptive capacity to the impacts of climate change, and evaluates the need to develop strategies for those at most risk.

[2] These objectives are clearly systematized in the Budapest Declaration on Cultural Heritage, 28 June 2002; and in Decision 31 COM 13B ("The fifth 'C' for Communities"); see *https://whc.unesco.org/en/convention/*.

their listing and the implementation of safeguarding instruments; 4) the Communication, including the promotion of World Heritage and the increase of public awareness about the importance of its protection through education and training; and finally 5) the active participation of Communities in the identification, protection and management of all World Heritage properties (UNESCO 2002).

Given the institutional importance of UNESCO, this framework became essential in the approach of public policies regarding the safeguard of properties of recognised cultural value, including, but not limited to, WHS, both domestically and universally.

This isn't however enough to frame the development of safeguard policies in the face of natural calamities, an endeavour that must also address the effort assumed by the United Nations in the areas of prevention and preparedness, through its permanent secretariat for the implementation of the UNISDR.

The question of the impacts of natural calamities gained global visibility when the United Nations designated, the 1990s as the *International Decade for Natural Disaster Reduction* (United Nations 1989). In this decade all member states should promote the appropriate measures to increase alertness, preparedness and responsiveness towards catastrophes, in order to reduce loss of life and property damage. This was the context of the first World Conference on Natural Disasters, held in Japan in 1994, from which stemmed a primary global programme to coordinate the response of the international community in such matter – the *Yokohama Strategy* (United Nations 1989). Its effective implementation was revaluated a decade later and the corresponding report was examined in the Second World Conference on Disaster Reduction, also held in Japan, in Kobe (Hyogo), in January 2005. *The Hyogo Framework for Action* (2005-2015) was approved on this occasion, in the aftermath of the catastrophic results of the Indian Ocean tsunami of December 2004, that affected several countries and killed more than 200.000 people.

The Hyogo Framework for Action reaffirms, above all, the political responsibility of States to protect populations from the eventuality of natural disasters, simultaneously presenting a global strategy for the development of a culture of prevention based in the reduction of vulnerabilities. To such effect, the plan emphasises the premise that the disaster risk reduction policies should be cross-sectional, including all different sectors and distinct levels of government (United Nations 2005).

Shortly after the entry into force of the *Hyogo Framework for Action*, and entirely assuming its emphasis on the transversality of politics aiming at disaster risk reduction, the UNESCO World Heritage Committee approved, in 2007, the *Strategy for Risk Reduction at World Heritage Properties* (UNESCO 2007), based on the Hyogo priorities, setting five risk reduction objectives adapted to the particularities of cultural heritage.

This Strategy, already focused in cultural assets, also encourages Member States of the 1972 Convention to include threats to cultural proprieties in national risk reduction plans, as well as to elaborate management plans including a risk analysis for world heritage located in their territories. These guidelines find their way in the *Sendai Framework for Disaster Risk Reduction* (United Nations 2015), a document that sets guiding principles for 2015-2030 and follows the *Hyogo Framework for Action*. In fact, this new political compromise emphasises risk management as opposed to disaster management, expressly anticipating the need for cultural property damage evaluation, as well as the need to support the safeguard of cultural heritage against natural risks. For this purpose, a multi-sectoral and multi-platform approach, engaging all stakeholders in risk reduction and preparedness against disaster from the perspective of sustainable development is to be encouraged (United Nations 2016).

Following this, in 2016 the European Commission also recommended the development of good practices regarding the inclusion of cultural heritage in the strategies of risk reduction to be developed by Member States as a key area in the Action Plan to implement in the scope of the Sendai Framework.

This short overview of some of the main international instruments regarding risks and cultural property shows a progressive concern for the safeguard and conservation of cultural assets in the policy of reduction and management of natural hazards. This will be the general reference framework in the approach of the development, at national level, of the public policies for the safeguard of cultural heritage threatened by calamities.

2. Safeguarding policies for cultural heritage facing natural hazards

In the 1976 UNESCO Recommendation on Historic Areas, the concept of safeguard refers to "the identification, protection, conservation, restoration, renovation, maintenance and revitalization of historic or traditional areas and their environment".

Safeguard of cultural heritage can therefore be understood as a larger concept covering distinct measures: on the one hand the protection measures *stricto sensu*, and on the other hand the valorisation and knowledge procedures (Figure 1).

Figure 1. The safeguard of the cultural heritage.

This systematisation allows to better realise that the identification of a cultural asset is of enormous value, whether due to its registration in an inventory, or through a designation procedure resulting in the application of a specific legal framework for the protection of cultural heritage. Therefore, the primary instrument of protection of the 1972 UNESCO Convention is the identification of cultural property, that is, the inscription of such assets in the World Heritage List. The international recognition of the properties inscribed in the List requires that the signatory States assume both positive duties and *non facere* duties. In fact, firstly there is a primary obligation of the State to guarantee the identification, protection, conservation, valorisation and transmission to future generations of cultural assets inscribed in the World Heritage List located in its territory; secondly the States commit to not taking any deliberate measure that may directly or indirectly damage their heritage or that of another State Party to the Convention[3]. In a non-legal level, the international recognition of the outstanding value of certain properties through their inscription in the World Heritage List may also lead economic agents interested in the sustainable development of their activity and in the promotion

[3] As seen in point 3 and 4 of article 6º of the UNESCO's 1972 Convention.

of their corporate image in the public's eyes, to abstain from practices that are harmful to cultural heritage.

In the UNESCO 1972 Convention, we can also recognise other instruments contributing to the protection of World Heritage, besides its identification and the consequent development of applicable legislation: the plans and management bodies promoting solutions as a result of the joint work of all stakeholders, and the financial support to the safeguard of cultural heritage through the World Heritage Fund. The Convention also foresees a list of cultural heritage in danger that embodies a manifestation of the principle of prevention, by demanding extra and immediate attentiveness towards the assets identified as being at risk of losing the values justifying its international recognition. All these instruments aim to avoid that a cultural property loses the outstanding universal value that substantiated its inscription in the World Heritage List, as well as the resulting negative consequences at the levels of local economy, permanence and social cohesion of communities.

The main question here is to know whether these instruments suffice for the protection of cultural assets in the face of the escalating of climate disasters and their effects on cultural heritage, also related to climate change. On the one hand, this is related to the Recommendation (UNESCO 1972) already mentioned, for each State to formulate, develop and apply, in accordance with its specific legislation, a strategy to coordinate and use all available resources in order to ensure the effective protection, conservation and public fruition of its respective cultural properties; on the other hand, it is a consequence of the fact that those instruments were elaborated in the 1970s, when the current reality is marked by sudden climate hazards provoking rapid and widespread devastation. Although the location might be predictable, the occurrence of such phenomena is characterised by a high degree of devastation and is rarely detected in a timely manner.

The Vantaa recommendations, approved in 2000, recognises that prevention is the most secure and sustainable way to ensure the future protection of cultural heritage through the identification of the risks it faces and the development of strategies and national plans. For the effective safeguard of cultural heritage, it is no longer enough to repair damage caused by time with actions of conservation or restoration (Gonzalés Delgado, Delgado López 2018).

Prevention acts to reduce the vulnerability or exposure of cultural property to the effects of disasters and necessarily calls for the coordination of Culture and other areas of government, especially in the fields of civil protection and territorial planning. In effect, the reduction of the vulnerability of cultural heritage can be done structurally, via interventions of adaptation or retrofitting of cultural assets to increase their resilience but will always keep a strong relation with non-structural measures, particularly the capacitation of stakeholders and local communities to use competencies and resources in order to deal with adverse conditions, namely through drills and similar exercises. In turn, the reduction of the exposure of cultural assets to natural hazards highlights the key role of development plans and restrictions to public land use, mainly in seismic or coastal areas, where a significant part of cultural property including many inscribed in the World Heritage List is already to be found (Tabborof 2003).

The reduction of risk vulnerability and risk exposure, integrating a preventive policy for the protection of cultural property against disasters exacerbated by climate change, poses new questions regarding the application of existent legal instruments (ACHEHCI *et al.* 2016), and namely of the 1972 UNESCO Convention:

a. Should a property be classified which, although meeting all the requirements for the recognition of its outstanding universal value, is subject to climate risk? This question assumes particular relevance in all instances when the loss of the outstanding universal value seems inevitable in the face of the risk vulnerability or exposure of such property, regardless of mitigation measures to be taken.
b. Can the inscription in the World Heritage List of properties located in risk areas recommend their displacement, in order to protect them more effectively? This question is of special importance in what regards to the relationship between the cultural property, its environment and the local communities, whether when opting for a broader demarcation of the property and its context for the purpose of its safeguard, whether in what respects to the capacitation of populations to preserve a connection with the cultural asset, thus contributing to its protection.
c. To what extent should retrofitting or adaptation interventions on the cultural property, aiming to increase its resilience against climate risk, be allowed? And, does it make sense to admit the recovery and rehabilitation of cultural properties affected by disasters as a principle?

Such questions are very important, not only due to the relevance ascribed to conservation based in the criteria of authenticity and integrity, but also due to the role of ruins in the collective memory on past disasters and, therefore, on the management of future risks (Meier, Wil 2007).

Solutions for these questions demand the consideration of values conflicting in space and time, among measures for economic development, the safety and wellbeing of people, the protection of landscapes, cities, sites, monuments and all material or intangible assets that constitute the cultural heritage of communities. In such interdisciplinary processes, summoning all stakeholders, we need to consider not only the socially cohesive role of cultural heritage, but also its added value to land development, and to integrate the questions relative to its protection in the risk management processes and disaster reduction plans.

3. Proposals to improve the Risk Management of cultural heritage based on the STORM experience

The following sections contain recommendations to improve the DRM of cultural heritage sites ensuing directly from the STORM experience. More precisely, the efforts carried out towards the implementation of a risk-oriented approach to the preservation of heritage sites, as per the STORM objectives, entailed revising and developing operative proposals towards the advancing of:

- Heritage Conservation and management guidelines and procedures at site and government levels;
- Communication between researchers and heritage managers, including government authorities, in particular concerning the scientific body of knowledge built on climate change;
- the Coping and adaptive capacities of heritage sites to meet their specific risks, and namely the actions that may enhance their resilience in the face of disasters; including the Capacity building of heritage sites' professionals, as well as of other pertinent stakeholders, via training at diverse levels in site-specific DRM measures;
- Cooperation between the different actors involved in the DRM of cultural heritage, which is demonstrably a cross-sectorial endeavour.

All of the recommendations suggested below considered both the work developed in STORM and literature reviews, identifying the areas where the advancing of resources is thought to have the highest impact in terms of heritage risk management: (heritage) Conservation; (climate change) Communication; Coping and adaptive capacities; Capacity building; and Cooperation. The first set of recommendations is centred around Conservation, Communication and Coping and adaptive capacities and is presented offering leads as to how they can be implemented at their respective levels of governance: site, local/regional or national. The subsequent proposals for policies improvement are particularly focused on reducing vulnerabilities and exposure of cultural heritage via Capacity building and Cooperation, and are intentionally open-ended, to allow a possible adaption to the national legal systems of the STORM partner countries, as well as for their appropriation by different communities.

3.1. Heritage Conservation

3.1.1. Disaster Risk Management for the Conservation of cultural significance

Conservation may be defined as "All actions designed to understand a heritage property or element, know, reflect upon and communicate its history and meaning, facilitate its safeguard, and manage change in ways that will best sustain its heritage values for present and future generations" (Nara+20 2016, 147). Conservation, in this sense, encompasses an extremely vast array of actions and procedures, as long as these are directed to this *sustainable management of change to a significant place*, including of course conservation interventions (Figure 2).

Figure 2. Conservation intervention at the Roman Ruins of Troia.

DRM, in turn, may be thought of as a planning instrument to deal with uncertainty upon objectives; applied to cultural heritage, DRM becomes a tool to deal with the potential for undesirable change to impact cultural significance.

The framework proposed by DRM approaches may serve as a conceptual tool allowing the integration of the diversity of factors at play in the phenomena that may cause the degradation (undesirable change) of heritage assets, for a more holistic conservation process (Revez *et al.* 2016). Moreover, it is hoped that the progressive adaptation of a risk management frame of thought to the conservation sector will constitute a meaningful step towards progressively more preventative – and more sustainable – conservation measures.

Seeing as DRM "is not a sector in and of itself" (UNISDR 2015a: 6), in what concerns its application, "It is for policy makers and practitioners to develop and implement sector instruments, policies, programmes, guidelines, standards as well as business practices" (UNISDR 2015a, 6). This means that standards and instruments, and namely conservation guidelines and precepts, must frame the adaptation of DRM to the heritage sector. It is deemed fundamental that conservation principles, as advocated by institutions such as the Council of Europe, ICCROM and ICOMOS (Council of Europe 2005; ICATHM 1931; ICATHM 1964; Australia ICOMOS 2013; ICOMOS 2017b; ICC 2000; E.C.C.O., ENCoRE, and ICCROM 2008), are transposed to the risk management of European historical sites, so that any measures addressing risks do not cause other types of damage to the significance of the sites. In other words: the focal point, the principles, and the ethical guidelines applicable to the heritage sector should likewise frame heritage risk management decision making.

The focus of conservation is, as said, cultural significance, which essentially corresponds to the array of values that are bestowed upon a heritage asset by its stakeholders, in a given moment of time and space. Thus, when dealing with cultural heritage, its values should be clearly stated and explicitly sustain management guidelines (Feilden, Jokilehto 1998). Seeing as values change in time and space, heritage management, be it risk management or, more generally, conservation management, must accommodate shifts in values and hence, evidently, a values-based analysis and planning has to be periodically reassessed. Additionally, the effectiveness of the chosen options and their impact on the significance of the heritage asset needs to be evaluated at regular intervals, and thus values-based management, including risk management, should always work on the basis of periodic plans. Integrating shifts in values is also about assessing the results of implementing each plan, learning from its shortcomings, understanding which objectives were not attained and why, and analysing new contexts that may have come into play and how the plan responded to them; each new plan starts from, and includes, the detailed revision of its predecessor.

In STORM, the procedures developed for the risk management of heritage sites directly include cultural significance as analytical parameter, and risk is assessed taking into account the different values bestowed upon the site – and, as any risk assessment procedure, it should be periodically revised.

Regarding the deontology of conservation, the aforementioned internationally agreed ethical principles and guidelines chiefly applicable to conservation decisions and actions that will have an impact in the material fabric of the heritage asset, and notably conservation-restoration interventions. By and large, conservation methods, including conservation-restoration, exactly correspond to the risk treatment strategies available to the heritage sector for the control of risk – to prevent and/or resolve undesirable changes from occurring in heritage artefacts. Ergo, conservation deontology is applicable to any risk control methods interfering with heritage fabric. In STORM, these conservation principles were included and/or operationalised into the risk treatment and decision-making recommendations (see next Section and Chapter 2). The experience of STORM allowed demonstrating that the heritage sector operative concepts – cultural significance and deontological ethics – can support the risk management of cultural sites, and are in fact inescapable to ensure that heritage is safeguarded according to social and expert standards.

Recommendation: **Develop and implement, for all tangible heritage assets, DRM programmes that are explicitly based on cultural values and comply with current conservation principles. Preventive approaches to heritage risks, using DRM procedures, should be preferred to merely reactive approaches and fostered at all governance levels.**

3.1.2. A common frame of reference

Multidisciplinarity was definitely acknowledged as crucial for decisions regarding cultural heritage at least since its consecration in the Venice Charter (ICATHM 1964). However, although the need for multidisciplinary work is widely recognised, there is often a lack of interdisciplinarity, i.e. interaction among the several disciplines drawn in (Avrami *et al.* 2000), effectively preventing a truly cooperative dialogue. Similarly, the multidisciplinary nature of the STORM consortium, undoubtedly one of its major strengths, risked inducing a Tower of Babel effect that could threaten effective collaboration.

A straightforward answer to this dilemma was the creation and sharing of an agreed-upon reference framework that would aptly describe the main issues at stake and, to some extent, provide guidance on how to address them.

The STORM Frame of Reference (FoR) described a common vision for the project by defining its boundaries, framework and terminology, harmonising the multitude expertise present in STORM. It summarised key heritage risk scopes to be used in the development, implementation and use of STORM methodologies and results by both partners and stakeholders. The STORM FoR encompassed:

- a Glossary, defining terms on: Heritage & Conservation; Hazards, Risks & Disaster risks; Policies, Economic analysis & Decision making; Earthquake & Engineering Seismology; Climatology; STORM Sensors; and Information Fusion Techniques & Technologies;
- a Hazard classification, listing and classifying (natural and anthropogenic) hazards and climate change-related events leading to sudden-onset and slow-onset disasters;
- Material classification, listing and classifying Cultural Heritage materials; as well as the expected (indicative) significance of the impact of hazards upon the different materials;
- Conservation Processes, listing, defining and categorising a heritage DRM cycle; and the processes and actors involved in each phase;
- Emergency Processes, listing, defining and categorising the processes and actors involved in emergency interventions upon cultural heritage assets within a DRM framework.

The development of the FoR was based on literature reviews, applied to the particulars of STORM contexts and updated when deemed necessary. By providing a common language and a shared vision, the FoR became a key tool in leveraging the interdisciplinarity of the STORM Consortium.

Likewise, at site level, any intervention that calls for the interdisciplinary involvement of heritage professionals should be framed by a common framework, concerting the efforts of all the stakeholders in an operative structure. While conservation charters and other international reference documents, as well as national norms, should provide overall guidance, each context requires a careful and tailored adaptation of this guidance. A conservation management plan, as applied by several institutions worldwide (Demas 2002; Australia ICOMOS 2013; Kerr 2013; English Heritage 2008; Croker 2017) is a value-based management tool that works as a common framework whereupon all decisions regarding the conservation, interpretation and fruition of a site must be based; each site's frame of reference should be included therein.

A common complement of Conservation Plans – but which may work as a standalone instrument – is the Risk Management Plan (Stovel 1998; UNESCO-WHC *et al.* 2010; Paolini *et al.* 2012; Jigyasu, Arora 2013), a tool for integrating and operationalising preventative and remedial conservation approaches. While, at site level, the implementation of such plans should not require a set of reference documents as extensive as the one built for STORM, it is advised that a framework document is developed that contains the shared vision of the stakeholders and any other elements deemed necessary to understand and implement the foreseen conservation/risk planning – framed by the wider approach of the country towards its heritage.

It should be noted that, while several international charters and recommendations provide an overall set of principles applying to (Western) heritage conservation policies, adjustments and adaptations of such principles into cultural policies at national levels are typically left to the discretion of the cultural heritage authorities of each country. Therefore, it is for these authorities to define and promote the common framework and vision that should ultimately preside over heritage management decisions in each of the levels of governance that they cover: central, regional or local. This is a fundamental instrument for:

- Guiding and legitimising interventions that interfere with heritage assets – by definition essential identity referents of a community –, making the heritage management process more transparent;
- Ensuring, as much as possible, that said interference serves the interests of the heritage stakeholder communities;
- Promoting a better understanding of heritage safeguarding terminology across different sectors, contributing to more consistent and reliable cooperation mechanisms.

Heritage authorities, as overseers of all heritage safeguarding endeavours, are in a privileged position to implement such a common framework and ensure its application, e.g. requiring it in mandatory intervention reports. This conceptual framework should be kept updated and/or be complemented by recommendations as knowledge and social perceptions evolve.

Recommendation: **Implement interdisciplinary DRM programmes at site level, beginning with the definition of a common frame of reference. Define and promote a central- and/or local-level frame of ref-**

erence, including Principles, Concepts, and Terminology documents, enabling and supporting the development and implementation of conservation and/or risk management initiatives.

3.1.3. Improving financial instruments

Heritage assets, in their material and immaterial duality, are key components in the identity of communities. However, arguably because communities (by definition) develop around them and therefore tend to overestimate their perennial character, resources made available for their conservation tend to be scarce, and heritage must compete with other social priorities (Orna *et al.* 1992). Heritage authorities are therefore doubly obliged to ensure that their management – both of the heritage elements and of the resources spent on their conservation – are sensibly, consistently and transparently used.

Regarding the heritage elements, it is critical that conservation frameworks and principles are duly acknowledged and clearly enter the decision-making process; as for the resources allocated to conservation – typically time, human and financial resources – these should be minimised, but only insofar as they do not restrict the level of conservation work deemed acceptable by the stakeholder community(ies).

"On average, every euro spent for reduction and preparedness activities saves between four and seven euros that would have been spent in response to the aftermath of disasters" (ECHO 2019). Although these numbers do not include actions targeting cultural heritage, the ratios should not be overly dissimilar, and there is therefore reason to believe that investing in preventive and preparedness actions can also alleviate post-catastrophe financial efforts towards heritage restoration. What is more, and given that (i) heritage values are unique and therefore subject to irretrievable losses in catastrophic contexts; and (ii) such values cannot be adequately captured by monetary measurements; social gains should more than compensate the required investment in overtly preventive measures.

The recent UN's *Sendai Framework for Disaster Risk Reduction 2015-2030* (United Nations 2015) clearly incorporates '*Cultural Heritage*' in disaster resilience, as well as in its respective reporting and monitoring methodologies (UNISDR 2017). Notably, Cultural Heritage was included as a disaster loss indicator (*C-6 - Direct economic loss to cultural heritage damaged or destroyed attributed to disasters* (UNISDR 2017: 59), which ratifying countries will have to report on, demonstrating the actual commitment of the UN towards heritage protection. Whilst the benefits of well-tended heritage assets, much like the full costs of their loss, cannot be adequately measured in monetary units (UNISDR 2017), it should be emphasised that "well-maintained cultural heritage assets provide a distinct identity and image, conveying a feeling of home, community, likeness and appreciation" (Scheffler 2011, 14), meaning heritage conservation is a critical tool for the *resilience* (Jigyasu 2016) and *sustainable development* of societies and communities (Avrami 2010).

The STORM Cost-Effectiveness Analysis (CEA) methodology was developed as a tool for the practical implementation of tangible heritage conservation interventions, supporting decision making while ensuring the application of the abovementioned conservation principles (STORM Consortium 2017a; *Revez et al.* 2018). The CEA developed within STORM is a decision-support system (DSS) specific to interventions affecting built heritage at site management level: it does not consider impacts outside the site, nor does it allow for comparisons among different sites. This means that it cannot aid government heritage authorities, be they central government, regional or municipal bodies, in deciding resource allocation between different sites. It can, however, support site managers in deciding where conservation resources will have a more positive impact; and in justifying their conservation investments more consistently. The STORM CEA methodology (STORM Consortium 2017a; Revez *et al.* 2018) can be used as part of a risk control plan or independently, as a conservation-restoration DSS.

In the STORM CEA, *effectiveness*, i.e., benefits assessed in a way other than monetary units, was parameterised so as to comply with current (Western), value-based, approaches to conservation by incorporating a key heritage conservation principle – compatibility, i.e., short-term and long-term non-harmfulness towards heritage values (Revez *et al.* 2016). Compatibility is the de facto key parameter in the evaluation of effectiveness in STORM. The proposed effectiveness rating guidelines (Revez *et al.* 2018), to be assessed via expert discussion, are believed to be sufficient to place the highest emphasis of decision making in the conservation of heritage significance, authenticity and integrity, enforcing an ethical approach to conservation. It is additionally held that the procedure may provide helpful directives towards more sustainable conservation approaches.

The STORM CEA can help demonstrating to decision makers the benefits of a planned maintenance approach to conservation, which is often more expensive in the short term, but by far more effective in the preservation of cultural significance in the long term (Revez *et al.* 2018). Beyond site level, as a funding requirement, the CEA may help justifying, and thus capture, investments in DRM – public, private, and/or 3rd sphere, as advised by the UN (2015)

–, and constitute a meaningful step towards the assessment of the socioeconomic impact of conservation, much needed but still "poorly understood" (Stubbs 2009: 15).

The STORM experience showed that the STORM CEA favours preventive interventions; furthermore, it encapsulates conservation principles and notably that of compatibility; and requires the careful consideration of cultural significance. The using of such a tool at government level as a project-selection criterium/quality demonstrator in heritage conservation would therefore: (i) support more transparent and consistent decisions in resource allocation; (ii) foster the implementation of the CEA tool at site level, thus promoting more preventive-oriented approaches to cultural significance conservation.

Recommendation: **Allocation of resources for DRM measures should be supported by comparative analyses weighing the costs against the effectiveness of the different options, both at government and site levels. These CEAs should clearly (i) involve an assessment of impacts in cultural significance and (ii) promote the application of current conservation principles and preventive approaches.**

3.2. Climate change Communication: best practices, research and policy needs

The acknowledgment that climate change is a global threat dates back to the early 1990s, which led to the founding of the United Nations Framework Convention on Climate Change (UNFCCC) in 1994, and to the agreement of the Kyoto Protocol in 1997. In these early days, the main focus was on climate change mitigation (i.e. the reduction of greenhouse gas emissions to prevent climate change, Delbeke, Vis 2016). However, despite these efforts, climate change is unequivocal (IPCC 2014a). To increase climate change resilience, it is therefore important to focus not only on a further prevention of climate change, but also on defining ways to react and adapt to these changes.

Although climate change is a global issue, adaptation to climate change should be considered locally, on a national or regional scale, as climate change effects are widely different for different regions. When looking at summer precipitation, for example, summers in northern Europe are projected to get wetter (increase in summer precipitation) and in southern Europe drier (e.g. EEA 2017). Hence, EU policy encourages member states to develop their own comprehensive climate adaptation plans (National Adaptation Strategies, NAS), covering local to national levels in coordination with neighbour-states (Delbeke, Vis 2016). Many EU member states have incorporated climate change policies and legislation in order to adapt to climate change impacts. However, generally these adaptation strategies do not address cultural heritage (Bonazza 2018), or when there are references to cultural heritage they present minimal measures or actions (Neto *et al.* 2018). In Italy a huge effort has been in progress to include cultural heritage dimension in the NAS, supported by a highly multidisciplinary approach, with more than 200 experts contributing to the document. Albeit still in progress, is a fruitful example that should be followed as an implementational model (Bonazza 2018).

Recommendation: **Incorporate cultural heritage in climate change research and governance to increase its consideration within climate and environmental policies.**

The risk assessment of cultural heritage sites can benefit their protection by highlighting risks that are not yet being considered, or draw attention to risks that may increase (or decrease) as a result of climate change. Based on such analyses, resources can be distributed in an optimised manner, giving priority to risk management strategies addressing the most serious threats to a site, highlighting the importance of including climate change in management plans and decision-making strategies (STORM Consortium 2018; Sesana *et al.* 2018).

For Europe as a whole, general documents, and in most nations more detailed documents, are available giving an overview of expected changes as a result of climate change (e.g. for Europe: EEA 2017, for the UK: Met Office 2018). These documents can provide a useful starting point for risk assessments, and give a first idea of the changes in climate a site can expect (Brimblecombe 2014). However, oftentimes the materials of cultural heritage sites are highly sensitive to environmental changes and as differences in regional climate can be large, it is advisable to perform a risk assessment considering high-resolution climate information, and to use climate indices to quantify climate change in an easy manner (Sabbioni *et al.* 2008; Brimblecombe 2014; STORM Consortium 2017b).

An accurate risk assessment is paramount for an efficient distribution of resources. Cultural heritage risk assessments addressing climate change risks should rely on high-quality climate local simulations and climate change information, which must become available more frequently. In addition, knowledge related to the vulnerability of the cultural heritage to these environmental hazards is needed. Further research could aid the assessment of these risks by providing even more specialised knowledge of climate change effects and their impacts on cultural heritage materials, which implies cooperation between academia and heritage authorities and managers. It is thus important to foster communication between all the stakeholders involved through integrated, participatory and multisectoral governance models, ensuring the scientific discourse translation and adaptation into management procedures; but also citizen participation, which can contribute with local and traditional knowledge on dealing with climate variability and implementing successful adaptation responses over centuries, to be articulated with modern solutions to improve resilience (Neto et al. 2018).

Recommendation: **Develop risk management strategies based on risk assessments considering information on climate changes, as well as heritage's vulnerability to these changes.**

3.3. Coping and adaptive capacities

3.3.1. Conceptual background

The interrelations between disaster risk and vulnerability associated with natural hazards or climate change have been discussed widely among scholars. This discourse generated such concepts as *adaptive and coping capacities* and identified their role in building resilience or reducing vulnerability. Taking into account the existing variety of approaches to assessing vulnerability, as well as considering the evolving understanding of the concept and its dynamic nature, it is important to illustrate the established definitions of terms in the context of disaster risks.

Moving towards the goal of reducing disaster risk for an effective protection of vulnerable elements from destructive impacts, J. Birkmann, stresses "the fundamental importance of examining the preconditions and context of societies and communities and elements at risk to effectively promote risk reduction" (Birkmann 2013, 10). As we turn towards shaping adaptation options for disaster resilience, the concept of vulnerability is key in pointing out areas of existing societal structures that need intervention. Among the variables which make up vulnerability, the concepts of coping and adaptive capacities are instrumental for transforming a state of fragility in a state of resiliency in the face of climatic changes and natural hazards.

According to UNISDR, coping capacity is "the combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience" (UNISDR 2015b). Similarly, IPCC indicates that coping capacity encompasses the ability of people, institutions, organisations, and systems, using available skills, values, beliefs, resources, and opportunities, to address, manage, and overcome adverse conditions in the short to medium term (IPCC 2014a). Adaptive capacity, on the other hand, is the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences (IPCC 2014a). While the focus of coping is on immediate reaction, adaptive capacity implies a "long-term strategy that enables community to change and transform in order to deal with expected negative consequences of climate change" (Birkmann 2013). Furthermore, J. Birkmann states, that the ability to adapt to permanent change, or to transform without reducing future adaptive capacity is essential in the face of current climate variability and future climate change (Berman et al. 2012). Considering the social, environmental, economic and institutional dimensions of vulnerability, the role of institutions is central in contributing to longer-term adaptive capacity for managing disaster risks.

3.3.2. Institutional coping and adaptive capacity

In order to perceive the influence of institutional adaptive capacity on disaster resilience, a clear understanding of key terms is needed. According to the definition by the Institutions Project of the International Human Dimensions Programme, institutions are "systems of rules, decision-making procedures, and programs that give rise to social practices, assign roles to the participants in these practices, and guide interactions among the occupants of the relevant roles" (Grothmann 2013, 3371). In light of this, institutional vulnerability refers to "modes and constraints in governance, underlying rules and norm systems that govern society and also to the capacity or incapacity of formal organisations to deal with risks and adaptation challenges", according to Lebel *et al.* (Birkmann 2013, 30). Furthermore, institutional adaptive capacity implies the inherent characteristics of institutions that "empower social actors to respond to short and long-term impacts either through planned measures or through allowing and encouraging creative responses from society both ex ante and ex post" (Gupta *et al.* 2010, 461). Notably, a number of scholars stressed, that the components of adaptive capacity are not limited to assets and resources, but involve processes, functions and willingness to convert resources into effective adaptive action.

Several adaptive capacity frameworks have been developed in recent years as a response to an urgent need for addressing increasing disaster risks. Remarkably, institutional arrangements play a central role in most of them. The current section aims to review available frameworks in order to uncover the channels through which institutionalised set-ups can generate positive outcomes for disaster risk management specific to cultural heritage. The concepts discussed below include the Adaptive Capacity Wheel (ACW) by Gupta *et al.* (2010), the framework for assessing institutionalised capacities by Lebel *et al.* (2006), framework for adaptive capacity at cultural heritage sites by Phillips (2014) and framework for adaptation of cultural heritage to climate change by Sesana (2018).

3.3.3. Coping and Adaptive Capacity Frameworks

According to Gupta *et al.* (2010, 461), institutions that possess an adequate adaptive capacity: 1) "encourage the involvement of a variety of perspectives, actors and solutions" (variety); 2) "enable social actors to continuously learn and improve their institutions" (learning capacity); 3) "allow and motivate social actors to adjust their behavior" (room for autonomous change); 4) "can mobilise leadership qualities" (leadership); 5) "can mobilize resources for implementing adaptation measures" (availability of resources); and 6) "support principles of fair governance" (fair governance). While the Adaptive Capacity Wheel (ACW) developed by Gupta et al is generic, this framework may be used to inform social actors of various sectors about the ways their institutions influence different aspects of adaptive capacity.

Comparably to Gupta's approach, Lebel *et al.* also looked for a method that would help assess institutional adaptive capacity and determine what can be done to enhance it in order to make local communities more resilient to hazards. However, the authors' conceptualisation pointed out a different set of capacities. In their Comparative Analysis of Institutions, Lebel *et al.* investigated Institutional Capacity in Disaster Risk Reduction for the states of Asia. According to the authors, "relationships among actors have different functions that may be institutionalised" (Lebel *et al.* 2006, 461). The developed assessment framework focuses on four classes of institutionalised capacities and practices: the capacity for deliberation and negotiation ("for ensuring that [...] different knowledge can be put on the table for discussion and that, ultimately, fair goals are set"); the capacity to coordinate resources ("for ensuring prevention and response actions"); the implementation capacity ("for skillfully using the resources to carry out actions"); the capacity for evaluation ("the basis for continual improvement, adaptive course corrections and learning by key actors") (Lebel *et al.* 2006, 462 emphasis added).

Different sectors, actors, regions and levels of decision-making are affected differently by climate change impacts and therefore, it is necessary that adaptations and adaptive capacities vary between these different social systems

(Grothmann 2013). Undoubtedly, there is a high value in the overall discourse on assessing and shaping institutional adaptive capacity to climate change impacts and disaster risks for various sectors. However, the field of cultural heritage has only recently gained attention within this discourse. An example of an adaptive capacity assessment framework for heritage sites is demonstrated, for example, in the work of Phillips. The author proposed the following key determinants of adaptive capacity at cultural heritage sites: cognitive factors, leadership, learning capacity, access to information, authority and resources (Table 1).

Table 1. Descriptions of the factors included in the framework of adaptive capacity relevant to cultural heritage management (Phillips 2014).

Factor	Sub-factors	Description/definition
Resources	Technological	The technological resources that are available for adaptation.
	Financial	Availability of financial resources to support policy measures and autonomous adaptation.
	Human	Availability of skills, expertise, manpower, local knowledge and experience.
Authority	Plans and policy instruments	Availability of plans and policy instruments to increase the ability of individuals to act.
	Political will	The political mandate to foster adaptation and raise resources.
Access to information	Futures thinking	Access and use of information such as scenarios of future conditions, in order to inform long term decision making.
	Guidance and information	Access to the necessary information, guidance and tools to support decision makers.
	Monitoring	Monitoring which provides information to inform how to act and to check progress on targets.
Learning capacity	Institutional memory	Memories and knowledge which transcends the individual.
	Heritage as a learning resource	Tapping into what can be learnt from heritage itself.
	Single loop learning	Ability to learn from past experiences and improve routines.
	Double loop learning	Learning which questions values, assumptions and policies.
Cognitive factors	Individual risk appraisal	Individual assessments of the probability and severity of potential risks.
	Perceived adaptive capacity	Individual perceptions of the efficacy and costs of adaptation.

	Approach to uncertainty	Openness to the uncertainties around climate change and adaptation.
Leadership	Buy in from the top	Commitment to adaptation at a senior level within organisation.
	Motivators/champions	Existence of individuals who are motivated and enthusiastic, who act as a catalyst for action.
	Creation of a vision	Long term visions which include adaptation.
	Holistic management approach	Incorporation of a systems thinking approach; managing system as a whole rather than in parts.
	Communication and collaboration	Good internal and external communication, and collaboration e.g. through formal/informal networks.

Comparably, according to the workshop and analysis conducted by Sesana (2018), the determinant factors for the implementation of adaptation of cultural heritage to climate change are divided into six groups (Figure 3): (1) Knowledge, education, communication, and awareness; (2) Management, regulations, governance, and drivers; (3) Economic factors; (4) Cultural values; (5) Health and safety concern; (6) Time.

Figure 3. Determinant factors for implementing adaptation of cultural heritage to climate change (Sesana 2018).

Best practice recommendations in managerial and decisional adaptation to climate change included: "to increase fundraising, increase the production of knowledge and its dissemination, engage those involved with the heritage (owners, communities, tourists) in adaptation, promote and strengthen monitoring and maintenance, upgrade management plans to include climate change, strengthen regulations and guidelines, keep working on mitigating climate change to reduce future risks" (Sesana 2018, 8).

4. Recommendations for policy improvement

4.1. Public policies improvement measures for an effective protection of cultural heritage

Together with the guidelines from the community of international organisations, the abovementioned conceptual frameworks provide starting points for addressing present needs of heritage sector. Although the efforts to fulfil identified objectives remain fragmented, the sphere of heritage management has been marked by a shift towards more holistic approaches that "manage change" proactively versus protecting heritage *post factum*. Such shift is characterised by a gradual bridging of the borders existing between development sectors, research disciplines, levels of governance and communities. Apart from being vital for strengthening disaster preparedness of cultural heritage, this integrated approach is essential for shaping the resilience of communities and nations to disasters through stronger synergies and innovative strategies.

A successful implementation of risk-preparedness at national and regional levels can be advanced by addressing a number of strategic aspects. One of the widely identified aspects is the need for mainstreaming of cultural heritage concerns in disaster risk reduction and climate change adaptation. This implies acknowledging that heritage is a cross-sectoral area which has strong links with various development sectors and strengthening the interrelationship between the agendas for sustainable development, disaster risk reduction, climate change adaptation and heritage conservation and management (Jigyasu, Arora 2013). More specifically, disaster risk management should be introduced into heritage protection and management, while the resilience of cultural heritage, in turn should become an integral piece of a larger disaster risk reduction and climate change adaptation strategy at local, regional and national levels (UNISDR *et al.* 2013).

Recommendation: **Acknowledge cultural heritage as a cross-sectoral area and strengthen the integration of heritage needs in disaster risk reduction and climate change adaptation agendas.**

As mentioned, risk-preparedness for cultural heritage is dependent upon prevailing risk-preparedness policies and practices established on a national, regional and local level, making it crucial for the cultural heritage management and disaster risk management sectors to reach greater coordination with one another. In order to achieve that goal and improve risk-preparedness for cultural heritage on a national level, Stovel (1998: 105-106) suggests to focus efforts, of course based on national needs and circumstances, on the following objectives:

- Strengthen collaboration between heritage management officials and disaster risk preparedness officials by organising symposia or setting up working groups with representatives of both fields and establishing networks to facilitate exchanges;
- Negotiate agreements between state, regional and local officials for ensuring appropriate response measures and procedures for cultural heritage protection in times of emergency;
- Improve the availability of required resources for emergency response, including national or regional reserve funds and appropriate conservation expertise during times of emergency;
- Ensure documentation resources for appropriately identifying cultural heritage and protecting it during response operations;
- Promote training opportunities bringing cultural heritage officials together with emergency response officials, in order to increase the sensitivity of both groups to the concerns, objectives and ways of working of the other (e.g.: develop emergency-preparedness guidelines for specific sites, providing staff training at universities).

Apart from bringing the knowledge and capacities of actors in the fields of cultural heritage and disaster risk reduction together, partnerships and collaboration should be fostered between government agencies, civil protection departments, heritage ministries, local communities, tourists, scholars, donors, private investors, etc. (Antomarchi 2016). Greater involvement of the public in decisions on all stages of the disaster cycle (assessment and monitoring of risks, risk reduction and response, and recovery and restoration efforts) is also of great significance in elaborating pragmatic opportunities to address the risks (Lebel *et al.* 2006). Collaboration between the abovementioned stakeholders is key along the risk-based decision-making process in regard to a heritage site and involves understanding, discussing, and incorporating stakeholders' input into the process (Michalski, Pedersoli 2016).

Recommendation: **Develop risk-preparedness policies and practices, at national, regional and local levels, mainstreaming cultural heritage through a collaborative approach.**

While adaptive capacity of cultural heritage to disaster risks is contingent upon a multitude of factors, the role of the governance context, including legal, policy, and institutional frameworks, is highly instrumental in facilitating a holistic management approach towards a resilient heritage. Setting up an effective risk governance for heritage on a national level makes resilience more attainable through improved actions of risk assessment and monitoring, development of DRM plans, capacity building and resource allocation for efficient preparation and response to disasters (Figure 4).

Recommendation: **Set up an effective risk governance for cultural heritage on a national level, promoting agreements between different actors, improving resources availability and increasing training opportunities.**

Figure 4. Drill at the Roman Ruins of Troia with the presence and involvement of several civilian and law enforcement entities.

4.2. Strengthening Cooperation

There are those who say that Europe will have to assume that in the long run will lose relevant cultural heritage, regardless of any mitigation measures adopted (Zanirato 2010). This does not mean, however, that we must give up vulnerability and hazards exposure reduction policies for cultural heritage, otherwise we will condemn it altogether.

From words to actions, much remains to be done regarding the protection of cultural property against catastrophes in each UNESCO signatory State, particularity in what respects to the European States (Vintzileou *et al.* 2018), where a large part of cultural assets inscribed in the World Heritage List is concentrated. It should be noted that the Sendai Framework 2015-2030 emphasises disaster risk management. Without underestimating the importance of disaster management processes, prevention and risk management are highlighted as an area to be explored, particularly in the case of cultural heritage. Indeed, only a truly preventive approach can guarantee an effective heritage protection, since its value can be irremediably lost as a result of the impacts of a catastrophe. In this sense, policies and measures to reduce vulnerability and risk exposure should focus primarily on the prevention phase – rather than on response and recovery.

To try and overcome this state of the art, according to the answers provided by the STORM partner countries in D2.1 (STORM Consortium 2016) and its update during the project, the improvement of the effective protection of cultural heritage in those countries, should comprise measures in three lines: an integrated approach of issues, aiming for sustainable development; a global strategy, but adapted to local solutions; a participation and capacitation approach of all stakeholders for the reduction of vulnerabilities and expose to disaster risk.

An integrated approach

> "[...] two of the most serious threats identified in the elaboration of local cultural policies: on the one hand, the sectorisation of policies, to the detriment of integrated strategies for the development of territories; and on the other hand the inadequacy of collaborative and networking processes at local, regional, national and sectoral levels" (Costa 2015).

The European Charter of the Architectural Heritage (1975) already recognised the need for the integrated conservation of heritage properties and for the cooperation of all players in territorial planning, aiming for sustainable development and the improvement of the quality of life. The *Hyogo Framework* *for Action 2005-2015* (2005) emphasised the premise that disaster risk reduction policies should have a transversal nature, including all areas of activity and distinct levels of government.

An integrated approach is a presupposition of disaster reduction policies and sustainable development and involves the cross-linking and integration of measures amongst all programmes, plans and policies that may result in a better protection of cultural properties against the risks these faces. It should thus be:

- Multisectoral, with the shared work of all responsible entities, including the public authorities with competences on the design and implementation of plans and actions to develop in all sectors of activity, particularly in the areas of culture, civil protection and territorial planning.
- Multi-risk: guaranteeing the training, the sharing of good practices, and the resources necessary for the elaboration and implementation of actions and plans in order to carry out the required protection of cultural heritage in view of all threats, specially the several kinds of natural hazards.

Global strategy, local solutions

The adoption of national emergency plans and measures of coordination of all players in the safeguard of cultural heritage against catastrophes should have an open nature and be able to manage the solutions to be applied in each case, according to the specific risk, properties and resources found in each territory. Several authors have emphasised the importance of the attitude of local stakeholders in the protection of World Heritage (Van der Aa. 2005), and the Synthesis Report Consultations on the Post-2015 Framework on Disaster Risk Reduction highlights the crucial role of authorities and local communities in the building of risk-resilient societies (UNISDR *et al.* 2013). The active engagement of communities is therefore to be considered a key factor for the effectiveness of the principles and orientations developed for the reduction of disaster risks menacing cultural heritage. The success of such initiatives demands the intervention of communities, which contribute decisively for the distinction between 'rules on paper' and 'rules in practice' (Ostrom 1990).

Capacity building for resilience

To make cultural heritage resilient to disasters deriving from climate change implies the mobilisation of several players and resources for the elaboration, adaptation and implementation of measures ensuring the safety and well-being of communities, as well as the effective protection of properties of a recognised cultural interest. The European Union Solidarity Fund, created in 2002, is a good example of an instrument in the field of cooperation designed to support the capacity for action of the states and their communities struck by natural disasters, which know no borders, and which intensity and dimension exhaust local response capacities. In a first, preventive, moment, the reduction of cultural heritage vulnerabilities implies a complex adaptive process covering the modernisation of buildings and infrastructures, the alteration of instruments of land planning and use, and a new reflexion on the application of legal and regulatory rules for heritage protection in the face of climate risks. In such context, the sharing of good practices, the thorough identification and characterisation of assets of relevant cultural value and of the risks threatening them, the financing of safeguard measures for cultural heritage at risk, and the legislative support, are all measures that allow the development of the communities' capacities, as envisioned in the *1972 UNESCO Convention for the Protection of the World Cultural and Natural Heritage.*

4.3. STORM Policy Recommendations

Preliminary remarks:

a. These recommendations take into account the constraints collectively identified by the STORM partner countries;
b. They must therefore be seen as proposals, to overcome the identified constraints which hinder the due development of policies to reduce hazard impacts, vulnerabilities and exposure of cultural heritage at risk;
c. They are based on a presupposition of prevention-focused concern, i.e. on the intention of reducing the hazard impacts on, and the vulnerabilities and the exposure of cultural heritage, rather than on preparedness, response or recovery;
d. They are imbued with international and European guidelines and good practices on this subject;
e. The formulation of these recommendations is intentionally opened to allow a possible adaption to the national legal systems of the STORM partner countries, as well as for their appropriation by different communities and different levels of implementation (central, regional or local);
f. No hierarchy or precedence is established in the recommendations among themselves, as it is assumed that any sequencing or prioritisation are possible, depending on the criteria and competence of the responsible entities.

Policy Recommendations:

1. **Ensure a political commitment of the national, regional or local government communities**, in articulation with the main stakeholders, on the goals of reducing vulnerability of cultural heritage facing natural disasters. This commitment does not necessarily require a legislative instrument; it can be set out in a Memorandum of Understanding, provided that it clearly enables the parties concerned to be committed to common objectives, deadlines and results. Such a commitment could work as a framework for resolving funding limitations and promoting preventive measures in the scope of shared management of endangered heritage assets.
2. **Create a High level Permanent Intersectoral Forum**, with a mandate to promote legislation review, establish guidelines and methodologies, disseminate good practices, promote articulation between central government and local authorities, and ensure the empowerment of actors involved in the protection of cultural heritage. Regardless of the institutional, organic and functional solution found, it should have the support of the organizational summit to guarantee mandate to the members of the Forum in the interpellation of the services of the public administration and other stakeholders.
3. **Include risk assessment information on the listing or designation procedures for cultural heritage.** The identification of hazards, vulnerabilities and exposure level of cultural heritage to threats, should be considered as criteria in the decision-making processes and thus facilitate the enforcement of mitigation measures to be adopted for the effective protection of heritage properties or sites.
4. **Involve communities in heritage safeguarding.** Participatory management models are widely recognised by international organisations, that promote the involvement of heritage properties stakeholders in the preservation and maintenance of outstanding universal values. The participation of local authorities in national heritage management and conservation can also work positively towards cultural heritage resilience; they play an important role in cultural heritage protection, often assuming the allocation of financial resources to support preventive measures (Filipe 2014). Finally, within communities, the strong connection that citizens develop towards assets that are close to them, and which may lead them to assume the role of "heritage guardians", should be acknowledged and streamlined, enabling the creation of alert networks for cultural heritage protection. Such

procedures furthermore contribute to the resilience of the heritage communities themselves.

5. **Set up Local Framework Plans**. This non-legislative instrument should allow to collect in a single document (which can contain both textual and graphic information) all normative references, whether legal, standards or good practice, that the political decision maker, or any interested party, must take into account in territorial planning where protected (or pending protection) cultural heritage is located. For a greater degree of functionality, these plans should be drawn at a local scale and identify, in the territory, the overlapping of preventive measures related to cultural heritage risk management.
6. **Implement risk mapping on heritage management.** This tool is recurrently mentioned by managers of cultural heritage as a missing and necessary key element to support decision making in planning processes. This instrument should also inform other territorial planning instruments, as well as emergency plans, and be communicated for the purpose of adequacy of the action of civil protection agents.
7. **Secure funding for the financing of preventive measures for cultural heritage**. Develop a line dedicated to risk prevention and management projects, including the financing of risk prevention plans. For instance, Portugal has the *Cultural Heritage Safeguarding Fund* allowing cumulation with other funds, which is an example that can be followed in other countries. In practice, however, most funds are mutually exclusive, often because managing entities from other governmental areas do not consider their participation in the risk prevention of cultural heritage. This aspect should be taken care of in the funds or other lines of financing to be developed.

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2.
Risk Assessment and Risk Management for the Protection of Cultural Heritage

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Introduction

This chapter develops an integrated methodology of risk assessment and management for cultural heritage properties in response to the adverse effects of natural hazards and climate change-related events. The conceptual and analytical frameworks and procedures of risk assessment and management that have been developed by international organisations and various disciplines dealing with risk reduction and climate change adaptation have been reviewed. Applicability of the assessment method to the field of heritage

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conservation and specific requirements of the STORM pilot sites have been particularly taken into account.

The proposed methodology of risk management was applied to the five STORM pilot sites: the Historical Centre of Rethymno, the Mellor Heritage Project, the Roman Ruins of Tróia, the Baths of Diocletian, and the Ancient City of Ephesus. Natural hazards and threats affecting each pilot site have been identified, analysed, and subsequently, mapped in the GIS environment. Following the assessment of the risk components, they have been incorporated into the risk index to measure the level of risks. According to the STORM risk map concept, relative risk maps have been generated to share a common understanding of the risks at the pilot sites among the risk management team, including the site managers and stakeholders.

The output of the pilot sites risk assessment will further support the decision-making process to determine risk treatment strategies. Moreover, the procedure of the risk assessment provided a clear perception of the risk elements for each pilot site to develop a site-specific risk reduction plan through various options including hazard mitigation, susceptibility reduction, and coping capacity building.

Following the risk assessment, risk management guidelines were presented for the mitigation of sudden-onset as well as slow-onset disasters as a result of natural hazards and climate-change related effects. The three major pillars of this risk treatment framework are: risk prevention and mitigation (including adaptation to climate change), risk preparedness and emergency response, and the recovery plan.

In addition to the risk management guidelines, specific measures and actions are proposed for the implementation of these strategies. To this end, a wide range of preventive hazard-specific risk treatment measures are suggested. These measures focus on the reduction of hazards and threats, the monitoring of hazards as well as warning systems, exposure reduction, reduction of the material susceptibility, and regular monitoring and maintenance of the site. Furthermore, to ensure rapid intervention in case of emergency in order to limit further damage, a broad array of first aid actions for a variety of cultural heritage typologies is included.

Based on the presented guidelines and measures, risk treatment plans have been developed for the five STORM pilot sites. The results from the risk assessment are considered to determine the relevant hazards and site areas for which the risks should be treated. Using an iterative approach, the existing risk treatment in place at the pilot sites was investigated, and new risk management measures were developed. The presented set of proposed actions target the protection of each of the STORM pilot sites, as well as specific monuments on the sites, against natural hazards and climate change.

1. STORM risk management procedure for cultural heritage

Risk Management process is "the systematic application of management of policies, procedures and practices to the tasks of communicating, consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk" (AEMC 2010). Risk management is an approach to shift from merely controlling hazards to managing risk by looking at the characteristics of elements at risk as well. Below, some of the more internationally recognised frameworks and approaches are mentioned.

Disaster Risk Management (DRM), which mainly refers to emergency and disaster situations, is defined as the "Application of disaster risk reduction policies, processes and actions to prevent new risk, reduce existing disaster risk and manage residual risk contributing to the strengthening of resilience" (UNISDR 2015a, 13). The UN's Sendai Framework for Disaster Risk Reduction 2015-2030 agreed in March 2015 in Japan set four specific 'Priorities for Action' as below (UNISDR 2015b):

- Priority 1: Understanding disaster risk;
- Priority 2: Strengthening disaster risk governance to manage disaster risk;
- Priority 3: Investing in disaster risk reduction for resilience; and
- Priority 4: Enhancing disaster preparedness for effective response.

According to the UNISDR approach, DRM comprises the following actions (UNISDR 2015a, 13-14):

- Actions designed to avoid the creation of new risks, such as better land-use planning and disaster resistant water supply systems (prospective disaster risk management);
- Actions designed to address pre-existing risks, such as reduction of health and social vulnerability, retrofitting of critical infrastructure (corrective disaster risk management); and
- Actions taken to address residual risk and reducing impacts on communities and societies, such as preparedness, insurance and social safety nets (compensatory disaster risk management).

In respect to the protection of cultural heritage from natural hazards, two different trends can be recognised: structural risk assessment of historic fabrics e.g. by Tolles *et al.* 2002, and the overall process of risk assessment and management for cultural heritage e.g. by Stovel 1998 and UNESCO World Heritage Centre *et al. 2010* (Ravankhah *et al.* 2017). National and international projects have also been dedicated to the subject, such as *Climate for Culture* (2009-2014) and Noah´s Ark '*Global Climate Change Impact on Built Heritage and Cultural Landscape*' (2001-2007) with a specific focus on the impacts of climate change on materials and structures of cultural heritage.

Figure 1 illustrates the STORM risk assessment and management (STORM RA&RM) procedure for cultural heritage that has been developed based on the above-mentioned RM and RA approaches and frameworks, while considering particular considerations on cultural heritage in the scope of the STORM project. Although the procedure portrays different steps sequentially to make its application easier, it is not a linear process; conducting each step may need re-evaluation and revision of the previous ones, and the procedure requires monitoring and upgrading based on the new situation or after the implementation. The STORM RA&RM (Figure 1) comprises four major steps as follows:

- Establishing the STORM context to determine the objectives and scope of the process;
- Assessment of risks, including the analysis of hazard, exposure, and vulnerability;
- Treatment of risks to develop strategies for risk mitigation, preparedness, and recovery plan; and
- Implementation of the treatment strategies and monitoring the plan.

2. STORM risk assessment procedure

"Risk assessment is the overall process of risk identification, risk analysis and risk evaluation" (ISO 31000:2009). STORM applies the risk index method for analysing risks to the pilot sites. "Risk Index is a semi-quantitative measure of risk which is an estimate derived using a scoring approach using ordinal scales" (IEC/ISO 31010 2009). Once the components of risk have been defined and measured, they will be combined to create a composite risk index. The scores of the components will be multiplied to rank different risks. The STORM risk concept comprises the following components:

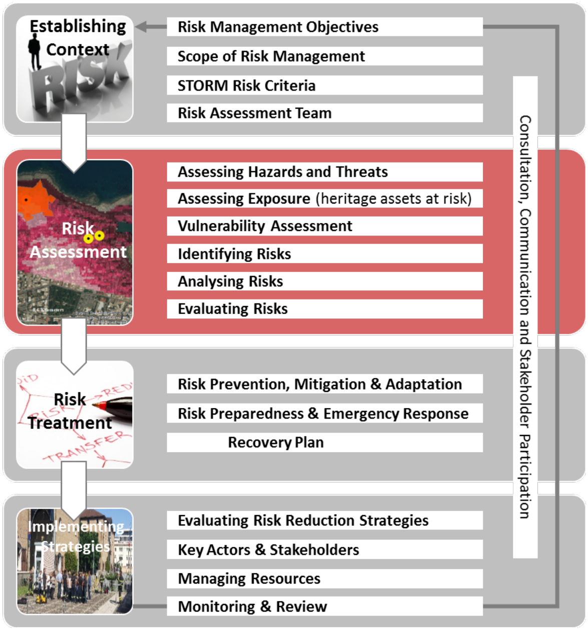

Figure 1. STORM risk assessment and management procedure for cultural heritage.

- Hazard: hazards leading to sudden-onset disasters (e.g. storms, flooding, wildfires) and those leading to slow-onset disasters (e.g. change in freeze-thaw events, heat waves, and prolonged wet/dry periods) are incorporated in the assessment procedure;
- Exposure: movable and immovable heritage assets and their associated values are considered as elements at risk. Therefore, exposure assessment is mainly focused on the analysis of the value of heritage assets within the pilot sites;
- Vulnerability: a vulnerability assessment method is developed to evaluate the susceptibility of the pilot sites to damage according to their structural and material characteristics. Furthermore, adaptive and coping capacity will be taken into account.

2.1. Assessing hazards and threats

The *STORM Classification of Hazards and Climate Change-related Events* has been developed based upon the existing literature, international frameworks (e.g. UNISDR 2015a), climate change adaptation (e.g. UNFCCC 2012; EU-Noah's Ark Project (2007), and heritage conservation (e.g. UNESCO World Heritage Centre 2007; Camuffo 1997). Furthermore, particular hazards and threats affecting the STORM's pilot sites have been identified and incorporated into the hazard inventory. Applicability of the hazard inventory to the field of heritage conservation and the specific requirements of the STORM pilot sites have been particularly taken into account. The STORM hazard classification will further facilitate the development of hazard and risk assessment methodologies in cultural heritage contexts.

UNISDR (2015a) defines the term 'hazard' as "a potentially damaging physical event, phenomenon or human activity that may cause the loss of life or injury, property damage, social and economic disruption or environmental degradation". Since the term 'hazard' in disaster risk management refers mainly to the catastrophic events, the term 'threat' is applied here to include a wide range of (non-catastrophic) environmental threats which may affect cultural heritage properties. Natural hazards and threats are categorised as follows:

- Geological (geophysical) hazards: "A hazard originating from solid earth. This term is used interchangeably with the term geological hazard" (EM-DAT n.d.);
- Hydro-meteorological hazards: including hydrological hazards "caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater" and meteorological hazards "caused by short-lived/small to mesoscale atmospheric processes (in the spectrum from minutes to days)" (EM-DAT n.d.); Climate change-related hazards fall in this category; and
- Biological hazards: "Process or phenomenon of organic origin or conveyed by biological vectors, including pathogenic micro-organisms, toxins and bioactive substances" (UNISDR 2015a).

To adequately address the short and long- term effects of natural hazards and threats on heritage sites, the above-mentioned hazards are further categorised according to their associated sudden-onset and slow-onset disasters. "A sudden-onset disaster is one triggered by a hazardous event that emerges quickly or unexpectedly. Sudden-onset disasters could be associated with e.g. earthquake, volcanic eruption, flash floods, chemical explosion, critical infrastructure failure, transport accident" (UNISDR 2015a). "A slow-onset disaster is defined as one that emerges gradually over time. Slow-onset disasters could be associated with e.g. drought, desertification, sea level rise, epidemic disease" (UNISDR 2015a).

Hazards and threats affecting the pilot sites have been identified according to the structure of the *STORM Classification of Hazards and Climate Change-related Events*. A preliminary hazard profile has been prepared for each pilot site to gather basic data regarding the historic frequency and severity of the hazards, as well as the information about the historic impacts of the hazards on the pilot sites. A semi-quantitative ranking (adapted from HAZUS-MH (FEMA 2004) is applied to analyse the potential hazards affecting the pilot sites and, subsequently, to determine which hazards or threats need to be integrated into the further risk assessment procedure. Three main ranking factors, likelihood, magnitude, and expected intensity of impact, are considered in the hazard analysis. 'Significance of hazards for site managers' was added to the ranking factors, as an additional criterion, reflecting site managers' opinion on hazard relevance in their pilot site. Accordingly, a table of hazard analysis was provided for each pilot site to determine the above-mentioned factors. All potential hazards and threats might be considered in the conservation of heritage properties, but might not necessarily be subject to a rigorous risk assessment procedure. Below, the process of hazard mapping and climate analysis for the case of the Roman Ruins of Tróia, as an example, is presented.

2.2. Climate analysis and climate change projection

To assess risks arising as a result of climate change, a methodology to incorporate climate change information in the risk assessment was developed. In the climate hazard assessment, as a first step in the risk analysis, climate change effects relevant to cultural heritage are summarised. Based on the identification of atmospheric processes relevant to cultural heritage, an evaluation which was performed by cultural heritage experts, climate indices defined by the Expert Team on Climate Change Detection and Indices were assigned to these phenomena to aid a quantitative analysis. In this process, 'intense rainfall' is for example defined by the indices 'heavy precipitation days' and 'maximum 1-day precipitation amount'. In total, 22 indices were chosen to define 14 climate hazards.

These climate indices are subsequently analysed based on observations for stations in the vicinity of the cultural heritage site, to derive the baseline situation for the climate normal period 1971-2000. Data used in this analysis are provided by the European Climate Assessment & Dataset (ECAD, Klok, Klein Tank 2008), where data for many European weather stations are freely available for non-commercial use. In case no weather station in the vicinity of the site was available in the ECAD dataset, the pilot site managers and local meteorological services were contacted to request data closer to the site.

To study the future changes in these parameters, climate projections based on two different greenhouse gas emission scenarios are considered (IPCC 2013). As 'upper limit scenario' the representative concentration pathway (RCP) 8.5 is taken, representing a "business-as-usual" scenario in terms of emissions. The RCP4.5, an active climate change mitigation scenario, is used as comparison. Site-specific climate change information for the middle of the century (time period 2036-2065) is derived from regional climate model simulations provided by the EURO-CORDEX initiative (Jacob *et al.*, 2013). By comparing the simulations of future climate to the historical model runs for the 1971-2000 baseline period, the climate change signal in the indices can be determined on a per model basis. The multi-model mean of the climate change signal, as well as the spread, is considered in order to increase the reliability of the analysis.

To crosscheck the results of the regional climate model simulations, a statistical downscaling of global model simulations driven by RCP8.5 from the Coupled Model Intercomparison Project (CMIP5, Taylor *et al.* 2012) is performed using the analog method (Benestad *et al.* 2008). Here, the time series of temperature and precipitation obtained near the site from ECAD or the local meteorological service are used as input to optimise the global simulation results for the specific location of the cultural heritage site. Based on the statistical downscaling results, the climate change signal is again determined following the same methodology as for the dynamical downscaling results described above.

To incorporate these results in the risk assessment, the base hazard level (under current climatic conditions) and the relative climate change signal (rate of change relative to the model-based baseline) is determined. Based on the relative signals obtained with the statistical as well as dynamical downscaling techniques, as well as a comparison between the observed and modelled baseline situation to determine possible model biases, a final climate hazard assessment is made. In this assessment, the hazard scale is defined for each of the relevant climate indices and the hazard level is assigned to one of five categories (ranging from 'very high' to 'very low'), based on which the climate hazards can be incorporated in the further risk assessment procedure.

2.3. Mapping the hazards

A series of hazard and risk assessment maps related to the main threats identified for the pilot sites were developed and generated through Geographical Information Systems (GIS) spatial modelling. Specifically, hazard maps were created based on the availability of data applying the following alternatives:

- Hazard map in the required resolution existed, from local, regional or national sources or even from available online EU sources;
- When these were not available, then the procedure was carried out by:
- Generating 3 the respective hazard map based on historic data, previous events and climate analysis by utilising hazard assessment modelling through GIS;
- When historic data was not available, then,
- Generating the hazard map based only on experts (site managers) opinion and by utilising hazard assessment GIS modelling.

For the Tróia pilot site, as an example, the above procedure has been employed as follows:

For *Earthquakes hazard assessment*, we acknowledged the Euro-Mediterranean Seismic Hazard Model (ESHM13) was acknowledged, a result of a probabilistic seismic hazard assessment carried out for the Euro-Mediterranean region, based on geological and seismological data. The probabilistic seismic hazard map expresses the peak ground acceleration with a 10% probability of exceedance in 50 years.

The *Tsunamis hazard map* was developed considering as input the European Digital Elevation Model EU-DEM (30m resolution), while the modelling process was conducted via spatial analysis algorithms for a corresponding sea-wave height of 3-4m penetrating into the mainland for a specific distance from the coastline (70-80m) and an around 4m run-up elevation in relation to the normal sea level (Baptista *et al.* 2011).

The *Landslides hazard map* was developed by applying a simplified weighted-factors model (Kouli *et al.* 2010) on various factors, such as geological and hydrogeological characteristics, the distance to tectonic structures (i.e. faults and thrusts), slope (EU-DEM derivative) and rainfall data (1971-2000 period). Hydrolithological formations were combined and categorised with regard to their relation to annual precipitation values, as well as to the distance to tectonic structures. The final landslide hazard map was based on the combination of the various reclassified and ranked datasets into a GIS environment to provide support to regions exposed to a potential landslide.

The *Strong Winds hazard map* was based on an assessment of the daily maximum wind speed data for a 6-year period, provided in the table of hazard analysis for the 'strong wind' hazard.

A *Coastal Flood hazard map* was developed by considering as input dataset the EU-DEM, while the modelling process was conducted via spatial analysis algorithms for 50cm sea-level rise for the area of interest.

The *Intense Rainfall hazard map* was based on the rainfall magnitude and severity information of the period 1971-2000 as well as the projected changes as a result of climate change, as provided in the table of hazard analysis.

The *Humidity Cycle Changes hazard map* was based on the assessment of the pilot site managers.

The *Heat Waves hazard map* was based on the heat waves duration information for the period 1971-2000 as well the projected change as a result of climate change, as provided in the table of hazard analysis.

The *Salinisation hazard map* was developed based on geomorphological characteristics (elevation and aspect) with respect to proximity to the coastline. Geomorphological characteristics can ensure the determination of the areas exposed in a higher degree of salinisation in relation to their lower elevation and the dominant wind direction (NW). A weighted overlay procedure was utilised for identifying areas with a higher susceptibility to salinisation.

2.4. Hazard evaluation

The above-mentioned ranking factors were inserted to the hazard analysis table to derive two main criteria of 'event parameter' and 'expected intensity of impact'. Below, the result of hazard analysis is presented in which the potential hazards affecting Tróia were classified in three zones to be considered in the further steps of the risk assessment. Those hazards which are placed in the very high, high, and medium zones need to be integrated into the subsequent steps.

- Hazards with very high and high significance: earthquakes, coastal erosion, tides, tsunami, wind-generated waves, rain, biological colonisation, landslides, rainstorms/ thunderstorms, strong winds, humidity cycle changes;
- Hazards with medium significance: strong winds, intense rainfall, sea-level rise, saline spray and salinisation, solar radiation, coastal floods; and
- Hazards with low significance: wind, wind-driven particles, wind-driven rain, heat waves.

2.5. Assessing exposure

UNISDR (2009) defines the term 'exposure' as "People, property, systems, or other elements present in hazard zones that are thereby subject to potential losses". Similarly, for IPCC (2014) exposure is "the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected". In the STORM project, heritage assets, their associated intangible elements and their values are considered as elements at risk; therefore, the exposure assessment procedure is as follows:

- Description of heritage elements, including immovable and movable assets, within the site and its setting;
- Characterisation of the values of all heritage elements, based on a value category system adapted from Worthing and Bond (2008) and the Burra Charter (Australia ICOMOS 2013);
- Assignment of value levels, ranking the relative importance of the site elements, based on Kerr (cited in Worthing and Bond 2008).

The value of the site as a whole can be derived from institutional heritage listings, which typically state whether its importance is relevant at local, regional or national levels. However, for site management in general, and for its risk management in particular, institutional listings are insufficient for the development of risk assessment and management. Thus, in this project, the value of the use cases at each pilot site will be individually considered rather than the value of the pilot site as a whole. This will provide more accurate data for further risk analysis and DRM strategies for each pilot site. Table 1 shows an example of the value assessment for the case of Tróia. The level of value, which represents the exposure score, falls into five equal-sized classes that are qualitatively interpreted as Very low (1), Low (2), Medium (3), High (4), and Very high (5).

Table 1. An example of the value assessment for an area of Tróia

Heritage values	Brief description	Level of value
Area 1: Fish-salting workshops		
Aesthetic	Remains quite well preserved of workshops with many complete vats, in an area surrounded by water, in a beautiful environment.	*High (4)*
Architectural/ technological	Fairly well-preserved examples of industrial buildings with a specific construction technique.	*High (4)*
Historical	The site is the largest fish-salting centre known to this day in the Roman Empire.	*Very High (5)*
Archaeological	A large site with remains along 2km and an outstanding archaeological value due to the good preservation on sand and the great potential for discoveries since most of the remains have not yet been excavated.	*Very High (5)*

Economic	C. 11.000 visitors a year (open only 8 months a year).	*Medium (3)*
Educational	Great educational value due to the documentation of an important economic activity that powered many areas of activity in the region.	*Very High (5)*
Scientific	Great potential of information through research. The site already attracts many researchers for its great scientific potential.	*Very High (5)*
Social	The fish-salting workshops of the site illustrate the first stage of the fish products industrial activity in the region, very important in medieval and modern times, with its peak in the first half of the 20th century when the nearby city of Setúbal had 140 factories of canned sardine. It is visited every year by c. 1300 students in school study visits.	*High (4)*
Environmental	The site is surrounded by the Sado estuary and a lagoon, and its setting is classified in an international environmental network (Natura 2000).	*High (4)*

2.6. Assessing vulnerability

The term 'vulnerability' has been defined differently by scientific communities and international organisations dealing with DRM and CCA (climate change adaptation). IPCC (2014) defines vulnerability as "The propensity or predisposition to be adversely affected". The concept of vulnerability, within the IPCC's CCA agenda, comprises the two main elements of sensitivity to harm and lack of capacity to cope and adapt. Within the DRM community, UNISDR (2009) defines vulnerability as "The characteristics and circumstances of a community, system or asset that make it susceptible to the damaging effects of a hazard". In the UNISDR's approach, coping capacity or resilience is an additional factor besides the vulnerability. "Despite differences in the interpretation of the concept of vulnerability, it has, however, become an essential element to underscore the importance of social factors and societal structures in the construction of risk and of adaptation options" (Birkmann 2013, 9).

The STORM project adapts the concept of vulnerability in the WorldRisk-Index (Birkmann and Welle 2015) that comprises the major components of susceptibility, coping capacity, and adaptive capacity. To assess the vulnerability of the pilot sites in the STORM project, the two following factors need to be analysed:

- Susceptibility: In the context of cultural heritage, susceptibility or sensitivity represent the extent to which a heritage asset might be adversely impacted by a hazard or threat;
- Coping and adaptive capacity: In the STORM project, coping and adaptive capacity describe the institutional capacity of existing heritage conservation and risk management system to manage risks of natural hazards and threats to cultural heritage through structural and non-structural measures. Although coping and adaptive capacity are highly interconnected, coping capacity mainly reflects the ability to mitigate, respond to and cope with the sudden-onset disasters while adaptive capacity comprises the ability to adjust to slow-onset disasters in a long-term perspective as well.

Vulnerability analysis of the pilot sites and their use cases is conducted through a structured open-ended questionnaire. The questionnaire is divided into two major sections, susceptibility analysis and coping and adaptive capacity analysis. The target group involves the pilot site managers, expert partners familiar with the sites, and local and national organisations responsible for the protection of the sites.

The susceptibility analysis is divided into four components that define the parameters and rank the elements that ultimately determine the susceptibility of a given heritage asset to suffer damage caused by sudden- and slow-onset disasters. The components involve structure (load-bearing walls, foundations, roofs, and Joints), structural materials (materials used in the load-bearing elements), (immovable) heritage interiors (e.g. decorative elements), and movable elements (e.g. collections and archives). It should be noted that in the STORM project, susceptibility to sudden-onset and slow-onset disasters are separately analysed in order to adequately calculate their contribution to the overall vulnerability and risks.

In addition to susceptibility, the degree of capacity to mitigate, respond to and recover from disasters contributes to risk level. Coping capacities rely heavily on the institutional and management systems of heritage sites and, in a broader context, on the regional and national bodies engaged in the protection of cultural heritage from natural hazards. In STORM, coping and adaptive capacities to slow-onset and sudden-onset disasters are assessed by measuring a set of defined indicators, including multi-sectoral cooperation, risk awareness, information and communication systems, risk mitigation and preparedness, and monitoring and maintenance plans.

2.7. Risk identification and analysis

Following the identification and analysis of the risk elements, including hazard, exposure, and vulnerability, potential impacts of the hazards on each pilot site can be identified. A potential impact associated with a hazard occurring in a particular area will be formulated as a risk statement. The risk identification procedure begins, in fact, with hazard assessment, and explores the interrelations between the risk elements to identify potential impacts. Detailed potential impacts of the hazards on each pilot site are determined according to the site manager and expert opinion while looking at existing relevant investigations (e.g. Stovel 1998; UNESCO World Heritage Centre *et al.* 2010; Kaslegard 2011; Daly 2011; UNESCO World Heritage Centre 2007b) as well. Accordingly, overall risk statements, which outline the hazards and their potential impacts, are determined, to be incorporated into the risk analysis.

In the case of earthquakes, for instance, the impacts could be structural cracks in building elements, damage to masonry joints and connections, collapse of building components or entire structures, displacement of freestanding items, loss of architectonic elements, deformation of structures, and loss of archaeological contexts. It should be noted that impacts from earthquake-related consequential hazards need to be also considered when developing risk management strategies. In the case of earthquakes, indirect impacts could be theft of collapsed or damaged fragments or movable objects within the site, damages from fires and explosion, or potential insensitive actions by emergency teams or volunteers.

Following the analysis of the risk components, they were incorporated into the risk index to rate the level of the risks. "Risk analysis aims at assigning each identified risk a rating in accordance with the agreed risk criteria" (AEMC 2010). The scores of the components will be multiplied to rank different risks. For each hazard, a risk statement was defined that represents the potential impacts of the hazard on the site. While considering the overall risk statement, the risk score for each area will be separately calculated. The risk scores fall into the range of 5 equal-sized classes ranging from 1 to 5, and will be interpreted qualitatively as Very high (red), High (orange), Medium (yellow), Low (dark green), and Very low (light green). Figure 2 shows the level of earthquake-related risk for the eight areas of Tróia and the earthquake risk map which has been generated by aggregating the risk elements.

Risk analysis and risk map for the Roman Ruins of Tróia will further assist the decision-making process to understand which risks need treatment strategies and on which level. The GIS map can facilitate the process of risk

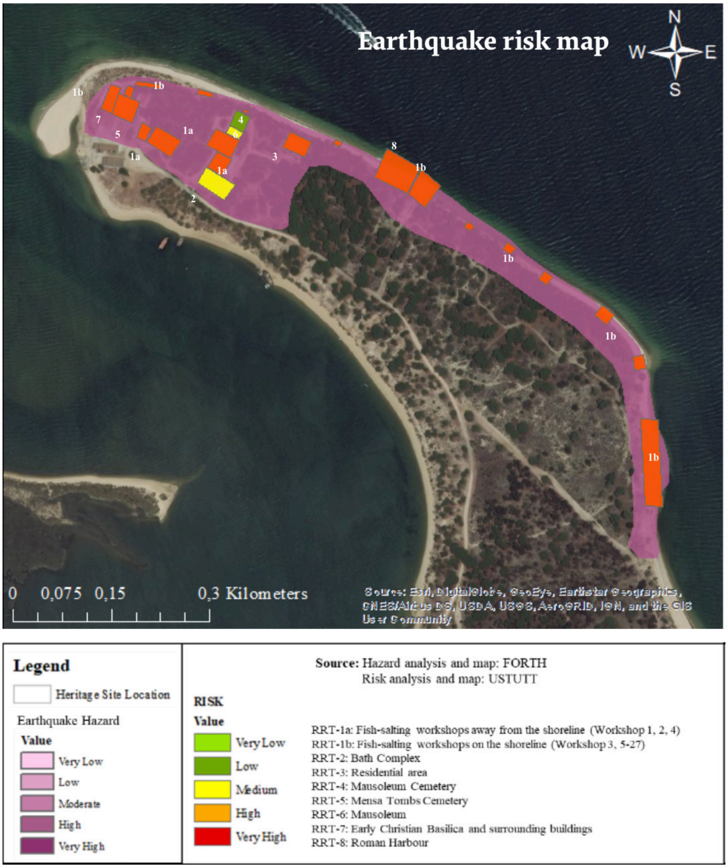

Figure 2. Developing the earthquake hazard and risk map for Tróia.

management planning by providing local authorities and planners with the essential inspection of different spatial data through geo-informatic approaches and computer-generated maps. The preparation of risk maps and their integration with various other infrastructure-mapping datasets can initiate the developing of mitigation, preparedness, response and possible recovery needs. Moreover, the above procedure of risk assessment for the Roman Ruins of Tróia will give a clear perception of the risk elements to develop a site-specific risk reduction plan through avoiding or reducing the identified hazards, reducing the structural susceptibility, promoting the coping and adaptive capacity, and increasing the effectiveness of emergency response using the GIS hazard and risk maps. A detailed description of risk treatment strategies is provided in the next section.

3. STORM Risk treatment framework

"Risk treatment involves selecting one or more options for modifying risks, and implementing those options" (ISO 2009). According to AEMC (2010), risk treatment may consist of different options, including avoidance of the risk, removing of risk sources, and changing the likelihood of hazards or their consequences. While considering these options, the STORM risk management framework provides cultural heritage sites with risk treatment strategies specific to sudden-onset and slow-onset disasters. In respect to sudden-onset disasters, the framework comprises the following three major plans in order to adequately address pre-, during-, and post-disaster phases:

- Risk prevention, mitigation and climate change adaptation plan, including monitoring, maintenance and conservation-restoration;
- Risk preparedness and emergency response plan; and
- Recovery plan.

After determining the areas for which risk treatment is needed, based on the different types of hazards, several risk treatment strategies can be considered. In order to implement these strategies, various 'measures' or 'actions' can be taken. To aid cultural heritage sites in the identification of such measures to manage risks as a result of natural hazards and climate change, several suggestions are compiled. It should be noted that heritage conservation and intervention principles play a key role in determining appropriate risk management strategies, and therefore, need to be adequately taken into account.

3.1. Criteria and requirements for interventions in cultural heritage sites

Heritage may be defined as a cultural practice (Smith 2006) whose material expression constitutes "a fundamental device [...] in the anchoring of human societies in the natural and cultural space and in the double temporality of humans and nature" (Choay 2011, 16). In fact, "A sense of identity must inevitably draw on a sense of history and memory – who and what we are as individuals, communities or nations is indelibly formed by our sense of history and the way individual and collective memory is understood, commemorated and propagated" (Smith 2006, 36).

In its broadest sense, conservation may be defined as "All actions designed to understand a heritage property or element, know, reflect upon and communicate its history and meaning, facilitate its safeguard, and manage change in ways that will best sustain its heritage values for present and future generations" (Nara+20 2016, 147). Conservation, in this sense, encompasses an extremely vast array of actions and procedures, as long as these are directed to this sustainable management of change to a significant property or element. In what it serves this ultimate goal, heritage DRM is, effectively, a conservation tool, and it should thus follow the same principles that preside over the practice of conservation (Revez 2016).

Conservation principles reflect the paradigms of societies in tending to their heritage assets and should be applicable to any decision, at any scale of intervention, from management plans to specific actions; from intervention methods to treatment product choices. Current principles and recommendations that should preside over decisions interfering with the significance of European heritage assets are consecrated in several international charters and codes of ethics, among which those endorsed by ICOMOS constitute the chief references in the (Western) Conservation field (ICATHM 1931; ICATHM 1964; Australia ICOMOS 2013; ICOMOS 2017; ICC 2000; E.C.C.O., ENCoRE, and ICCROM 2008). Underlying all principles listed in such charters critically stand heritage values (significance) and the communities that hold them (CoE 2005), and that is the context in which all principles should be interpreted and understood. It is from the social will to preserve the present and future commonality of heritage that the principles guiding modern conservation today are derived; including, as per the abovementioned reference texts:

- Compatibility: the extent to which a product, method or action may be used upon a heritage object without putting its present or future significance at risk (adapted from CEN 2011); it encompasses present and future non-harmfulness towards the material and immaterial attributes of the heritage element;
- Minimum intervention: "a cautious approach of changing as much as necessary but as little as possible" (Australia ICOMOS 2013, art. 3), meaning that specific intervention goals must be clearly stated beforehand, so that a 'minimum' can be defined;
- Reversibility/ retreatability: reversibility may be defined as the extent to which a treatment can be undone without damage to the object (CEN 2011); seldom fully applicable, it has been gradually replaced by retreatability, recommending that treatments performed upon a conservation object should not preclude future treatments (Appelbaum 1987);

- Discernibility: requires that the introduction of new material into the heritage fabric “should be identifiable on close inspection or through additional interpretation” (Australia ICOMOS 2013, art. 20);
- Interdisciplinarity: heritage interventions “must have recourse to all the sciences and techniques which can contribute to [its] study and safeguarding” (ICATHM 1964, art. 2), provided these are coordinated in a truly integrative approach;
- Sustainability: “applying a long-term perspective to all processes of decision-making within [heritage] properties, with a view to fostering intergenerational equity, justice, and a world fit for present and future generations” (UNESCO 2015, para. 7).

In order to be meaningful (and operative), all conservation principles must be defined in reference to the primary goal of conservation, i.e., preserving the values or meanings that each heritage object has for its respective community or communities (CoE 2005). This means that conservation – including heritage DRM – decision making necessarily entails an assessment of cultural significance, from where the impacts of conservation choices can be appraised and checked for compliance with current conservation ethics. In the above-mentioned risk assessment methodology, this is achieved in the exposure assessment; but it will likewise have impact in the planning of risk treatment strategies.

For instance, archaeological structures, such as the STORM pilot sites, are a specific type of heritage objects that are chiefly characterised by the high prominence of their scientific/evidential and historical values, even when other values, e.g. symbolic or aesthetic, also contribute to their overall significance. Scientific/evidential values rely very heavily on the fabric of the heritage objects or, more specifically, on its ability to provide information about their history and associated communities via scientific research. Thus, in archaeological structures, any loss in information, including, but not limited to, any form of material loss will be generally perceived as damage (STORM Consortium 2017b). For this reason, the applicability of conservation principles in these contexts will be heavily concerned with the impacts of decisions on the whole of the object’s fabric. Conservation actions applied to such structures will, in general, primarily aim at the physical and chemical stabilisation of materials, seen as evidence and knowledge sources, and protection from future losses; and, within STORM, conservation principles will be applied considering the preservation of the whole of the fabric as ultimate goal.

3.2. Risk prevention and mitigation (including adaptation to climate change)

Prevention (i.e. disaster prevention) expresses the concept and intention to completely avoid potential adverse impacts of hazards, vulnerability conditions and exposure through action normally taken in advance of a hazardous event. Examples include dams or embankments that eliminate flood risks, land-use regulations that do not permit any settlement in high-risk zones, and seismic engineering designs that ensure the survival and function of a critical building in any likely earthquake" (UNISDR 2015a). In cultural heritage context, prevention options to fully avoid hazards or their associated risks are limited, and therefore, the strategies need to be focused more on reducing the risks through mitigation.

The term 'mitigation' in the DRM framework means "the lessening or limitation of the adverse impacts of a hazardous event. Mitigation measures encompass engineering techniques and hazard-resistant construction as well as improved environmental policies and public awareness. It should be noted that in climate change policy, 'mitigation' is defined differently, being the term used for the reduction of greenhouse gas emissions that are the source of climate change" (UNISDR 2009). Thus, the term 'adaptation' is also incorporated in this phase to address climate change-related threats, its slow changes, and gradual impacts on heritage properties. IPCC (2014) defines adaptation as "the process of adjustment to actual or expected climate and its effects". Within the STORM context, and considering the relevant hazards determined in the risk assessment stage, the following structural options are proposed to reduce the risks to cultural heritage:

- Reducing the hazards and threats affecting the heritage sites (e.g. constructing levees and embankments to avoid flooding water and debris flow);
- Monitoring of hazards (and warning systems) for early warning as well as providing an information database;
- Reducing the exposure of the elements-at-risk;
- Reducing vulnerability, including enhancing the coping and adaptive capacity; and
- Regular monitoring and maintenance of sites.

3.3. Reducing hazards and threats

Depending on the characteristics of hazards, there might be different ways to reduce a hazard and threat to cultural heritage sites. In some cases, measures can be taken in order to reduce the likelihood of the occurrence of a hazard.

This is the case for (wild)fire, where discouraging the use of naked flames as well as smoking or the removal of dry and easily flammable vegetation could reduce the likelihood of the starting or spreading of wildfires (Colombo and Vetere Arellano 2003). When considering e.g. floods, such an approach is not feasible. However, in many cases the construction of dams or levees is an efficient measure to prevent flooding of large areas (e.g. Colombo and Vetere Arellano 2002a). In some cases, a reduction of hazards and threats will not be possible (for example in the case of earthquakes).

When considering e.g. heat waves or intense rainfall, the occurrence and intensity of which is expected to change as a result of a changing climate, a method to reduce the hazard is not immediately obvious. However, a way to address this would be by reducing the level of climate change. Due to the regional or even global nature of climate change, it is hard to address the issue of climate change mitigation at cultural heritage site level alone (although it should be noted it is addressed in UNESCO 2007b) and a broader approach, including policies, is needed.

3.4. Reducing the exposure of elements-at-risk

As mentioned earlier, 'exposure' corresponds to the elements present in hazard zones that are thereby subject to potential losses (UNISDR 2009). In the STORM project, heritage assets are considered as elements-at-risk. As exposure is directly linked to the value of heritage assets and their location, a clear example for reducing exposure is the moving of cultural heritage outside the hazard zone. However, as relocation of heritage assets is not necessarily a desirable option in heritage conservation (e.g. UNESCO 2007), it could be merely acceptable in case of movable assets. In the case of immovable heritage, options such as the covering of structures with protective shelters, or different types of fabric, as well as the reburial of archaeological remains, could be considered.

3.5. Reducing the vulnerability

Reducing structural vulnerability to potential hazards is an effective option to reduce risk; however, different considerations should be taken into account when it comes to interventions on historic structures. In the case of an earthquake for instance, "efforts to increase earthquake resistance must be based on an adequate understanding of a building, its structural systems, construction materials and techniques, its evolution, history and conservation, its condition, its heritage values and its likely earthquake performance" (Stovel 1998, 62). The following considerations in respect to design criteria and reinforcement recommendations are suggested (Stovel 1998; Paolini *et al.* 2012, UNESCO World Heritage Centre *et al.* 2010):

- Avoiding the potential loss or impairment of the special interest or integrity of the historic property resulting from proposed interventions;
- Preference should be given to respecting, retaining and enhancing existing structural systems and materials where possible;
- Preference should be given to the use of traditional materials and techniques in reinforcement;
- Ensuring the compatibility of new materials and reinforcement techniques with the already existing structures; the intervention should be durable and reversible, as far as is practicable;
- Earthquake-reinforcement analysis should be based on building performance, rather than on simple application of code requirements, with due consideration given to improvements offered by technical developments;
- Interventions should be performed against realistic probability assessments of disaster occurrence, intensity, and associated risk levels; and
- All enhancements and strengthening measures should be fully documented in order to provide the possibility of the long-term review and establishing appropriate international standards.

Finally, some specific considerations for archaeological sites are mentioned, as the STORM pilot sites are mostly in this typology of heritage. "Archaeological sites may best be understood to be in their present condition as the result of past disasters or neglect, and so their care should be seen in a long-term perspective" through the following requirements in the planning process (Stovel 1998, 31 and 32):

- Considering the site security (e.g. vandalism and arson, looting and illicit removal of heritage objects or fragments, and safety of visitors and residents);
- Respecting the heritage values of a site and its various constituent elements in ways which can guide response during times of disaster. Documentary values and presentation values need to be distinguished; it should clarify existing site integrity and it should focus on remedial action in appropriate ways to maintain desired integrity and authenticity;
- Ensuring the principles contained in the conservation documents, e.g. the UNESCO Recommendations for Archaeological Sites (New Delhi 1956, but currently under revision); the 1972 Council of Europe

Convention on the Protection of the Archaeological Heritage; and the ICOMOS Charter and guidelines for Archaeological Heritage Management (Lausanne 1990; Salalah 2017).

3.6. Regular monitoring and maintenance of sites

In many cases, climate change does not necessarily cause new problems, but rather emphasises long-standing preservation issues (Cassar 2005). This highlights the importance of continuous monitoring and well-considered maintenance of the cultural heritage objects and structures in order to improve their stability. However, oftentimes, funding mainly becomes available for repairs post-disaster or for capital works (Cassar 2005), and the "lack of funds and absence of laws explicitly requiring specific maintenance operations to be carried out often means that these are considered to be of lesser importance". To stress the importance of regular monitoring and maintenance, this is included as a separate risk treatment strategy in the STORM framework.

An important point in terms of risk prevention related to this step is setting up a monitoring program, aimed at the early detection of damage or change to the heritage asset, as well as changes in the environment for a discussion related to monitoring of environmental changes that might have to be addressed. Documentation of the monitoring as well as maintenance results should be performed in a fully functional online heritage information system in order to have all information available in a single database (Cassar 2005).

Maintenance "means the continuous protective care of a place" (Australia ICOMOS 2013), hence also the monitoring and maintenance of risk-reduction infrastructures and related measures are taken to fall in this category. The regular monitoring and maintenance of hazard- and/or exposure-reduction measures are key to guarantee their proper functioning, and therefore for the protection of the cultural heritage site. Regular inspection aids the timely discovery of infrastructure malfunction allowing for immediate reparation, and regular maintenance ensures the infrastructure functions as intended.

Although under this strategy the monitoring and maintenance of both cultural heritage and infrastructure are considered, measures related to the heritage assets should clearly be distinguished from those related to the general cleaning, landscaping or other non-heritage related maintenance of the site. In addition, when considering key actors to plan and perform such measures, this distinction should be addressed.

3.7. Non-structural strategies

Non-structural strategies aim at a reduction of the vulnerability of cultural heritage to natural hazards and climate change through promoting the coping and adaptive capacity of the institutional and management system. One key method is raising risk awareness among engaged organisations and stakeholders. A lack of awareness poses barriers to an effective adaptation to natural hazards and climate change (e.g. Fatoric and Seekamp 2017 and references therein), and hence increasing the risk awareness is a starting point for the development and implementation of an adequate risk management system.

Admittedly, capacity building and training should be addressed through cross-disciplinary educational and training programs among a wide range of stakeholders engaged in the planning and implementation of risk preparedness strategies. To fulfil this, promoting legal frameworks and multi-sectoral cooperation becomes important. To address the maintenance issues raised under regular monitoring and maintenance of the site, again the cross-disciplinary education and training programs in basic maintenance procedures for staff and contractors should be highlighted as an example of multi-sectoral cooperation. Furthermore, it is recommended that instead of funding only becoming available for repairs post-disaster or for capital works, good maintenance should be promoted by maintenance grants. To enable sustainable, forward planning, it is important that this funding would be available long term, requiring a legal framework supporting this approach. Here, synergies with the insurance industry could be sought, and tax incentives for sustainable maintenance could be considered (Cassar 2005).

As the impacts of climate change are location-specific and very diverse across the EU territory, and hence adaptation measures will have to be defined locally, the EU policy encourages Member States to develop their own comprehensive climate adaptation plans (National Adaptation Strategies, NAS), covering local to national levels, in coordination with their neighbours (Delbeke and Vis 2016; EU 2013). Many EU Member States have incorporated climate change policies and legislation, although cultural heritage is generally not addressed. An exception is e.g. Italy, where cultural heritage was explicitly addressed throughout the NAS (Bonazza 2018), showing that cultural heritage could be incorporated in these climate change adaptation frameworks.

3.8. Risk preparedness and emergency response

Preparedness is "The knowledge and capacities developed by governments, professional response and recovery organizations, communities and individuals to effectively anticipate, respond to, and recover from, the impacts of likely, imminent or current hazard events or conditions" (UNISDR 2009). Risk preparedness particularly aims to prepare a response plan in advance of a disaster to guide how to act during an emergency situation. Emergency or disaster response, on the other hand, occurs post-disaster. "Disaster response is predominantly focused on immediate and short-term needs and is sometimes called 'disaster relief'. The division between this response stage and the subsequent recovery stage is not clear-cut. Some response actions […] may extend well into the recovery stage" (UNISDR 2009).

After the occurrence of a major accident, the first stages are characterised by a high level of chaos. At these times, cultural heritage can be exposed to inappropriate (but well-meaning), or even deliberately offensive, actions damaging the site. Recognising the above challenge, specific emergency considerations for cultural heritage need to be developed. 'Cultural First Aid' is a term coined by ICCROM, drawing parallels to the field of medicine, where "first aid generally consists of some simple, often life-saving techniques that most people can be trained to perform with minimal equipment". (Nordqvist 2016). ICCROM refers to 'Cultural First Aid' as "initial actions taken to secure and stabilise endangered cultural heritage during a complex emergency", based on the idea that "rapid response can help contain damage to cultural heritage" (ICCROM & Smithsonian Institution 2016). Such emergency situations demand protection measures that are easy to implement, and, mostly, do not require sophisticated equipment or special conservation materials (ICCROM & Smithsonian Institution 2016). Within the STORM framework, risk preparedness and emergency response include the following steps:

- Heritage documentation constituting a base for developing the response plan;
- Emergency response plan including asset evacuation and salvage;
- Condition (damage) assessment and post-disaster documentation; and
- Stabilisation and protection of the damaged structures.

As mentioned by Stovel (1998, 27), "The effectiveness of recovery measures is in large part a function of measures planned and implemented in advance of the disaster. The quality of mitigation activities, focused on reconstruction, for example, depends on the quality of documentation prepared for the building before loss". As a result, heritage documentation constituting a base for developing the response plan is highly relevant to take into account in the preparedness phase. ICCROM & Smithsonian Institution (2016) has developed a framework of action for providing first aid to cultural heritage in the emergency situation that involves the following three steps:

- Context analysis, which includes recognising the anthropogenic or natural hazard, risk factors, safety and security risks to the emergency teams and other stakeholders at site. This is highly connected to the pre-disaster risk assessment and mitigation measures;
- On-site survey for conducting a first assessment of the damage, and the risks the affected cultural heritage is exposed to that could lead to more damage and hamper recovery. This will help determine the immediate needs at site and prioritise for intervention;
- Security and stabilisation actions to stabilise the endangered cultural heritage sites, buildings and collections. The outcomes of this step can develop a full damage assessment report, which includes needs as well as costs for the recovery of tangible cultural heritage. This step comprises different actions, including security, evacuation, salvage, triage and stabilization, and temporary storage.

3.9. Recovery plan

Post-disaster recovery includes "Decisions and actions aimed at restoring or improving livelihoods, health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development, including build back better to avoid or reduce future disaster risk" (UNISDR 2015a).

As mentioned, the effectiveness of recovery measures increases when these measures are implemented prior to disaster, and the success of mitigation activities depends on the quality of the documentation prepared before the occurrence of any loss (Stovel 1998). Stovel emphasises some essential principles, which need to be considered during the recovery planning and process, including (Stovel 1998, 20):

- Preparedness requirements should be met in heritage buildings by means which will have least impact on heritage values;
- Heritage properties, their significant attributes and the disaster-response history of the property should be clearly documented as a basis for appropriate disaster planning, response and recovery;
- Securing heritage features should be a high priority during emergencies;
- Following a disaster, every effort should be made to ensure the retention and repair of structures or features that have suffered damage or loss; and

- Conservation principles should be integrated where appropriate in all phases of disaster planning, response and recovery (Stovel 1998, 20).

Within the STORM framework, the recovery plan phase comprises the following steps:
- Preparing repair and reconstruction plans; and
- Upgrading the risk management cycle.

Based on the Condition (damage) assessment and post-disaster documentation, the process of post-disaster recovery planning and action takes place. The post-disaster repair and reconstruction plans should prioritise actions based on:
- Elements of the site which are at highest risk due to the disaster;
- Elements which are of the highest significance and are the most vulnerable;
- Elements that have suffered the greatest damage but are retrievable;
- Relatively stable aspects; and
- Irretrievably damaged elements (NDMA 2017).

Post-disaster recovery needs to meet the heritage conservation principles and avoid additional impacts to the structures and heritage values. Prior to implementation, these plans oftentimes have to be approved by the relevant (local) authorities.

At the same time, it has to be kept in mind that the recovery process can provide an opportunity to promote future risk management of cultural heritage sites. The post-disaster documentation and assessment helps professionals to better understand susceptible elements, structural performance, and multiple risks that have not been addressed in the previous risk management plan (NDMA, 2017). Hence, upgrading the risk management cycle based on an analysis of the course of events in the emergency timeframe is important to increase resilience.

4. STORM Risk Assessment and Management Tool

The STORM Risk Assessment and Management (RA&M) Tool aims to assist site managers and experts to assess the level of risks in different areas of the site and determine site-specific strategies to mitigate the risk associated with natural hazards and climate change. The Tool has been implemented according to the Risk Assessment and Management Methodology.

As presented in Figure 3, the RA&M tool comprises three major phases of Site Hazard Assessment, Risk Assessment, and Risk Management Strategies. The Hazard Identification step allows the user to identify and analyse hazards potentially affecting a pilot site. The Risk Assessment module, as mentioned in the risk assessment methodology, involves Hazard Analysis, Exposure Analysis, Vulnerability analysis, Risk Identification, and Risk Analysis. The Risk Management Strategies module (Figure 4) categorizes each site's area per level of priority concerning a specific hazard and enables the user to define risk treatment strategies and associated measures in response to each hazard. Apart from the semi-quantitative and qualitative ranking scales, a colour coding system is applied in the assessment process to better illustrate the priority levels for a wide range of end-users.

The Tool provides a shared understanding of the risk data and assessment processes among the multiple stakeholders engaged in the protection of cultural heritage sites to facilitate the decision-making process. The STORM RA&M Tool will enable the users to identify and analyse the natural hazards affecting a heritage site, assess the value of areas of the site, analyse the vulnerability of the site, measure the level of risks in different areas of the site, and finally determine site-specific strategies to mitigate the risk associated with each hazard.

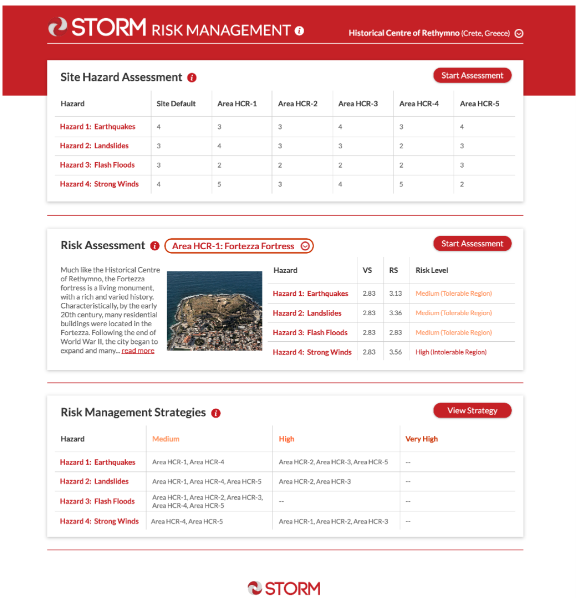

Figure 3. Risk Assessment and Management tool: an example of the home page.

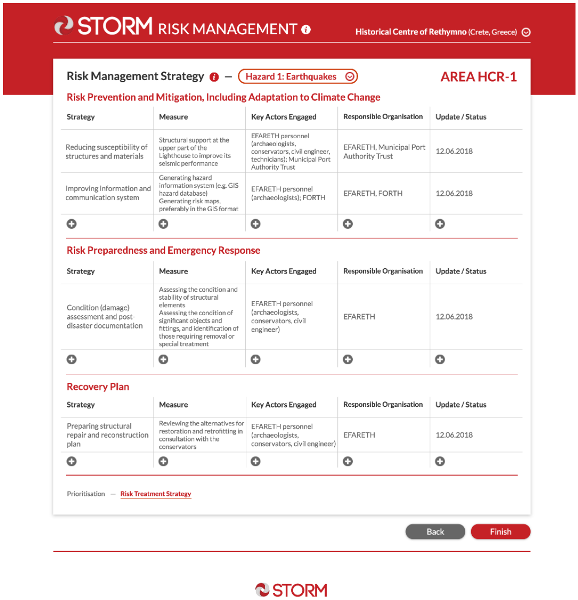

Figure 4. Risk Assessment and Management tool: an example of the page of Risk Management Strategies.

5. Conclusion

The proposed procedure of risk assessment provides a clear perception of the risk elements to develop a site-specific risk reduction plan through avoiding or reducing the identified hazards, reducing the structural susceptibility, promoting the coping and adaptive capacity, and increasing the effectiveness of emergency response using the GIS hazard and risk maps. The risk assessment further assists the decision-making process by providing the necessary information to understand which risks need treatment strategies and on which level.

In the development of risk management, actions associated with the areas of a site are prioritised based on the output of the risk assessment, by considering risk management for those areas with risks that fall in the intolerable and tolerable region. In case of structural risk reduction or first aid measures, the risk management actions may be hazard-dependent and in the implementation of the risk treatment plan, the various relevant hazard as well as their expected impact on the cultural heritage, have to be considered separately. Based on the presented guidelines, risk treatment plans have been developed for the five STORM pilot sites: the Historical Centre of Rethymno, the Mellor Heritage Project, the Roman Ruins of Tróia, the Baths of Diocletian, and the Ancient City of Ephesus; supported by the output of the risk assessment, the relevant hazards were determined for all site areas individually and their associated expected impacts on the cultural heritage were described.

In STORM, a Risk Management tool was developed to guide cultural heritage responsible through the risk assessment and risk management process. The information collected in the tool provides a shared understanding among the multiple stakeholders engaged in the protection of sites, and facilitates the decision-making process to determine the level of risk in different areas of the sites. Accordingly, risk mitigation, preparedness and recovery strategies can be developed in response to the potential hazards.

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3. Advanced sensing and information technologies for timely artefact diagnosis

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Becoming increasingly important, the artefact diagnosis occupies a special place in the diverse area of sensing technologies used in the non-destructive evaluation. Significant recent progress in materials science made it possible to improve the key characteristics of the involved sensors, especially, the resolution, defect discrimination capability, and the measurement speed and even extend the measuring principles to new physical phenomena. The chapter describes a plethora of the most significant and promising non-destructive methods that have been used in the STORM project activities, which were chosen at the initial stage of the Project (workpackage 1) and have undergone significant development towards higher technology readiness levels during the later stages, especially within the framework of workpackage 4.

1. Assessing structural performance by vibration

Computation of the structural performance of historic buildings is an important step for the timely diagnosis of artefacts. It can be used to improve the earthquake performance of structures by use of innovative technologies and materials, hence, for the purpose of earthquake risk mitigation. Advanced sensing and information technologies constitute the main components of measuring the performance of structures. This section provides an overview of both empirical and analytical methods for assessing structural performance by vibration with a particular focus on historic structures.

Ambient vibration testing is an empirical method for assessing structural performance. It is also an important element of structural studies of complex systems. It is used to identify the dynamic characteristics of structures, such as mode shapes, frequencies and damping ratios, hence, in turn, helps to calibrate the numerical structural models. Low amplitude vibrations caused by daily-life sources such as traffic, human noise, wind etc. can be measured by very sensitive vibration sensors called seismometers. Measurements are generally made by a temporary deployment of seismometers or accelerometers. The testing system usually consists of an array of interconnected devices, which are placed in such a way throughout a structure to give the optimum information for its dynamic structural response. The method has been widely used by many researchers, usually for taking short term measurements from buildings, bridges and historic structures. It is particularly effective for determining the properties of long-period (flexible) structures — like bell towers or chimneys — in linearly elastic ranges, see, e.g., (Lopes *et al.* 2009; Binda *et al.* 2002; Cakir *et al.* 2016). Since the structure analysed in Ephesus is very rigid, the ambient data provided from the site is mostly noise.

Forced vibration testing is based on assessing the dynamic properties of a building by producing man-made vibrations. Such tests are especially used when the signal to noise ratio is low so as to increase the signal level. The source of vibration is usually a unit with a rotating mass that is mounted on the top of a structure during testing. Such tests are not suitable for historic structures as can cause accidental damage in the structure due to brittle nature of historic elements. Alternatively, heavy vehicles may be used to produce impact loads on the ground surface near the structure. A series of forced vibration tests were performed to measure the structural vibrations of Roman remains in Ephesus. The sensor locations and to loading point is shown in Figure 1. Data from a rigid rocking frame were used to calibrate the numerical model of the structure. The overturning thresholds of the structure were calculated.

Strong Motion (SM) Monitoring Arrays: Structural Health Monitoring (SHM) networks provide real-time vibrational characteristics of historical buildings and projections regarding their future earthquake performance under a possible major earthquake. The structural monitoring networks record the dynam-

Figure 1. Sensor locations and truck loading nearby the rigid rocking frame.

ic motions of the structures continuously, and the data are transmitted in real time to the monitoring centre. SM arrays can be used to identify structural damages and nonlinear behaviour of structures due to earthquakes.

SHM of historic structures for emergency response: Damage estimation using recorded vibrations can be performed based on different algorithms. These algorithms relate dominant frequencies with structural stiffness, whose change can, in turn, be correlated with damage. Measured relative displacements at the top of a building can be checked against thresh-hold displacements for different damage levels. Such arrays are generally permanently installed, therefore the long term variations in the structural characteristics can be measured.

Within the STORM project, two high precision force balance (GEOSIG) accelerometers and two low-cost mem sensors were installed at the base and top of the structure, respectively. An automatic near real-time warning system was also set up to inform authorities about the possible amount of damage in the structure immediately after the earthquake. For this purpose, different acceleration threshold levels were determined by performing analytical studies.

Digital signal processing (DSP) algorithm was adopted to a MATLAB (*https://www.mathworks.com/*) code to calculate the dynamic properties of the stone blocks during earthquakes. Basic signal processing tools such as baseline correction, band-pass filtering, windowing, Fast Fourier Transform (FFT) and Spectral ratios of the input and output signals from up and down sensors were used. The locations of sensors and recorded- real time processed data during the M=2.1 event earthquake are shown in Figure 2.

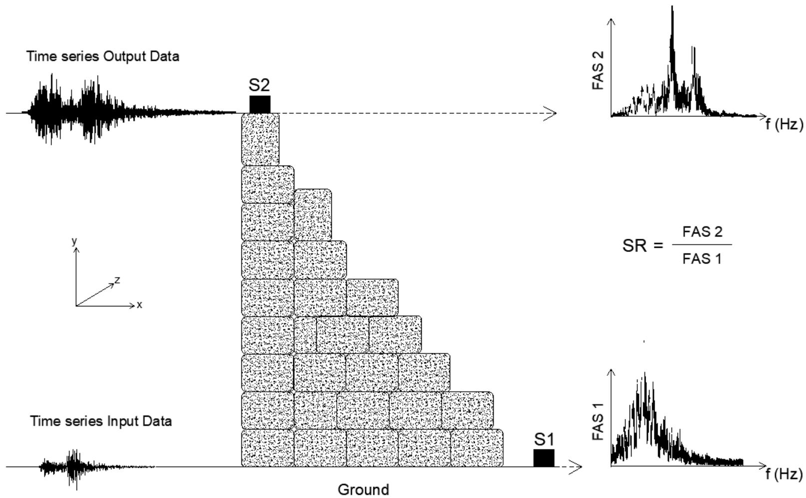


Figure 2. Sensor locations and recorded/real time processed data during a 2.1-magnitude earthquake in Izmir.

Since last decades, Boğaziçi University (DEE-KOERI) has been operating a significant number of structural monitoring networks in a large number of historical structures (i.e., mosques, minarets, and museums) in Istanbul, Kaya (2015) has developed new real-time software to be used in SHM to define the modal characteristics of Hagia Sophia by real-time tools and techniques. Force balance accelerometers where installed at different locations of the structure. (Erdik 2014; Çaktı, Safak 2018). The network was established immediately after the 1999 Kocaeli earthquake and before the 7.2-magnitude 1999 Duzce earthquake, therefore strong-motion data were available.

The ultimate aim of the STORM project is to establish a global integrated platform to monitor historic sites. It is expected that, in the near future, all such independent monitoring systems be integrated into the STORM platform to establish a global monitoring platform for different cultural heritage sites.

Analytical Assessment of Structural Performance: It is usually difficult to determine the seismic behaviour of historical structures by the use of common engineering methods. The response of complex historical masonry structures requires the use of finite element analysis. Numerical modelling depends on the solution of dynamic equations of equilibrium equations through satisfying displacement compatibilities. The mass, stiffness and energy dissipation properties of the structure and the input dynamic excitation needs to be determined or approximated. The constitutive relationships (i.e. the stress-strain relationship of the material) should be determined. Dynamic equations of equilibrium is calculated by equating the internal member forces and stresses with the applied loads and displacements. Computation of the seismic response of structures involve dynamic (loads change in time) and nonlinear (loaded beyond elastic limit) approaches. Linear dynamic analysis involve response spectrum analyses in which the dynamic effects are included but material nonlinearity is ignored. Nonlinear static involves the pushover analysis in which the dynamic effects are ignored but the material nonlinearity is included. Nonlinear time history analyses involve both dynamic effects and material nonlinearity. Depending on the complexity of the model, one of these approaches can be used to assess the structural performance of the structure due to ground excitations.

Numerical modelling is the most preferred method for the masonry structures. In order to solve the engineering problems correctly, it is essential that the numerical model is established correctly. The modelling depends on the solution of dynamic equations of equilibrium equations through satisfying displacement compatibilities. Different material models such as rigid, micro, macro, discrete and continuum, can be considered to analyse different types of structures (Erdik 2019). Masonry structures are composed of different elements with different shapes and properties. Their materials can be classified as continuous or discrete.

Continuum models treat masonry as combination of bricks or stones and mortar. Some examples of continuum modelling are shown in Figure 3, where the wall oscillate in the stacked mode during low amplitude vibrations. The continuum modelling will fail to show the actual behaviour of the structures after the onset of sliding. Therefore, the post elastic response of the structure was studied by discrete element modelling.

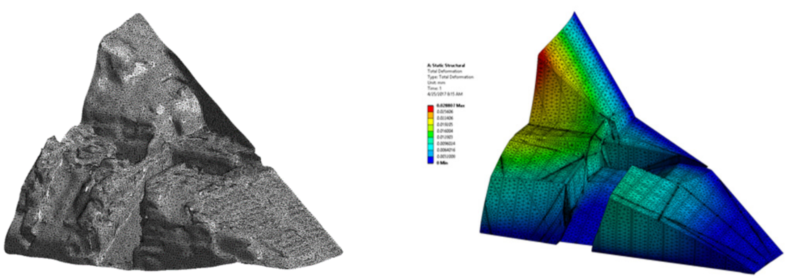


Figure 3. Continuum modelling for masonry structures.

Discrete models consist of large discrete elastic elements where the contact surface between them is described by a friction law. The sliding behaviour of the stone blocks in Ephesus was modelled by discrete elements, corresponding model is illustrated in Figure 4. Using the general purpose finite elements (FE) program (ANSYS 2018), possible damage-related modes are calculated for different earthquake loads.

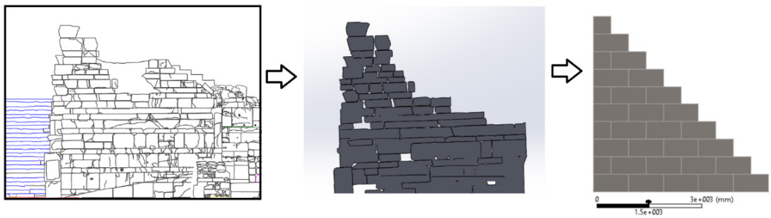


Figure 4. Discrete modelling of the Ephesus walls and possible modes of failure based on different earthquake levels.

Performance based assessment (PBA) is a new stream line of research on heritage buildings to assess the structural performance. Evaluation of seismic performance and damage for existing historical structures has been mentioned in many standards (ASCE 41, 2006; EC8-3, 2005). The state of the art procedures for the seismic evaluation of these structures is usually carried out by linear or nonlinear procedures. ASCE 41 (2006) is applicable to all types of buildings and structural materials (concrete, steel or masonry) for seismic rehabilitation, i.e. it is not solely intended to be used for historical structures. The idea is that a reliable assessment procedure of heritage buildings requires the assessment of structural as well as the architectonic and artistic assets contained in them. Modelling and verification requires PBA of the structure which suggests pushover analysis be used until a target displacement is reached according to the selected performance level (PL).

Risk mitigation: Earthquakes can cause direct loss and amplify existing damage from past earthquakes and settlements. Remedial and retrofit measures for earthquake action should ensure continuity of structural elements within the structure and improvement of structural performance (seismic capacity), hence, should aim risk mitigation by improving the performance of the structure to future earthquakes. For ordinary buildings the risk objective is to avoid the total collapse, hence, to provide of the building but for historic structures some additional criteria should apply due to architectural and artistic concerns.

Stabilisation and Retrofit are the remedial actions to increase the performance of structures. The retrofit techniques should be selected on the basis structural engineering and material sciences supported by historical analysis. Any intervention should be reversible and as little intrusive as possible (Erdik 2019).

2. Crack monitoring

The condition assessment of the fortification walls of the Fortezza Fortress, as well as that of the Episcopal Mansion within the fortress, is under development through the STORM technologies and services. One of the methods employed for the assessment of structural stability is that of crack monitoring.

The Structural Health Monitoring (SHM) methodology (Sohn 2007; Lorenzoni 2013; Lorenzoni *et al*. 2016; Modena *et al*. 2016) selected for the assessment of the Fortezza fortress was the continuous crack monitoring of 4 different existing cracks of the structure. More specifically, three different cracks of the fortress fortification walls were selected as representative and necessary to study, one in the south wall of St Elias Bastion, one the south wall of St Luca Bastion and one the east wall of St Paul Bastion) and a vertical crack on a load bearing west wall of the Episcopal mansion, a building inside the fortress. The criteria for their selection were their relatively large width and their existence in critical points for the structural integrity of the monument.

In the past, the crack monitoring was carried out by the Ephorate of Antiquities of Rethymno in an empirical manner, via regular macroscopic inspections. One characteristic of the empirical crack assessment was the use of glass slide placed within the crack and secured by the mortar in one of its sides. In the case where a crack displacement was taking place, the glass slide would be found displaced or detached. However, this method did not provide any kind of accuracy or information relevant to the extent of displacement. The assessment of structural stability was also carried out by a civil engineer of the EFARETH, in order to proceed with restoration works where necessary. However, no continuous monitoring was employed before the STORM project activity.

The establishment of a system of crack sensors provides measurements in a continuous manner with accuracy and precision qualities that can further be used in the analysis of the causes of damage and the factors influencing the degree of damage. The crack meters installed in the selected areas since July 2017 are real-time sensors that monitor continuously wall crack linear displacements and record data every 2 hours. It is a system of 4 crack meters -

loggers, one Radio Frequency (RF) antenna and one repeater that strengthens the RF signal in order to reach the area of the local server.

The data will be further utilized through the SHM methodology developed by two private civil engineers that collaborate with EFARETH for the specific task. Data (crack displacements) are collected for one year in order to cover one environmental cycle (4 seasons) together with other environmental quantities such as the temperature of every crack meter during linear displacement.

The weather data for the external temperature and air humidity recorded through the weather stations will be also used in the interpretation of the crack behaviour.

The expected outcome is a statistical model of crack displacement which will allow the prediction of extreme values of the crack. The model is still under construction but the methodology has already been developed by the data of the first three months of monitoring. The expected date of model assessment is expected during spring of 2019, after the completion of the environmental cycle.

The use of the statistical model of crack displacement and the interpretation of its outcomes will be interpreted in combination with the analytical outcomes of Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) in order to link crack behaviour to the impact of soil infill and moisture content behind the fortification walls. Doing so the condition assessment of the fortification walls will be done in a holistic approach that will provide targeted restoration actions.

3. Electrical resistivity tomography

3.1. Survey design and data collection

The purpose of the Electrical Resistivity Tomography (ERT) method is to extract quantitative information on the resistivity of the subsurface, both vertically and horizontally, along specific transects. Such kind of experiments were deployed on the walls of Fortezza castle in Rethymno to monitor cracks on the walls and other deficiencies related to the structural integrity of the fortification walls. ERT tries to address questions related to the thickness of the walls, the identification of the vertical stratigraphy in the interior of the fortress from the walls through the correlation of the measured resistivity values with the different soil formations in relation to how they behave under different climatic conditions. The temporal variations of the subsurface resistivity, which can be recorded through time lapse monitoring (4D ERT measurements), can help towards the identification of moisture flow paths via the calculation of the percentages of resistivity decrease.

ERT was employed in St Paul and St Lucas Bastions within a time period of eleven months, between April 2017 and February 2018. Custom made multimode cables with the electrical wire outputs were constructed and laid along vertical profiles, having a length of 11.5m and 10.5m, on the respective walls of St Paul and St Lucas Bastions, see Figure 5 (a,b). Each wire output was connected to small metal nails that were inserted carefully in small openings of the walls in a constant separation of 0.5m, as shown in Figure 5 (c). Thus, the profiles in the St Paul and St Lucas Bastions had 24 and 23 sensors (electrodes) respectively. In order to increase the effective surface and decrease the contact resistance, each nail was covered with wet bentonite mud to help the current penetration into the wall, see Figure 5 (d). The lay out of the cables was accomplished with the aid of experienced climbers that hiked along the walls making the necessary actions to firmly secure the cable and connect the wires with the respective nails.

Along the Fortezza walls, the dipole-dipole electrode configuration was used since it exhibits the highest vertical resolution. The basic electrode distance (*a*) was 0.5 m along the profiles in St Paul and St Lucas Bastions and the same electrode measurement protocol was used in all the profiles. Multiple combinations of *N* separations (N_{sep}=1-8) were used, defined as the distance between the potential and current dipoles, and unit electrode spacing (1*a*-3*a*) in order to increase the signal to noise ratio and map the deeper stratigraphy.

The line in St Paul Bastion was monitored during four different time phases in April, July, October 2017 and February 2018. The time-lapse ERT measurements were repeated during May, July and October 2017 along the profile of St Luca Bastion. The specific survey schedule managed to complete the requirements and specifications of the 4-D ERT survey that were established at the launch of the project, with some minor modifications on the final schedule.

Two different kinds of automated resistivity meters were used to collect the field resistivity measurements. The Syscal SYSCAL Pro Switch is a compact electrical resistivity meter that comprises a transmitter, a receiver and a switching units placed in a single housing. The measurements are carried out automatically (output voltage, stacking number, quality factor) after a selection of limit values by the operator and are stored in the internal memory. The ten channels of the system permit to carry out up to 10 readings at the same time for a high spatial and time efficiency and time-lapse monitoring.

Figure 5. Layout of the vertical ERT line along the walls of the St Paul (a) and St Lucas (b) Bastions. Details of the connection between the metal nail and the wire output of the custom made multimode cable (c). Covering the metal nail with wet bentonite to decrease the contact resistance (d). Arrows indicate the direction of the ERT profiles.

The earth resistivity meter 4-point light 10W is considered as a high precision instrument with a resolution of 0.1 μV and accuracy better that 0.1% used for the determination of the soil resistivity and the water content of soils and rocks. The instrument produces constant output currents (from 1 μA to 100 mA), independent of the contact resistance of the electrodes in a spectrum of 16 different frequencies (0.26 to 30 Hz).

A systematic way was followed for the pre-processing of the raw tomographic data. Initially the measurements having a potential value of two orders of magnitude more than the resolution of the instrument were removed from the data sets. In practice, this strategy allowed us to keep all the data with potential values more than 100 μV. Additional de-peaking filters were also applied to the data by removing those with high geometric factor and low injection currents and finally s exporting the most informative resistivity values (i.e. normalized potential values based on the current intensity multiplied with the geometric factor). The specific pre-processing approach assessed and validated the high data quality for all the collected ERT measurements. Among the processing options, the standard smoothness-constrained least squares method attempted to minimize the square of the changes (L_2 norm) in the model resistivity or resistivity correction values. This resulted on a model that has a smooth variation either in the resistivity values or in the perturbation resistivity vector. This inversion approach is more suitable in cases where we face relatively smooth resistivity variations. The monitoring ERT from the same area were processed within a 4-D context to recover the spatial and temporal variations of the subsurface resistivity (Kim *et al.* 2009).

3.2. Individual and comparative data analysis

3.2.1. St Paul Bastion

The 2D resistivity inversion model of the ERT data from the 26th of April 2017 provided the basis for describing the stratigraphy along the plane located vertically to the wall. The specific model also comprised the base for monitoring the spatial and temporal variations of the subsurface resistivity. The respective 2D vertical section shows a stratified medium down to a depth of about 2.5 m from the surface of the wall. The vertical wall is registered as a resistive feature, with values of the specific electrical resistance ranging from 150 to 800 Ω·m, and shows a variable thickness of 0.25-0.6 m. The silty and sandy filling material inside the wall appears with resistivity values of 5-50 Ω·m and probably exhibits increased moisture. The isolated targets towards the two edges of the section, with resistivity values 60-200 Ω·m, are probably related to buried retaining walls. The inspection of the respective 2D resistivity models from July 20th and October 21st, 2017 verified the above conclusions (Figure 6).

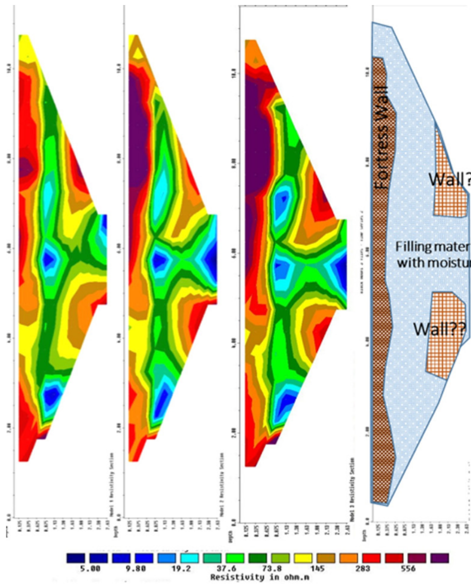


Figure 6. From left to right: 2D inversion resistivity models for April, July, October 2017 and interpretation of the geophysical anomalies for the line of St Paul Bastion.

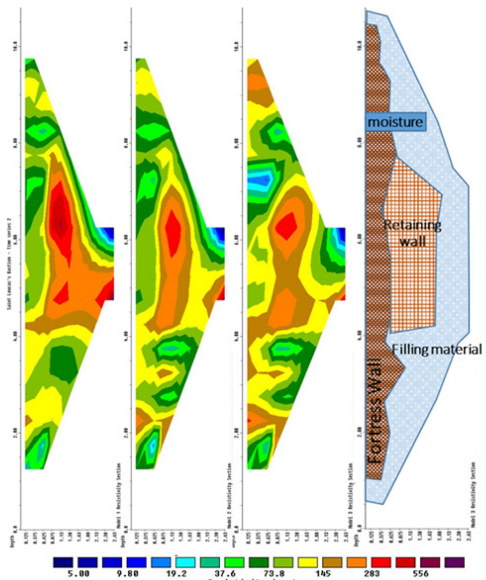


Figure 7. From left to right: 2D inversion resistivity models for May, July, October 2017 and interpretation of the geophysical anomalies for the line of St Lucas Bastion.

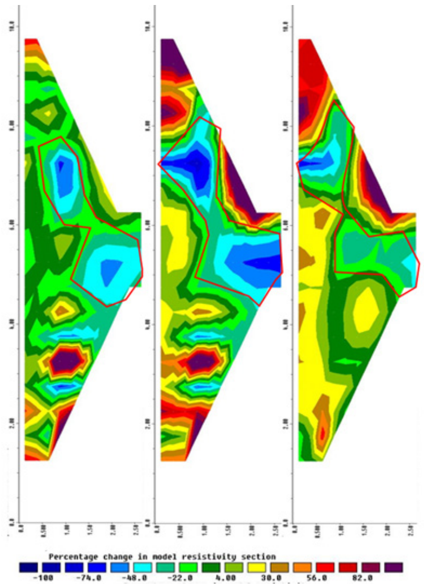


Figure 8. From left to right: Percentage change in model resistivity values between May–July 2017, May–October 2017 and July–October 2017 for the line in Saint Lucass's Bastion. The red polygons indicate the area of increased moisture during the monitoring period.

3.2.2. St Lucas Bastion

The superficial layer along the line of the Bastion of St Lucas, corresponding to the fortress wall, seems to appear more conductive with regard to the respective layer in the line of St Paul Bastion. More specifically the wall is registered with resistivity values of 70-150 Ω·m giving a variable thickness of 0.2-0.6 m, assuming similar thickness for the wall as in case of St Paul Bastion. The conductive signature of the wall in this case is attributed to the increased moisture retained within the filling soil material. This is also more obvious along the vertical distance of 8.0-8.5 m where a pronounced superficial conductive area is shown in the resistivity section. Along the vertical distance of 4.5-7.5 m the resistivity sections of all the time periods outline a resistive region (150-800 Ω·m) of about 1.0-1.3 m thick that is possible related to a retaining wall (Figure 7).

The percentage change of the resistivity values between the different time phases shows a resistivity decrease of more than 50% in the central and upper part of the section, as outlined with the respective red polygons on the sections. This comprises a significant verification of increased moisture due to water flow in the specific parts of the wall, which had been indirectly noticed from the low contact resistances values of the electrodes during the field data collection. At the same time, the almost 30% resistivity increase on the top part of the section is related to loss of moisture on the wall, since the measurements were conducted during dry period (Figure 8).

3.3. Conclusions

The ERT method was employed along individual lines, which were laid out in two different areas on the walls of Fortezza (St Paul and St Lucas Bastions). The aim of the specific survey was to extract the stratigraphy of the sediments in the interior of the walls, to map the thickness of the walls, to locate sections of increased moisture and define paths of moisture flow though resistivity monitoring. The 4D ERT monitoring experiments were quite promising and fulfilled the initial expectations in signifying the efficiency of the method in assessing the integrity of standing cultural monuments. ERT method can be used in tandem to GPR for the efficiently monitoring of monumental architecture indicating areas of structural deficiency due to natural incidences.

4. Ground penetrating radar

Ground-penetrating radar (GPR) is a geophysical technology that uses radar to explore the subsurface. Archaeologists have employed this technical procedure for many years and it is also common in other scientific fields such as geology, environmental studies, and even engineering. Within the STORM project, the GPR technology was employed at the Fortezza of Rethymno and Baths of Diocletian pilot sites. Below we discuss the peculiarities of its application for these two case studies.

4.1. Hazard monitoring experiments

The area of interest for the GPR hazard monitoring experiments at Fortezza of Rethymno pilot case study is located at St Lucas Bastion. The survey focused on a wall, part of which that part of it collapsed at the end of spring 2017 (Figure 9a to Figure 9b). The construction consists of a double wall. A large crack extends vertically from the top to the bottom of the wall and is located approximately on the middle of it (Figure 9c). This particular section of the wall was used as our testing monitor site for the experiments of the GPR in an effort to test its capability to detect cracks and estimate the wall thickness contributing to the avoidance of collapse incidences in the future. For the purposes of STORM project, a series of data were collected every 2 to 3 months. A GPR system employing Sensors& Software NOGGIN plus smart cart equipped with 250 and 500 MHz antennas was employed during the experimental phase of the project. The combination of the two antennas provided a more detailed mapping regarding the inner structure of the wall. For every data collection phase, both antennas were used on the wall, where several lines were collected on both sides in order to examine a) whether cracks can be detected/register or not in the acquired GPR radargrams and b) if there are any changes noticed in the wall thickness (Figure 9). Besides the GPR lines collected on the wall of the Bastion, a GPR survey grid was also performed at the area extending at the foot of the wall using the 250 MHz antenna aiming to the study of the subsurface.

To assist the interpretation and to establish a beneficial data processing workflow, a synthetic approach was followed using the software gprMax (Giannopoulos 2005). Representative models were created with the aim to simulate the crack and the geometry of the case study at Fortezza Rethymno. Three discontinuities were introduced to the models as planes of air: a “V” shape discontinuity with maximum width of 4cm and minimum width of 1cm; a discontinuity of 2cm width representing an interior crack at the boundary of the two walls; a discontinuity of 2cm width that extends along the overall geometry (Figure 10a).

Figure 9. Details of the survey area of St Lucas Bastion: a) location of the survey grid named as GRID1, b) scan line at the front wall labelled as WALL A, c) scan line at the back of the wall, labelled as WALL B, d) the width of both walls is presented; e) orientation of the collected scans at WALL B with both antennas; f) orientation of the collected lines at the survey grid and g) orientation of the collected lines at WALL A.

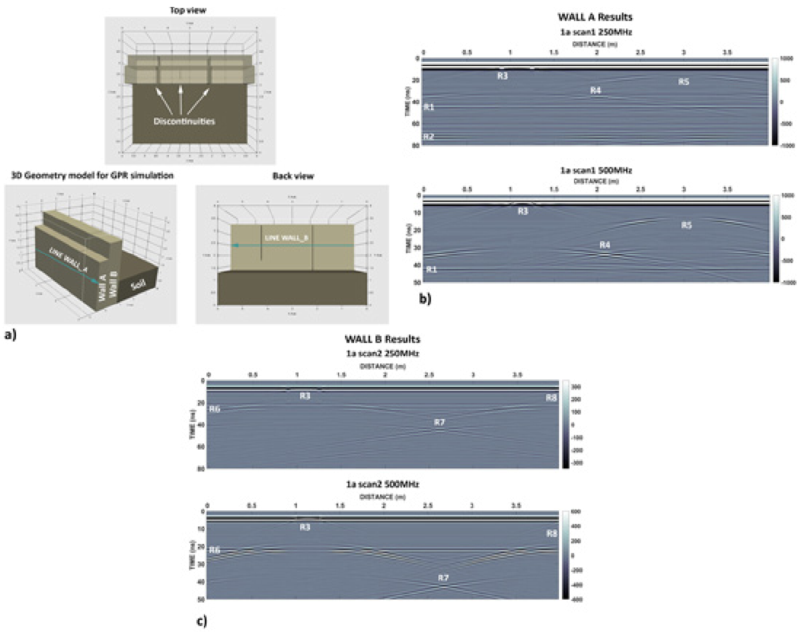


Figure 10. The synthetic approach created with gprMax where in a) the different views of the geometry of model 1 and the direction of the scan lines at the front and back side of the wall are shown, in b) the resulted synthetic Bscans derived from WALL A Model 1a for the frequencies of 250 MHz (top) and 500 MHz (bottom) are indicated and in c) the synthetic Bscans from WALL B Model 1a for the frequencies of 250 MHz (top) and 500 MHz (bottom) are presented.

For each of the above geometries, the simulations were performed using Hertzian dipole sources of 250 and 500 MHz central frequencies on both sides of the double wall. To simulate a GPR B-scan from a common offset mode, the source and receiver are placed accordingly to the model and a series of traces simulations are executed for a step that is defined for both the receiver and the EM source. Starting with the section at the front side of the structure (WALL A results in Figure 10b), the boundary between the two walls appears as a horizontal reflector (R1) in both 250 and 500 MHz results. The cracks create reflections of hyperbolic form. The 2-cm width appears to be the minimum size that both antennas can detect, as R3 is visible but the pick of R5 is not. R4 responds to the inner structure discontinuation. In the case of 250 MHz measurements, an additional horizontal reflector appears that is related with the soil at the foot of WALL B. Similarly, the results obtained from the simulated lines at the back side of the structure for both frequencies present the horizontal reflector, R6, that is identified as the outer boundary of WALL B. The artificial fault, R3, is better shown with the 500MHz frequency antenna (WALL B results in Figure 10c). Overall, the wall thickness can be easily detected by both frequencies, while reflections from cracks and other discontinuations of small size are more challenging.

Furthermore, different processing workflows were also examined on the resulted synthetic Bscans in order to establish the most beneficial one. The filters and corrections involved are dewow, bandpass filter, different types of gain and background removal. It emerged that two different workflows should applied: One that aims to highlight the horizontal reflections related to the wall-air or wall-soil boundaries, serving at the same time for the wall thickness monitoring (thus background removal is avoided); and another one to improve the overall quality of the data enhancing reflections from the inner structure of the wall. These workflows were applied on real data that were collected during all phases using both antennas. Representative Bscans for both workflows and antennas are presented in Figures 11 and 12 for WALL A and WALL B respectively.

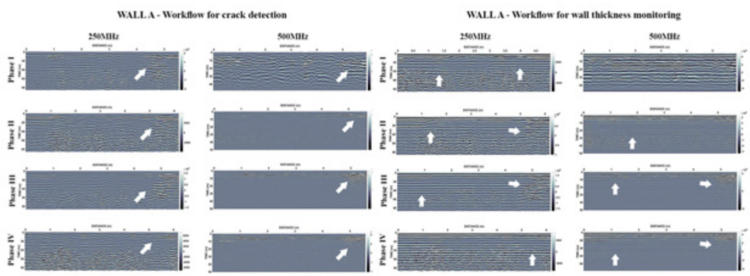


Figure 11. Representative resulted Bscans of WALL A for the first four phases of surveying for both GPR systems and workflows. With white arrows the most important reflections are marked.

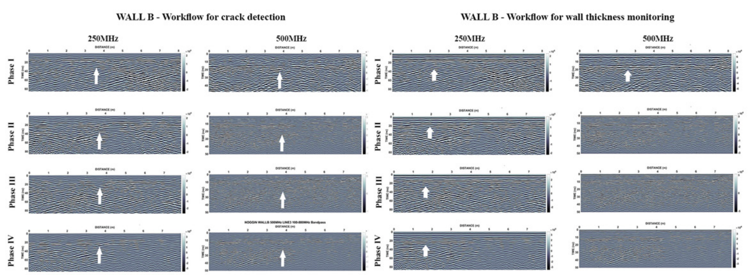


Figure 12. Representative resulted Bscans of WALL B for the first four phases of surveying for both GPR systems and workflows. With white arrows the most important reflections are marked along with the position of the crack at the middle of the sections.

Starting with the results on WALL A and the workflow for crack detection (Figure 11), the data appear very noisy due to the rough surface of the wall. The location of the crack is located towards the end of the sections at a distance of about ~5.0 m from the starting point of the transects. At that position that is marked with white arrows, multiple hyperbolas are observed for both frequencies and within all the phases. This zone could indicate a multiple fracture zone that needs further attention. As for the results obtained from the workflow to monitor the thickness of the wall, the 250 MHz antenna yields better results compared to the 500MHz antenna. Horizontal reflectors that can be related to wall-soil and double wall boundaries are well represented, especially in Phase IV results. The horizontal reflections are also visible at the 500MHz results but appear more attenuated. The most important ones are marked with vertical white arrows. Any change in the time when the reflectors are recorded can be linked with changes in thickness. In this case, there have been no significant changes observed between the various data collection phases. As for the case of WALLB (Figure 12), the data are extremely noisy due to the airwaves that out shadow all the inner structure reflectors. As for the wall thickness, the boundary wall-air can be identified as a horizontal reflector for both frequencies.

For the data that were collected within the survey grid, a third processing workflow was followed to extract slices of the horizontal distribution of reflectors with increasing depth using the Hilbert transform and by creating a 3D volume in MATLAB. Representative slices that were acquired with the 250 MHz antenna for 8ns (~40cm depth) and 18 ns (~90 cm depth) are presented in Figure 13. At 8 ns (~40 cm depth), a linear reflector appears with black colour that is identified as a manmade construction. It extends in the same direction within the first three phases but its signature appears attenuated in the fourth phase of measurements. This change of signature of the particular reflector is cause most probably to changes in water content. At a deeper depth level, a wider linear reflection is visible with black colour and is more likely related with subsurface architectural remains. Slight differences in the intensity of the reflector are also related with changes of soil's water content. There is no reflection identified related with a possible failure zone.

An important fact regarding GPR method is its site dependency, namely that its performance varies significantly from site to site depending on the soil conditions. The same holds for the way that the data are collected, treated, processed and interpreted afterwards. Our final remarks concern the pilot case study of Fortezza Rethymno. Starting with the data collection, GPR was used within areas that the operator could access and walk. In other cases, the

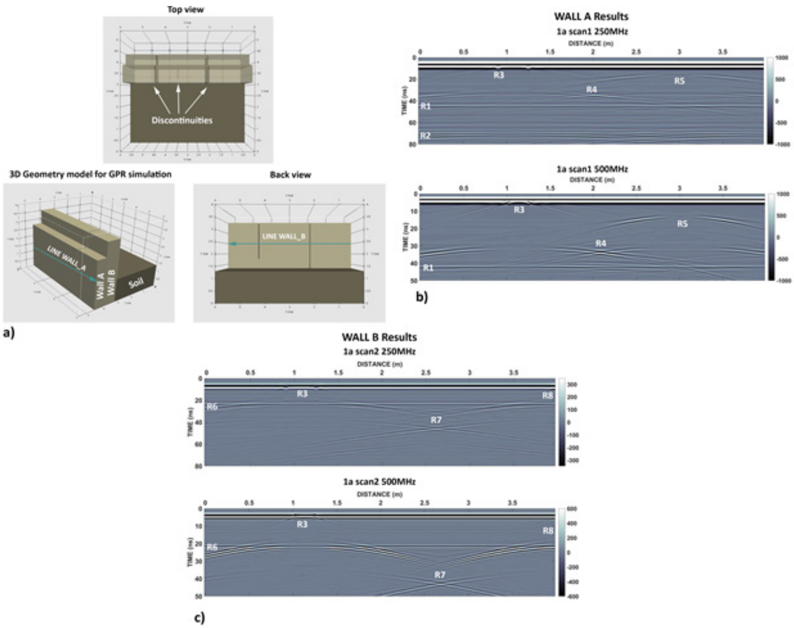


Figure 13. Representative depth slices for GRID1 at the foot of WALL A measured with the 250 MHz antenna.

acquisition of the measurements can be challenging due to cable limitations, the weight of the antenna carrying cart, etc. Thus, special constructions with scaffoldings might be required to obtained quality and reliable data. As for the antennas used for the crack detection, there were a few notable reflections observed in the data of the 500MHz antenna but due to high noise level they are difficult to evaluate and reach a safe conclusion. A higher frequency antenna, e.g. 1000MHZ, might be better for this task. As for the wall thickness, the boundary between the two walls, the wall-air and wall-soil interfaces are visible for both antennas and very well described even in the raw data for some cases. The 250 MHz antenna returned better results compared to the 500 MHz as they were less noisy due to the wider wavelength of the emitted pulses. As for the time-lapse approach, no significant changes were observed and thus no information could be extracted with respect to the temporal variations of the targets under investigation, which is well justified as there were no any significant seismic or tectonic episodes recorded during the specific period. In the results obtained from the survey grid through depth slices, two linear reflectors related with manmade constructions are identified at ~40 and ~90-cm depth. Observed changes of the particular reflectors are more likely due to the water content that differs from phase to phase due to the rain intensity, which influences the humidity of the soil. Other than that, no reflection was identified to provide any useful information regarding the conservation state of the subsurface structural remains. To conclude, GPR can be employed as a complementary method regarding risk assessment and especially for monitoring historical buildings.

4.2. Using GPR technology in emergency situations

With the aim of evaluating innovative technologies which could improve the management of emergencies involving cultural heritage, the Italian Ministry for Cultural Heritage and Tourism, acting through its *Special Superintendence for the Colosseum and the Archeological Heritage of Rome* (SSCOL), and the Ministry of Interior, acting through its National Firefighters Corps (CNVVF), considered the GPR to ascertain if its ability to detect voids or structural discontinuities could be of value in the course of emergencies. In fact, GPR is used in the domain of CH studies both for examining the subsurface of the soil and also studying the structural integrity of monuments (e.g., the internal structure of monuments, crack monitoring, fracture detection, etc.). As to other technologies, firefighters and CH experts organised a common set of tests, based on the use of GPR carrying out two scans in two different areas into the premises of the Baths of Diocletian. The first to be investigated was the area just outside the building walls, while the second examined part of the floor of Hall 1 of the Roman Baths.

The data collected through GPR scans outside the building walls are illustrated in Figure 14. The first two data sets, (a) and (b), reveal the drainage manholes near-to-the surface scan, while the following images, (c)-(f), illustrate signatures of tubes/channels perpendicular to the scan direction.

The survey within Hall 1 (Figure 15) was aimed at acquiring deeper knowledge over the structural integrity of the south pillar of Hall 1 and the adjoining walls. More in particular, the survey was intended to detect foundations, hidden drainage structures, tubes and anomalies, which could have impacted on the stability and structural integrity of the structure. To reach such goal, the two GPR scans were carried out in perpendicular directions (a). The retrieved 2D graphs of GPR returns, (b) and (c), revealed two intersecting one-metre-deep tubes whose 3D and GIS views are given in Figures 15d and 15e.

Due to the tests described above, it was possible to confirm how important is the role of GPR for the cultural heritage site technicians. In fact, the survey enabled us to retrieve the whole bunch of data and information which will allow a better assessment of the factors which directly influence the structural integrity of the building.

On the contrary, the interpretation of the 2D graphs of GPR returns had to be developed by highly experienced technicians and is obviously too complex to be carried out by rescuers in the course of a crisis.

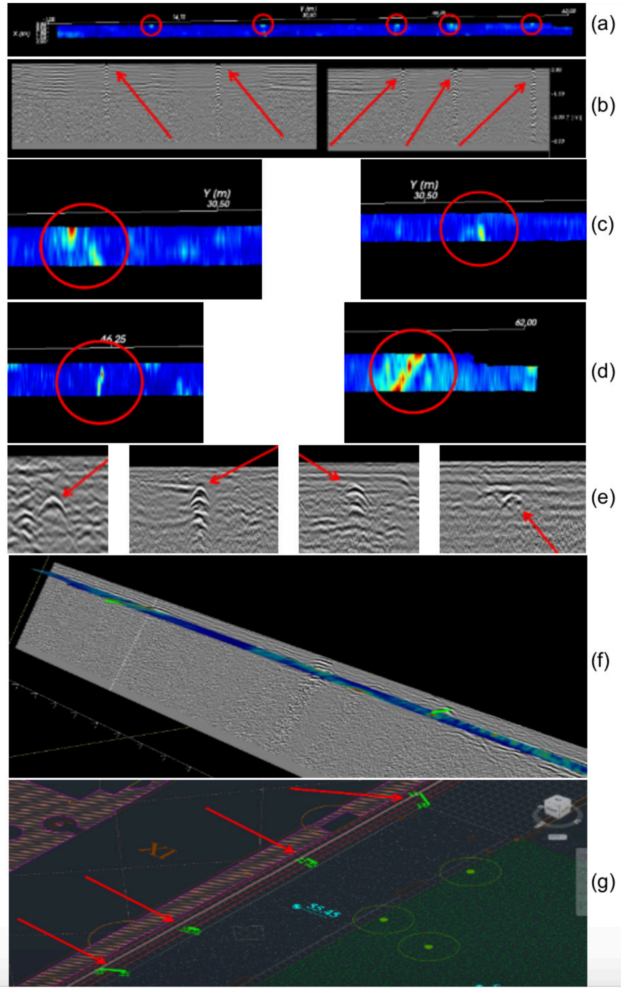


Figure 14. Some illustrative GPR data sets: (a) near-to-surface scan with five revealed manholes (red circles); (b) complementing radar maps; (c), (d) and (e) deeper tomography containing signals from tubes/channels perpendicular to the scan direction and complementing radar map; (f) 3D view of the revealed tubes/channels perpendicular to the scan direction; (g) signatures of the revealed tubes/channels perpendicular to the scan direction, imported into the CAD/GIS tool.

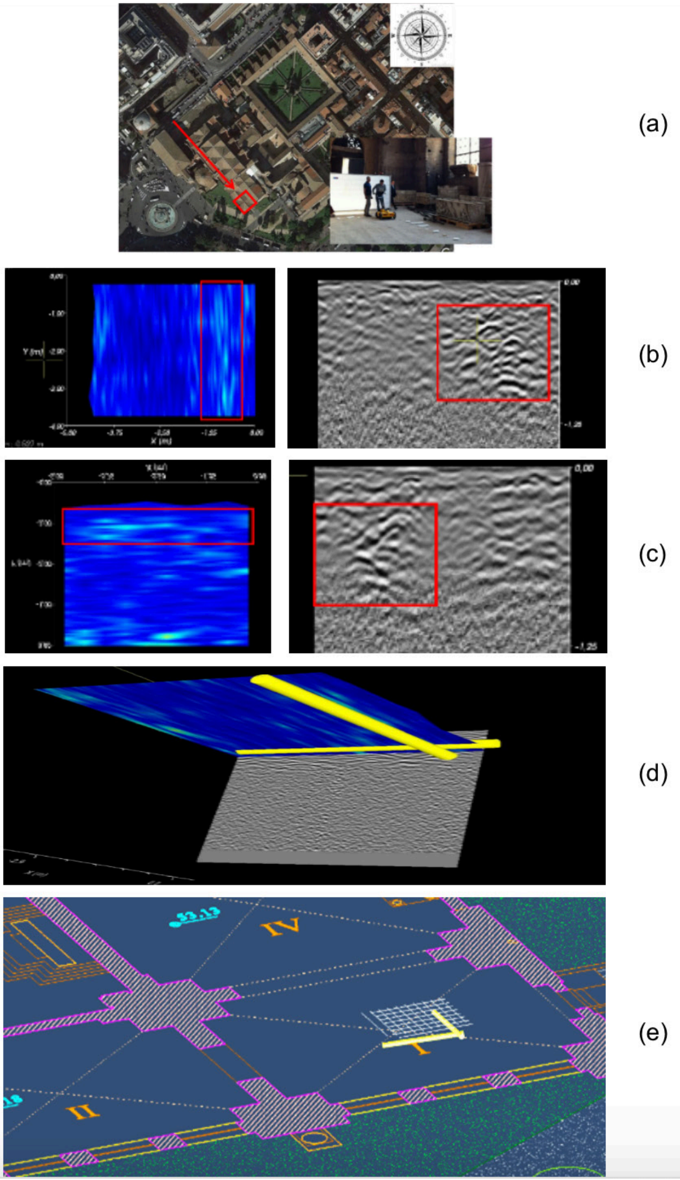


Figure 15. GPR scans inside Hall I: (a) general outlook; (b) longitudinal scan towards Hall 2 revealing a signature of a transversal artefact located near the centre of the hall, slightly on the south-east; (c) latitudinal scan of Hall I towards Hall 4, indicating the presence of a transversal artefact located on the south-west side of the hall; (d) 3D view of the highlighted tubes/channels under the Hall I pavement; (e) GIS view of the highlighted tubes/channels under the Hall I pavement.

5. Terrestrial interferometry for emergency situations

With the aim of evaluating innovative technologies which could improve the management of emergencies involving cultural heritage, the SSCOL and CN-VVF extended their interest to the Terrestrial Radar Interferometer as well.

This technology can detect sub-millimetre 3D displacements in real time. In the course of the survey set-up, the instrument detects the structure scatterers, normally corners or sharp surfaces, able to bounce back large part of the incoming signal. Experienced technicians can, then, recognise such spots over the structure and use them for the following measurements of displacements in the line-of-sight direction between the sensor and the artefact. From then on, the Radar interferometer will detect in real time displacements with sub-millimetre accuracy and it will be able to carry out it continuously up to when the geometric configuration remains valid (e.g., when the instrument is moved).

In the framework of the project cooperation, the Radar interferometry was taken into consideration to survey the south pillar of Hall 1 in the Baths of Diocletian, with the target to assess vibrations induced by the traffic and the underground passing by. The scanning area and the obtained displacement diagram are illustrated, correspondingly, in Figures 16 and 17.

Figure 16. Radar interferometry measurements, the south pillar of Hall I.

To this aim, scans were carried out from the inside and the outside. The first measurement has been carried out within the Hall I aiming at the pillar at the south corner. In that case, it was possible to take for reference two scatterer at 3 and 7 m of height over the pillar. Their analysis did not detect major displacement: all of them were less than 0.1 mm. In the course of the survey it was measured a slight increase of the displacements, which was then possible to correlate to the increase of air temperature and its influence over the electromagnetic wave propagation speed.

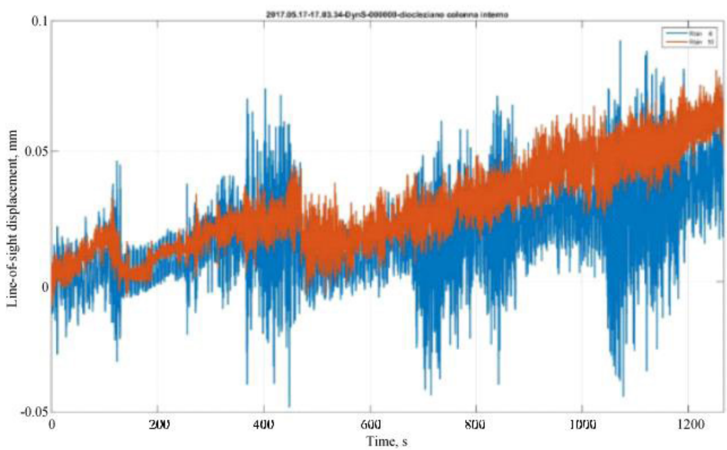


Figure 17. Hall I, south pillar: displacements measured with range resolution corresponding to the binning of 6 (blue) and 10 (red). The increase is due to the interaction of air and the variation of temperature.

The measurement was then repeated after changing the position of the instrument, and from that perspective it was possible to take for reference three scatterers at 5, 8.5 and 11 m of height over the pillar: in this case too, no major displacement was evident, apart from a slight increase of displacement related to the increase of air temperature and an higher amplitude of the vibrations after 10 min. Afterwards, the measurements were carried out at the external side of the same pillar. There the protruding cornices provided two good scatterers at 12.2 and 14.6 m height from the planking level. The temperature change in the course of the measurement was negligible, as highlighted by the flat trend of the curve. In this latter case, having better scatterers, it was possible to obtain the vibration frequency of the building, which was 3.6 Hz. An additional peak at 10 Hz corresponds to the proper frequency of the instrument. Figure 18 reports the measurements at the external side of the pillar obtained for two different spatial resolutions.

The survey described above confirmed that the Terrestrial Radar Interferometer technology could be precious for the CH site technicians. In fact, the ability to not-intrusively measure vibrations frequency and intensity can decisively improve the risk assessment of the CH site and, of course, detecting real-time sub-millimetre deformation could prove most useful too.

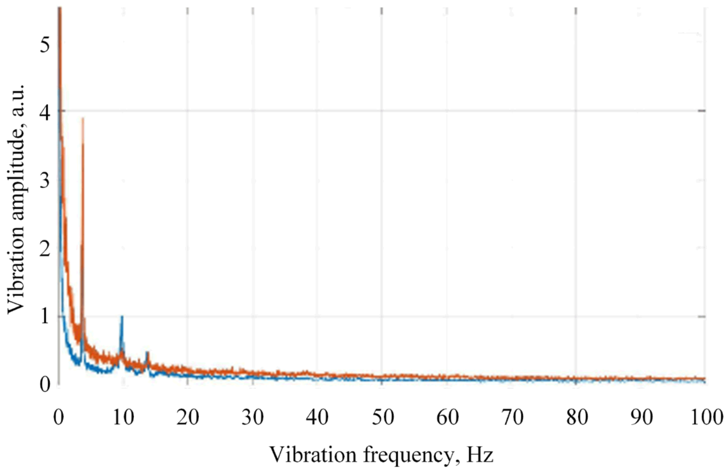


Figure 18. External side of the pillar, vibration spectra obtained for two spatial resolutions. The first peak (3.6 Hz) corresponds to the vibration frequency of the building.

Even in this case, the set-up of the system required some good knowledge of the technology and required experienced technicians, while the interpretation of the displacements was quite straightforward. As such, this type of instruments could even be used by rescuers in the course of an evolving crisis (e.g., a CH building drifting down the hill due to a landslide), provided that a more experienced technician set it up properly. This last need could strongly limit the possible application of the technology to cultural heritage artefacts. On the contrary, if applied to simpler structures (e.g., modern bridges), the instrument set-up could become simple enough to be used in emergency — as a matter of fact, this very instrument was really used to assess rescuers residual safety in the course of rescue activities carried out for the Genova 'Morandi' bridge collapse of 14th August 2018, as well as in the course of the search and rescue activities carried out for a huge crater opened in Rome in February 2018.

6. Crack monitoring by using Fibre Bragg grating

In order to do some experiments about innovative technologies to be used for monitoring activities on risks affecting the Cultural Heritage, within the STORM Project, Tuscia University proposed the use of FBG (Fibre Bragg Gratings) sensors, in the Baths of Diocletian, the aim was to acquire stress data induced by different phenomena: variations of temperature and humidity, material movements.

An optical fibre is a filament which can conduct radiation inside itself and is generally composed of a cylindrical transparent core surrounded by a cladding, a material that has a lower refractive index than the core. In turn, it is surrounded by a protective plastic sheath (jacket) that prevents mechanical damage. Fibre Bragg Gratings (FBGs) are optical fibres whose core contains a so-called Bragg grating, comprising alternate bands of material with different refractive indices. This fibre can be used as a sensor to measure strain of the materials in which it is immersed or glued, as it also deforms causing changes in the reflected wavelength.

The optical fibre, composed by the three layers described above, has a very thin diameter, of the order of a few hundred microns. Despite its dimension, this kind of sensor gives a possibility to measure and collect a huge number of data, at very narrow time intervals, in very large areas. More fibres can, moreover, be combined together, and give the possibility to create measurement networks, which can be installed in different kinds of structures, obtaining continuous information on the chosen parameters.

Fibre optics, therefore, were chosen for the monitoring for several reasons: first of all, as seen in Figure 19, they have a very low aesthetic impact, their minimal dimension allow to use them also in very large areas, without compromising the appearance of the work of art or the structures; moreover, the FBG installation does not require an invasive intervention, ore the use of methods and instruments that could damage the structure; in fact for their positioning is only needed a removable adhesive, without the use of instruments like nails, drills, hammer etc; this kind of sensors is also easier to be placed it in areas that otherwise would be quite difficult to be reached.

6.1. Areas chosen for the monitoring in the Baths of Diocletian

It was proposed to choose the Hall I and the Michelangelo's Cloister, in the Bath of Diocletian. This proposal arises from the fact that these two areas are affected by numerous issues related to the damage caused by changes in temperature and humidity and by the increase of some cracks on the walls.

Figure 19. Wall of the Hall I, demonstrating the low aesthetic impact of FBG glued by silicone.

The Hall I is part of a larger complex of halls which are currently used as a warehouse for the storage of various archaeological material. The Hall I overlooks the external garden to which it is connected by a metal door. Both external walls are still on place, they are both made of bricks, one has numerous glass windows. Inside the hall there are numerous archaeological finds, for a total number of 42 including sarcophagi, capitals, friezes, columns, basins, statues and bases. All these objects, although in stone material, can be subject to variations in temperature and humidity of the area. Moreover, in the external wall of the hall numerous bricks are unstable or partially damaged due to rising humidity coming from the ground and from the areas where there is an excessive accumulation of rainwater, as seen in Figure 20. The brick instability can endanger the strength and solidity of the entire structure. In the internal side of the wall, on the surface have been identified some evident salt efflorescence and numerous cracks affecting the masonry, which, in some areas, is also covered by layers of plaster rather damaged, which are not firmly attached to the masonry.

Michelangelo's Cloister is accessible from a corridor to the left of the ticket office, and it is surmounted by the museum's offices. The structure is entirely covered with white plaster. After recent restoration work, the whole structure has been completely repainted. Although the interventions date back only a few years ago, many cracks and damages are already noticeable, in different areas of the Cloister. In particular, the south-east area of the structure is affected by numerous cracks on part of the masonry and the vault and by significant detachments of plaster due to the rising humidity from the ground, as a result of rain, as seen in Figure 21.

Figure 20. External wall of the Hall I, affected by rising humidity; the area chosen for monitoring is shown in red.

Figure 21. Wall and vault of the Cloister chosen for the humidity and lesion monitoring; the areas chosen for monitoring are shown in red.

Along the whole cloister there are numerous statues of different sizes and stone masks are attached to the walls. In the south east wall there is also a painted wooden door which, as an organic material, is very sensitive to variations in temperature and humidity. The damage to the masonry and humidity can therefore damage not only the structure, but also the materials it contains.

6.2. Monitoring of the Rising Humidity

Rising humidity has been monitored both in the external wall of Hall I and in Michelangelo's Cloister. It is important to know that not all the typologies of optical fibres can be used for the monitoring of humidity, it is in fact mandatory to use those that are coated by particular polymer, which can swell in case of variations. For this reason, a fibre coated by Polyammide has been installed on the both structures.

The installation has been made from the top down, by using silicone on a film of Paraloid. The sensors have been positioned in contact with the wall, so that they can register all the variation of humidity.

6.3. Monitoring of cracks in the structures

Lesions are being monitored both on the internal wall of the Hall I and on the wall and the vault of Michelangelo's Cloister, by using a fibre optic coated by Acrilate. During the installation, made from the top down, the X60-A glue has been used; this particular glue has been chosen because of its resistance and its very short drying time. This procedure allows to give to the fibre the tension needed for the registration of the movements; in fact, depending on the materials' movements, which may cause enlargement and narrowing of the lesions on the wall and on the vault, the fibre, fixed to the wall, can stretch and shorten; this variation can be collected and monitored.

It is important to know that, for a proper data analysis, the distance between the two adhesives has to be measured and registered.

6.4. Installation Problems

The installation of the fibre optic may be quite difficult; the fibres are rather delicate, while they have a considerable resistance in case of tension they break very easily if subjected to pressure. Moreover, the fibres are very thin and being of a transparent material, for this reason they are very difficult to be seen with an inadequate light; the fibres are also rather difficult to handle, in fact it is possible that the cable roll up on itself. The choice of the adhesive to be used is very important, since some glue can prove to be inadequate, due to the very long laying times before drying. For this reason, during the installation of Fibber Optics in Baths of Diocletian, it was decided to proceed with the X60-A glue which has much faster setting times and allowed a better stability of the fibres.

Should also be considered that, in case of dusty materials or surfaces, a more massive amount of adhesive can be required and this may extend the drying time of the glue.

6.5. Data collection and analysis

The wavelength data corresponding to each FBG sensor are collected using a specific Interrogation tool, the so called Interrogator, which is able to continuously interrogate more fibres at the same time and which write a file with all the data (wavelengths) taken, according to the date and time. Both for humidity and strain, the collected wavelengths have to be compensate, in order to have correct measurements, for this reason a sensor which can register the temperature variations and allows to subtract them from the registered wavelengths is needed.

In order to calculate the wavelength, change for each sensor and then to obtain the value of the strain and the Humidity of the wall is necessary to calculations using specific formulas obtained through in situ calibration using portable instruments.

The data analysis allows to verify if the strain and humidity is approaching to those thresholds which may represent a risk for the materials, but also to control the dimension of each lesion affecting the structures (Figure 22).

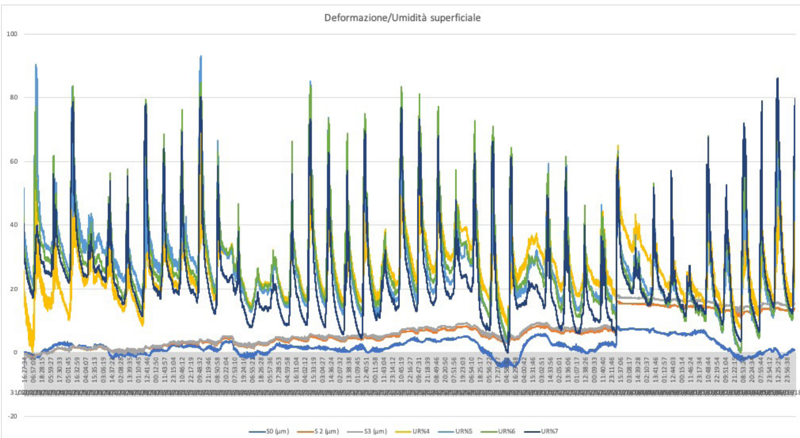


Figure 22. Trend of the values recorded inside and outside for the measurements of humidity and lesion monitoring by the FBG sensors installed in Hall I (measurement period from October 2017 to June 2018).

7. Induced fluorescence spectroscopy

Spectroscopy is the study of the interaction of electromagnetic radiation in all its forms with matter — see e.g. (Crouch and Skoog 2007; Rsc.org 2016) and references therein — which implies the measurement of radiation intensity as a function of wavelength or frequency. The *induced fluorescence* method is based on the excitation of the molecules of a sample to higher energy levels via the absorption of light. The molecules then return to one of the possible levels of their ground electronic state, usually emitting a photon in the process, whose energy, as well as the wavelength and frequency, are determined by the difference of the energy levels of the molecular structure and thus is characteristic of each type of molecules. Thus the *induced fluorescence spectroscopy* can be used for the identification of organic and inorganic compounds.

Within the STORM project, such compound identification met the need of early detection and assessment of biofilms developing on the walls of an early Christian basilica located in the Roman Ruins of Tróia pilot site (Grândola Municipality, Portugal): Nowadays the observed gradual changes in the ambient parameters at the Tróia Peninsula — such as humidity, temperature, and salinity, as well as the tidal and ground water-levels — create increasingly favourable conditions for the proliferation of different biofilms composed of moss, algae, lichen, fungi, and/or bacteria. Such biofilms can cause irreparable damage to the antique frescos covering one of the Basilica walls.

Two methodologies have been used within the framework of the STORM project: laser induced fluorescence (LIF) spectroscopy and spectral fluorescence signature (SFS) detection.

The LIF spectroscopy is based on the excitation of a sample by strong monochromatic laser light ($\lambda_{ex}= const$) and subsequent detection of the induced fluorescence emission spectrum $F_{LIF}= F (\lambda_{em})$ with a low-noise CCD (charge-coupled device) spectrometer, thus offering high sensitivity. The developed LIF sensor is capable of detecting fluorescence of in vivo chlorophyll (that is, the presence of moss, algae, and lichen), efficiently exciting it with the green light of λ_{ex}= 532 nm, produced by a frequency-doubled Q-switched Nd:YAG solid state laser, emitting 3 ns pulses of the energy ~5 mJ with the pulse repetition frequency of about 5 Hz. A typical fluorescence signature of a lichen biofilm, obtained using the sensor, is illustrated in Figure 23.

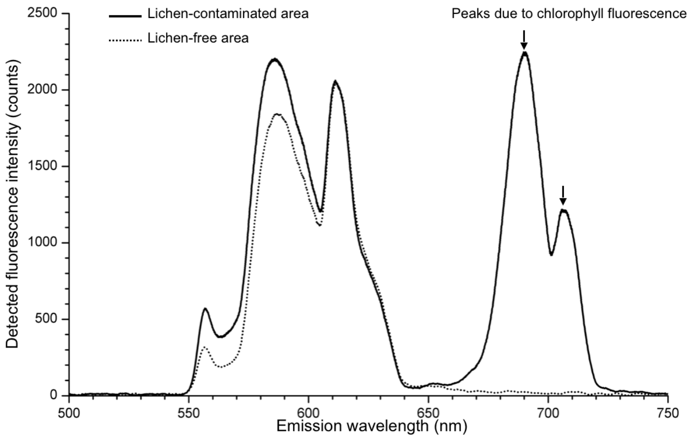


Figure 23. A typical fluorescence signature of lichen obtained using the LIF sensor.

The SFS detection is a novel technique, scarcely represented in the literature, harnessing the lamp-induced fluorescence: a wide spectrum of the lamp radiation permits to scan the excitation radiation wavelength using a computer-controlled monochromator. This will introduce a new variable parameter into the measurement conditions, turning the fluorescence spectra graphs $F_{LIF}= F(\lambda_{em})$ into surfaces $F_{SFS}= F(\lambda_{ex}, \lambda_{em})$, in which the detected spectral density of the fluorescence emission is a function of both the excitation and emission wavelengths. Due to the relatively less intense excitation radiation, the sensitivity of this methodology is, in general, less than that of the LIF spectroscopy, albeit:

- the loss of excitation yield is partially compensated by a more sensitive detector with internal amplification, a photomultiplier tube (PMT),
- for some areas of the two-dimensional fluorescence map $\{\lambda_{ex}, \lambda_{em}\}$ the sensitivity of SFS detection may be of the same order or even superior than that of LIF due to high, "resonant" quantum efficiency of the fluorescence process for a particular excitation-emission wavelength pair.

Due to the latter fact, the SFS spectrometer is capable to detect both the chlorophyll emission (in the VIS-IR range) and the fluorescence signatures of specific proteins (in the UV-IR range) composing bacteria and fungi (Marques da Silva and Utkin 2018; Utkin *et al.* 2018). SFS sensor was built around 10-W pulsed Xe lamp. Its mass-dimension characteristics are 6.6 kg and 15 × 34 × 35 cm^3. The low power consumption of the lamp source, about 30 W, allow the instrument to be powered either from 100-240 V, 50-60 Hz mains or 14.8 V battery, thus enabling the user to carry out the cultural heritage diagnosis without any supporting infrastructure.

Detection and monitoring of biofilms in the Basilica (Figure 24) are carried out on a monthly basis, the SFS sensor used in the measurements is shown at the figure bottom, the principal application being the early detection of biological infestation on the north-east painted wall (providing this way a *surveying and diagnosis service*). The location of the corresponding measurement points (1-4) is shown at the top of the figure. Due to its very wide range of excitation wavelengths, the SFS sensor detects several types of parasitic signals, such as elastically reflected light of the irradiating lamp, coming to the detector from the higher diffraction orders of the gratings used or from high angles of incidence and fluorescence emissions from the base material (for the case in question, the underlying plaster).

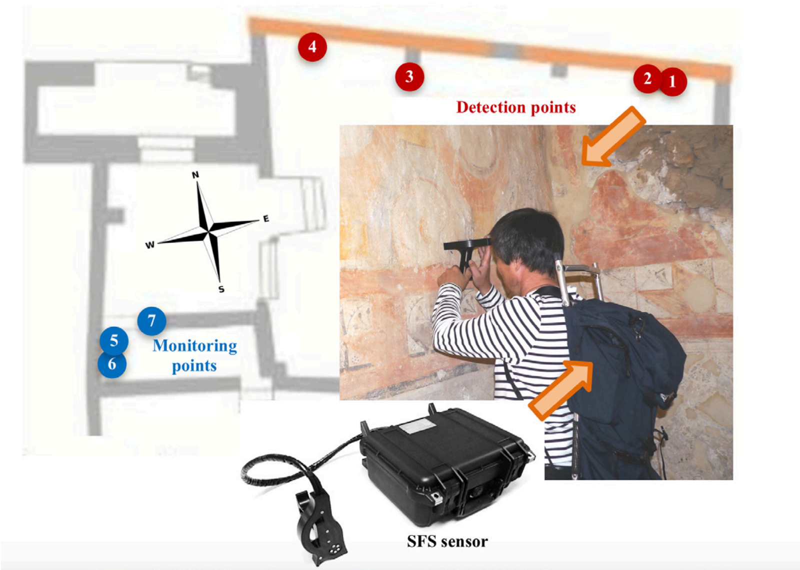


Figure 24. Detection and monitoring of biological infestation on the Basilica walls.

For this reason, SFS detection is carried out in two distinct areas, free of strong spurious light, representing the VIS-IR emission range – an area centred at $\lambda_{ex} \approx 500$ nm, $\lambda_{em} \approx 670$ nm – and the UV-VIS emission range – centred at $\lambda_{ex} \approx 300$ nm, $\lambda_{em} \approx 400$ nm.

The measurement points 5 to 7 are related to biofilms freely growing in the painting-free area of another wall, whose photo-physiological status is tracked, providing a *surveillance and monitoring service* that uses the concept bio-community as a sensing agent. Examples of SFS signatures of such biofilms, obtained in the VIS-IR and UV-VIS ranges (characteristic fluorescence of *in vivo chlorophyll and fungi proteins, respectively) are given in Figure 25.*

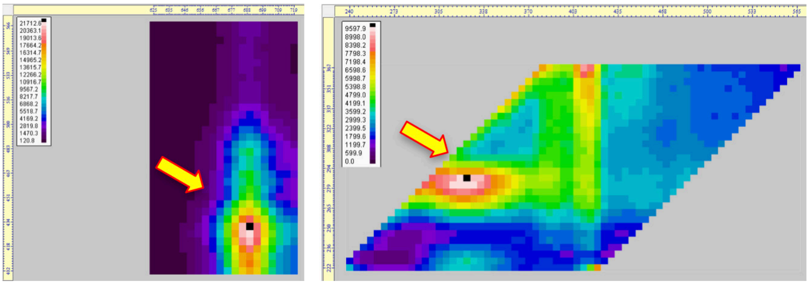


Figure 25. Chlorophyll, VIS-IR range. Proteins, UV-VIS range. Typical chlorophyll and protein signatures detected at the monitoring point 7.

As seen from the figure, both signatures are very pronounced, which testifies to the viability of the chosen technical solution — a fact proven during a long campaign of monthly measurements in Tróia, started in August 2017. A detailed description of this experimental campaign and discussion of the achieved results given in Chapter 9, devoted to the practical work at the pilot sites.

8. Multispectral aerial photography

Across Europe Cultural Heritage faces many threats. The value of Cultural Heritage to all states across the EU is great, often forming a large part of their economies through heritage tourism. For example, in the UK alone the Cultural Heritage sector is estimated to contribute to £12.4bn to the UK economy (Light 2015). Whilst many of the concerns and risks highlighted in the book are of great importance, and often leading to quick-onset issues for Cultural Heritage. There are also many slow-onset risks that STORM does consider and help managers of Cultural Heritage to manage, prevent and mitigate. Once such hazard has been the term, in the context of STORM, biological colonisation. In effect what this is concerned with is the growth of organic matter on, and around, Cultural Heritage structures and items. Already discussed is the use of induced fluorescence to assess the Cultural Heritage material in a way that will allow early detection of such growth on an important asset or structure. However, STORM also adopted novel techniques to try to assess the vegetation growth, and die-back, around ground-based archaeological remains, with a specific focus on the UK pilot site – Mellor Heritage Project.

One area of the Mellor Heritage Project is an archaeologically significant burial site called Shaw Cairn and this is on top of Mellor Moor, 293 m a.s.l. This area was excavated between 1970 and 2010 and found were remains including bone fragments and significant archaeological items that suggest the area was a burial site from the Bronze Age, over 10,000 years ago. This area became a good test bed for the monitoring of the vegetation around the site. The archaeological cairn remains uncovered since excavations were halted in the 2010s and are located at ground level. Therefore, the grass surrounding the cairn will grow over the summer months and die-back over the winter months. The field in question is sometimes used for grazing of sheep, which does provide some management of the grass growth, however, in general, the area is not maintained. The Mellor site is not one in which there is control over the flow of people as all three areas in Mellor are open to the public, often as a right-of-way. So, for the example of Shaw Cairn, the field in which the cairn lays is not owned by the Mellor Heritage Project trust, but by a local farmer. Nevertheless, Mellor has taken on responsibility for maintenance with agreements with landowners for the benefit of the local area. One issue impeding regular maintenance at the Shaw Cairn is the location and access. There is a short hike up to the summit of Mellor Moor, and in the winter the roads surrounding the site are sometimes impassable.

STORM enabled the small trust, made up of around 20 trustees, to develop novel and inexpensive ways of monitoring such heritage sites. As part of the project, Mellor was able to purchase a UAV (unmanned aerial vehicle) to monitor its heritage. At first, this was to be done solely using a regular RGB camera to create 3D models of the heritage using photogrammetric techniques. These techniques proved to be useful and allowed the trust to more easily monitor their asset. With that in mind, an adapted camera was purchased. This was modified in a way so that RGB filters were added, and the near-infrared sensor filter was removed. This, therefore, can take photographs in the red and near-infrared spectrums.

Near-infrared photography allows for measurements of "plant health" via a proxy (DeFries, Townshead 1994; Pettorelli *et al.* 2005). It is possible to assess the density of vegetation utilising indices that compare the ratio of reflected light within different bands from crops and vegetation. A common index used is the NDVI (Normalised Differential Vegetation Index), which assesses the ratio between light reflected in the red spectrum, and light reflected in the near-infrared spectrum. Plants reflect light in the near-infrared, whereas they reflect less and absorb more in the red spectrum. The abortion of red by chlorophyll in the process of photosynthesis, explains why humans observe plant, when healthy, as green. Green is also heavily reflected although our eyes are not able to see light in the near-infrared. In the Autumn, when vegetation changes and photosynthesis declines, leaves become browner as more of the red light is reflected. Therefore, the difference in light between the red reflection and near-infrared would be greatest in the summer when plant life is at its healthiest. In the autumn and winter, plant life wains and the ratio between the two falls. The NDVI ratio ranges from -1 to +1, where less than 0, NDVI suggests no vegetation, and at +1 NDVI suggests the vegetation is extremely healthy. Figure 26 highlights how the changing ratio of reflected light contained in different bands of the spectrum is modified throughout the seasons. NDVI is calculated by the simple equation Near-infrared photography allows for measurements of "plant health" via a proxy (DeFries, Townshead 1994; Pettorelli *et al.* 2005). It is possible to assess the density of vegetation utilising indices that compare the ratio of reflected light within different bands from crops and vegetation. A common index used is the NDVI (Normalised Differential Vegetation Index), which assesses the ratio between light reflected in the red spectrum, and light reflected in the near-infrared spectrum. Plants reflect light in the near-infrared, whereas they reflect less and absorb more in the red spectrum. The abortion of red by chlorophyll in the process of photosynthesis, explains why humans observe plant, when healthy, as green. Green is also heavily reflected although our eyes are not able to see light in the near-infrared. In the Autumn, when vegetation changes and photosynthesis declines, leaves become browner as more of the red light is reflected. Therefore, the difference in light between the red reflection and near-infrared would be greatest in the summer when plant life is at its healthiest. In the autumn and winter, plant life wains and the ratio between the two falls. The NDVI ratio ranges from -1 to +1, where less than 0, NDVI suggests no vegetation, and at +1 NDVI suggests the vegetation is extremely healthy. Figure 26 highlights how the changing ratio of reflected light contained in different bands of the spectrum is modified throughout the seasons. NDVI is calculated by the simple equation $NDVI = \frac{NIR - RED}{NIR + RED}$. The data is retrieved as two images, one image has captured the light in the near-infrared and the second in the red bands. An image is basically a raster matrix of pixels and each pixel contains a value between 0-255, where 0 represents little reflection and

255 represents a lot of reflection. These two images can be compared to calculate the ratio between the two for each individual pixel. The output of this calculation is a third image, a false-colour image where the pixel values are the NDVI ratio. For ease of analysis, this false-colour image is usually coloured in a way where healthy vegetation is represented as green, and no vegetation is represented as red.

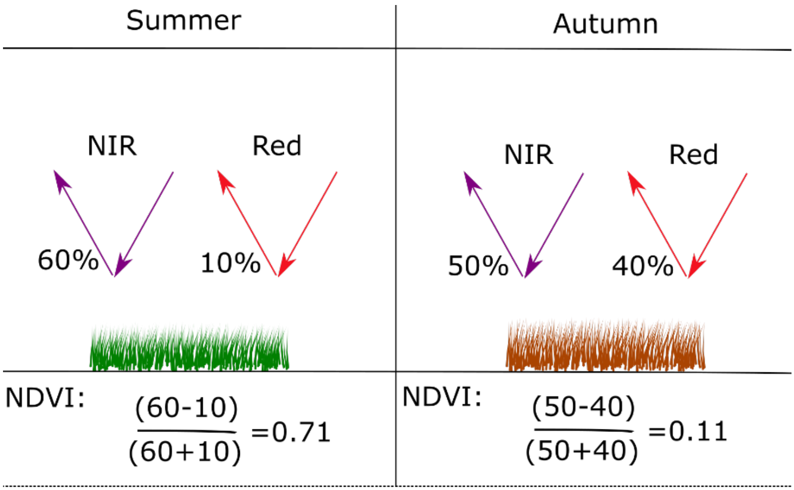


Figure 26. Schematic diagram illustrating the changing NDVI of vegetation with respect to seasonal changes in reflected visible (red) and near-infrared (NIR) light. Note reflected light figures are not real-life values and are not representative.

8.1. Mellor Heritage Project

As previously mentioned, the STORM project enabled the UK pilot site to test aerial near-infrared photography at Mellor, close to Manchester in the UK. This surveying technique would be deployed, as further detailed in Chapter 5, in the Surveying and Diagnosis component of the STORM service. Surveying and Diagnosis is a constituent part of the STORM Prevention and Mitigation process, specifically in the monitoring phase. This service should provide a set of aims and objectives that sites should adhere to so that they monitor the state of their Cultural Heritage structures and assets, and therefore can act to prevent and mitigate any damage that may occur, keeping in line with conservation management plans. One of the aims defined in the Mellor Prevention and Mitigation Monitoring plan is to conduct NDVI scans of Shaw Cairn on a three-monthly basis.

Table 1. The Mellor pilot site Surveying and Diagnosis Schedule with the NDVI surveys italicised

Surveying Technique		Use	Frequency	Baseline
Photogrammetry	Terrestrial Photogrammetry	Wheel pit at the Mill site/Ditch at Old Vicarage site	1scan / 3 months	Scans from the 2000s
	Aerial photogrammetry	Ground-based archaeology at Shaw Cairn, Old Vicarage	1scan / 3 month	July 2017
	Near-infrared Terrestrial	*Ditch at Old Vicarage site, wheel pit at Mill site*	*1scan / 3 months*	*July 2017*
	Near-infrared Aerial	*Vegetation growth on ground-based archaeology at Shaw Cairn*	*1scan / 3 month*	*July 2017*
Laser Scanning	Terrestrial	Wheel pit at the Mill site/Ditch at Old Vicarage site	1scan / 3 months	Scans from the 2000s
	Aerial	NA	NA	NA
WASN	Acoustic	Vandalism at the Vicarage site	NA	Jan 2019
Visual Inspections	Terrestrial	Mill, Vicarage and Shaw Carin sites	1 walkaround every 6 months	NA

As shown in Table 1, a set of objectives in the form of tasks have been devised for the Mellor Prevention and Mitigation process. From there, it was necessary to define the frequency for which the tasks would be conducted.

A baseline scan was conducted in June 2017 utilising the NDVI modified camera, a DJI Inspire 2. The use of the DJI Inspire drone and proprietary software allowed the pilot to create a flight plan which the drone would fly automatically after take-off and taking pictures and regularly spaced intervals. Then, at each interval, the drone pauses, and takes a photograph, before continuing to finish the designated flight plan. The image overlap was set to 75% in both directions so that once all of the images are collected they can be easily stitched together within photogrammetry software to produce an orthophoto. A period of testing occurred in advance of this baseline scan. This involved experimenting with the Drone software, learning how to develop and analyse the results from the data and also how to interpret the results once they were produced. This involved multiple scans across different vegetation types around the village of Mellor, collecting a lot of data and processing the data using tools such as QGIS for creating the false-colour NDVI images. An aim of the STORM project is to ensure that as well as being low cost and innovative, solutions that are created should be applicable to the users. It was important, therefore, that the data analysis was not too intensive and could be realistically conducted by the owners of Cultural Heritage who may not be able, in ordinary circumstances, to call upon the skills of data analysts and technicians.

8.2. Method

The process of creating the thematic map showing NDVI across the heritage site involves the following steps:

1. Calibration of images;
2. Creation of orthomosaic (photogrammetry);
3. Calculation of NDVI;
4. Preparation of map/image.

The first stage involves calibration of the collected images. The reason for calibration is that, as mentioned, each pixel on the photograph represents a value for reflectance of light in that spectrum, therefore the photograph will contain two bands, one in which each pixel represents the reflected light in near-infrared and the other each pixel would represent the reflected light in the red. Unfortunately, the recorded reflectivity is dependant or influenced by outside factors. These include sunlight levels, topography shading and cloud cover. Therefore, all pixel values need to be calibrated using a known value, and for this during every flight a photo is captured of a calibration target (Figure 27) for which laboratory tests have determined the value of reflectivity.

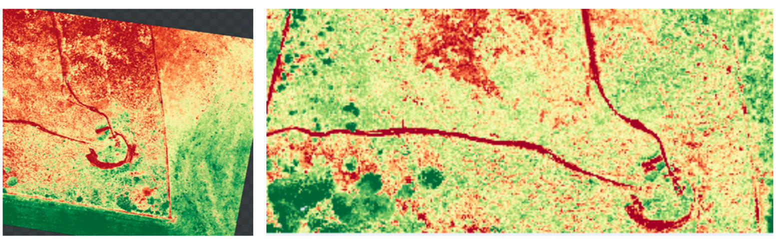
Figure 27. Spectral camera photograph of the calibration target (lower) with a QR code to help distinguish the location of the calibration reflectance pads.

All other values must be calibrated accordingly. Once calibrated photos must be stitched together, in the Mellor case this is because the CH asset that we are scanning covers a large geographical area and so photogrammetric software is used to mosaic and create and orthophoto. The calculation of NDVI can be computed in most GIS software using the inbuilt raster calculator and the above stated equation. It is then a simple task of creating a thematic map (usually where red indicated no vegetation and green indicated healthy vegetation). These outputs are what is analysed visually to understand the impact of vegetation growth across the ground-based CH asset. A more detailed description of the methods employed can be found in Deliverable 4.1 (STORM Consortium 2018).

8.3. Results

The multispectral camera (detailed in D4.1) was attached to a DJI Inspire UAV. The drone is flown over a pre-programmed flight plan at a height of 15-20 m a.g.l. with 99 waypoints. At each waypoint, the drone hovers and images the ground directly below. The flight plan is programmed so that the individual pictures overlap, both frontal and side, by 75%.

So far, five data collection surveys have been completed at the Shaw Cairn site. Of the three surveys, the first set of data was collected at 50 m a.g.l. This altitude proved too high, with image quality not being sufficient to analyse the data in any meaningful way. It was at this point that testing of the sensor was undertaken to ascertain at which altitude the images would be of good enough quality that they could be analysed to clearly show small changes in vegetation across the site. Two NDVI maps of Shaw Cairn are given in Figure 28.



(a) (b)

Figure 28. July 2017 (a) and October 2017 (b) thematic NDVI maps of Shaw Cairn.

It is difficult to assess the two scans that have been collected so far in the project. What the data does show is the clearly defined footpaths which have been created over the years as people visit the summit. Also extremely evident is the Cairn itself, the circular patter atop the summit. Being stones, the NDVI is very low, although there is some small evidence of vegetation growth in and round the stones with green patches showing within the red. This cursory analysis show there may be some use to NDVI cameras as a tool for surveying CH assets. However, many more scans are necessary to truly show the benefit of vegetation indices as a method for monitoring CH assets from the threat of biological colonisation and vegetation growth.

8.4. Conclusion

The application of an adapted NIR camera for use on a DJI Drone to assess the impact of vegetation growth on ground-based archaeology has been assessed within the framework of the EU-H2020 STORM project.

Photogrammetric surveys of the landscape utilising the NIR camera have been conducted since July 2017 on a regular ongoing basis. This has led to the creation of a time series of data that show the decrease in vegetation from the summer to the winter, although it is difficult to assess the damage that may be occurring to the ground-based archaeology. Many more scans will be required to gain a fuller picture of what damage the growing vegetation is creating, with the few available scans showing little variation. The results do appear to highlight smaller areas of vegetation growth within the ground-based archaeological assets, and further research and data is needed to really highlight the benefits of a modified near-infrared camera as a tool for surveying CH assets.

The Mellor Pilot site, along with the University of Salford, has a long-term plan to continue the NDVI data collection surveys for the foreseeable future, and this is likely to form part of future research with the university including students and researchers. The use of the NDVI camera has been included in the Mellor *STORM Conservation Management Plan* as a *Monitoring activity* and should, therefore, be continued regardless of changes to the site or university.

9. Photogrammetry and terrestrial laser scanning

Photogrammetry is a rapidly evolving field of research (especially in its digital form) in Cultural Heritage studies and it involves the ‘translation’ (using specific and sophisticated algorithms) of historical or modern pictures in sets of three-dimensional points (i.e. point cloud). Paradoxically, “photogrammetry started long before photography was invented, with geometrical studies of the laws of perspective and projective geometry” (Doyle 1964, 259), but the development of computer processing power and the availability of user friendly computer applications favoured the boosting of digital photogrammetry in many areas of study where photographs (broadly speaking) constitute means of documentation, i.e. mainly Remote Sensing.

Digital photogrammetry is a process based on projective geometry (on which also the human perception of depth and three dimensions is based) and homologous points matching between two (or more) images. Although the result of such processing is a measurable digital copy of the photographed subject, photogrammetry is not just about recording historical artefacts (from large portions of landscape to small movable objects), since 3D information can now be processed and produce new information on the detailed shape of a surface. Indeed, when sufficient pictures are available for a given object, it can be easily reconstructed digitally and give birth to a copy (i.e. in a digital environment or via 3D printing) of the original object that can be used in museums exhibitions or to foster the analysis of the item per se.

This makes 3D data an affordable and important tool in archaeological research, providing the possibility to look at details beneath design or texture, or to create replicas and even replace damaged parts by 3D printing artefacts.

In order for photogrammetry to produce accurate and precise results, besides the need of using a good digital camera (preferably, DSLR with prime lens, to minimize distortions), the placement of a series of coded targets (Figure 29) is required around and on the object to be measured.

Figure 29. Images of the installation process of stable target references on the wall surface of Fortezza Fortress, Rethymno (Greece).

The automatically recognized targets are then used during the photogrammetric image processing procedure to enable the model scaling and orientation. In the case of aerial photogrammetry (Cantoro 2015), where the capturing of pictures is done with the use of flying devices (namely RPAS, Remotely Piloted

Aerial Systems), the targets normally need to be bigger (to be clearly visible from distance) and their distribution needs to be spread over larger distances.

Another important and quite efficient documentation method employed in architectural or geomorphological survey is definitely the one involving the use of Terrestrial Laser Scanner (TLS). The technology behind this approach is based on advances in light detection and ranging (LiDAR) and new generations of fast high-resolution laser scanners: the scanning machine emits a laser beam from a rotating head and measures the time and intensity of the return. When the laser hits a surface, part of its power is absorbed by the same surface and part is returned back to the emitter. Given the known position of rotation axis of the laser emitter and the time used by the beam to go and return, the three-dimensional information of a specific point can be calculated in a relative or absolute coordinate system. The head of the scanner rotates around all axes thus generating a set of points with known distance and position from the scanner itself. This point-cloud can then be joined with clouds from other location to obtain a seamless metric representation of the scanned object (with resolution and accuracy dictated by the specific characteristics of the employed scanner and of the undertaken survey).

The added value of photogrammetry as a tool for damage assessment analysis is quite similar to that of laser scanning (Andrews, Bedford, and Bryan 2015, 22): both surveying methods provide a precise, digital and measurable copy of the object under investigation (Cantoro 2017). The main advantage of photogrammetry over TLS consists in the possibility for the first to work with historical photographs as well as recently acquired ones (particularly useful capability for irreversibly damaged cultural heritage). The repetition and comparison of a time-series captures can assist for example in highlighting or quantifying damages, changes or loss of material on a wall surface, as it was the case of STORM approach for timely artefact diagnosis.

While laser scanning is still a more expensive technology (with respect to costs normally involved in a digital photogrammetry campaign), its cost is rapidly decreasing and maintains some edge on photogrammetry in specific cases, i.e., when light conditions are sub-optimal. In planned surveys, both TLS and photogrammetry do not present major problems, since it is usually possible to provide sufficient illumination to work with photogrammetry (while TLS can work also in the dark). On the opposite, in case of emergency this could be an important constraint: providing bright and uniform illumination to indoor sites with complex geometries could be nearly impossible and TLS may result the only possible approach in cases of emergency (if colour texture is not essential to the project).

With one of the main vocation of Fire Fighters – partner in STORM – being the detection of collapse precursors in sensitive buildings, TLS was the preferred documentation method in several emergency situations where the rapid assessment of structural damages was an essential asset. Most prominent example of such need for quick and efficient assessment is related to the most recent earthquakes, which stroke Italy (Emilia Romagna 2012 and Central Italy 2016). There, the CH sites, whose damage was not promptly assessed, suffered even more damages from the following strikes in the coming days/months. In fact, while vast efforts are usually devoted to monitoring activities to preserve CH, the outcome of such activities are actually not prepared for first responders, who normally act on the basis of poor or no data.

It was therefore important to put in place, in the framework of STORM project, a workflow or set of procedures and tools to monitor and detect changes in Cultural Heritages in a fast and efficient way. Proposed approach often required the integration aerial (RPAS aided) and ground photogrammetry with TLS, with the one filling gaps or integrating the data derived from the other. Indeed, the technology of TLS is such that point density varies proportionally with distance within a set of measurements, with denser point-cloud close to the scanner (normally the low part of a façade, when the scanner is positioned to the ground at the foot of the wall) and sparser at distance (upper part of walls). Hence, ground and aerial photogrammetry are normally employed as methodologies able to provide complementary information in specific contexts to measure.

9.1. Non-destructive and non-contact documentation and monitoring

9.1.1. STORM project use cases

STORM project provided a common ground for the application of non-destructive and non-contact documentation technology for the purpose of damage assessment on Cultural Heritage assets from different countries. Each one of the monuments (namely, the historical centre of Rethymno, Greece; the archaeological site of Mellor, United Kingdom; the Baths of Diocletian in Rome, Italy; San Domenico square in Norcia, Italy; Roman Ruins of Tróia, Portugal; the Theatre of Ephesus, Turkey) had its own characteristics and peculiarities with respect to the scanning strategy to be adopted to better achieve the defined monitoring goal. When it was possible, both digital photogrammetry and TLS surveys were undertaken at multiple time slots and then it was possible to compare between them to highlight and interpret possible differences. The accessibility of the areas in terms of optimal documentation (i.e. availability of space around the selected areas for the measuring operations and absence of obstacles) during the period of the project, together with the possibility to position stable reference points of different types in specific locations, dictated oftentimes the strategy that was adopted for the damage assessment protocol. Indeed, although TLS is particularly suitable for mid to far distant scanning of objects, the completeness of documentation of its final output highly depends on the surface micro-morphology of the object to be measured. Typical is the case of gaps of information for the well-known 'data shadowing' (or 'laser shadowing') effect, due to the fact that the laser beam essentially acts as a light source, which will cause objects to shadow one another and holes or voids to appear in the data. In such situations, only the co-registration (advanced form of 3D point cloud alignment) of multiple scan stations can assure the completeness of the final output (Figure 30).

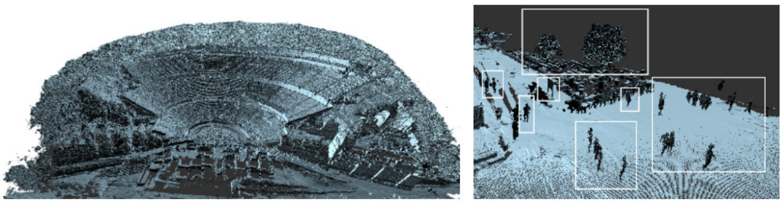


Figure 30. (a) Point cloud at the Great Theatre of Ephesus (Turkey) as results from the registration of 70 scanning stations. (b) Identification and removal of noise and inaccurate points from the final model.

The goal of the measurements in all STORM case studies was to obtain accurate information, with controlled errors, in a defined time interval so that possible changes in the wall/structure surfaces could be highlighted. To do so, data collected in each measuring session should have been comparable in terms of overall accuracy, position of scanning, covered area and final resolution. Therefore, individual measurements were taken with overall accuracy compatible with the expected minimum change to be detected and then all datasets were imported in a common reference system for comparison and analysis.

The process of data acquiring, importing and files merging was simplified with the use of stable targets (Figure 31) positioned on the surfaces to be investigated. Indeed, photogrammetry and TLS processing software often provide the possibility to recognize in automated manner targets with specific patterns in the surveyed subject. In particular, both pieces of software for photogrammetry, i.e. Agisoft MetaShape, former Agisoft Photoscan (Agisoft LLC 2019), and TLS, i.e. Faro Scene (Toth 2017), Leica Cyclone (Leica Geosystems 2019), are capable to recognise targets with a checkerboard pattern, given that their distance from the scanner/camera is compatible with the scanning

(a) (b)

Figure 31. Example of checkerboard targets (a) in a Laser scanning session in Norcia (Italy) undertaken by the Italian Fire Fighters (b) after a strong earthquake.

resolution. Furthermore, the use of common reference system allowed also the comparison of data in 2D environment, i.e. the overlaying of orthophotos from different scanning sessions, whether from the ground of from the air.

In the case of the archaeological site of Mellor (UK), the specific asset and diversity of artefacts therein (namely, the Mellor Mill, the Old Vicarage and the Shaw Cairn, Figure 32) required the integration of TLS, ground and aerial (RPAS aided) photogrammetry for the detection of potential changes triggered by winter storms and/or flooding. Indeed, the use of TLS is one part of a range of sensing and monitoring techniques in use at the Mellor Pilot site, with the Mellor Archaeological Trust (MAT) utilising UAV (drone) photogrammetry techniques in both RGB and near-infrared to survey selected areas.

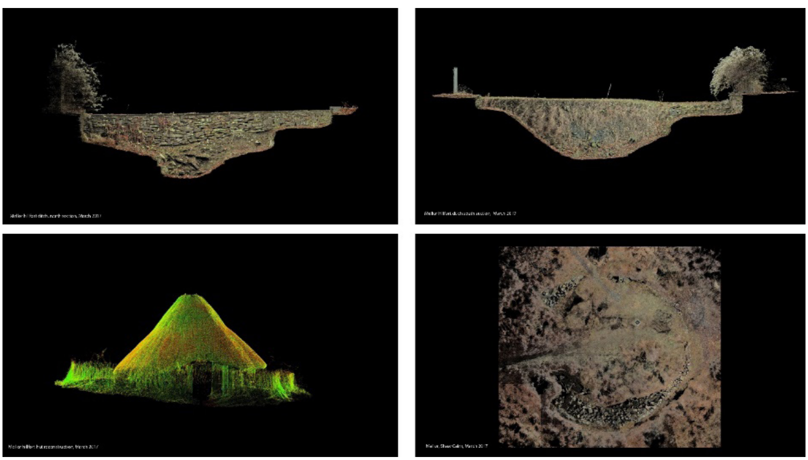


Figure 32. Point cloud generated using TLS techniques at Mellor Hillfort (Iron-Age ditch), top; Mellor reconstructed roundhouse, bottom left, and Shaw Cairn, bottom right.

In San Domenico square in Norcia (Italy), two laser scanners have been used to document the same item. At the moment of the tests, the façade of the Basilica in the homonymous square was held in place by an extensive scaffolding, built to prevent and minimize further damages following the earthquakes. Laser scanning was undertaken also with the goal to estimate the influence of scaffolding in the final accuracy and in the framework of fast change detection analysis of subsequent scannings.

In the case for the Baths of Diocletian in Rome, the goal was to assess the stability and potential damages derived by the vibration induced by the urban traffic and metro line in the close proximity of investigated structures. This was achieved mainly with the use of TLS scanning with various resolutions of sensitive areas of the complex structure (Figure 33) undertaken in 3 dates.

Furthermore, the TLS was carried out with different resolutions and purposes in Hall I and part of the Michelangelo cloister for structural analysis. Scanning was also extended with lower resolution to almost the entire building complex to ensure continuity of the 3D model to be built.

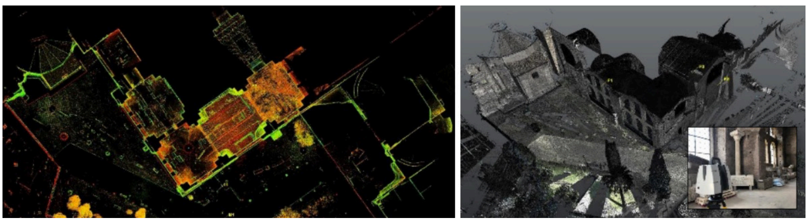


Figure 33. Baths of Diocletian: orthophoto and sample images derived from the laser scanning survey.

Different threats needed attention in Troia (Portugal), where tides and other natural agents endanger and damage coastal structures. In this case, even the simple visual comparison of 3D point cloud allows to highlight few changes in the structure of the well, more notably the lower line of stone blocks being more exposed in 2018 (Figure 34).

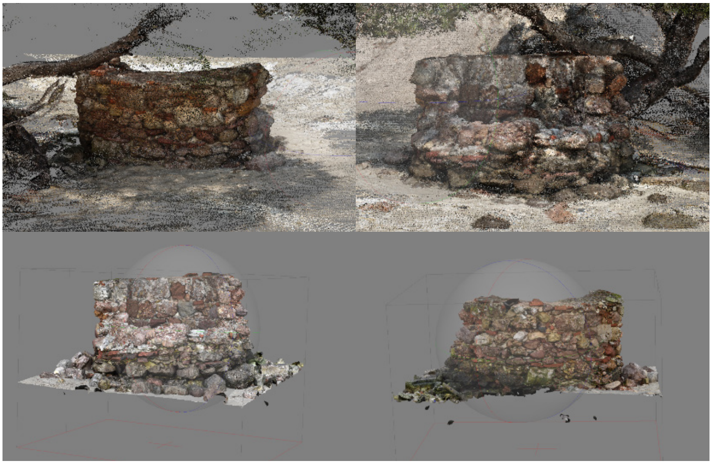


Figure 34. Views of the well as reconstructed with photogrammetric survey from September 2017 (above) and March 2018(below).

9.1.2. Conclusive remarks

The possibility to have metrically accurate digital copies of an artefact (broadly speaking) is an indispensable component especially for the documentation and monitoring of cultural heritage (Cantoro, Sythiakakis, and Manolioudis 2016). Precise digital documentation offers the basic mathematical model for further stability calculation – as for the seismic investigation at the Lighthouse in Rethymno (Greece) – and provides room for dissemination and promotion of cultural heritage at different levels (Figure 35).

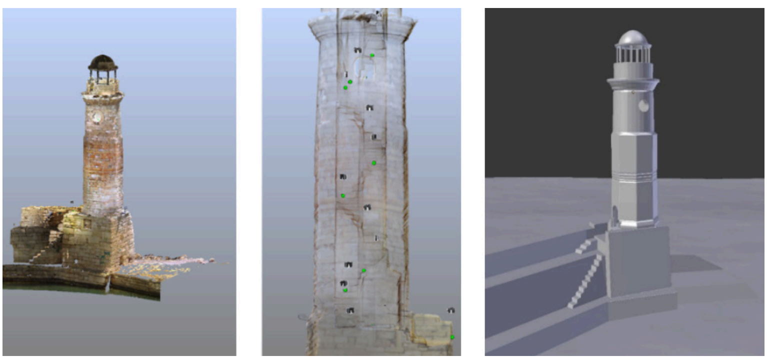


Figure 35. Point cloud (left) of the Lighthouse at Rethymno (Greece) with transparency visualization (centre) and reconstruction in computer graphics. Note also the scanning stations (represented by the TLS symbols) and the calibrated spheres (green dots) employed for the alignment of the interiors' scans in the central image.

Also in the Basilica of San Benedetto, Italy, it was possible to verify the immense utility of single scanning. Indeed, after few minutes of laser scanning, it was possible to visualize the data in colour scale and appreciate the about 20 cm overhang deformation of the upper side of the façade of that building.

Another striking example of application of single laser scanning in endangered contexts was provided in a specific area of the Diocletian Baths in Italy. In the course of the trials a further opportunity came out. On 19 Feb. 2018 a crater opened into the Baths of Diocletian garden and the CH site technicians disposed the closure of the area for safety reasons and to investigate the incident. Given the danger in approaching (let alone entering) the crater, the assessment of shape and dimensions of the area to be restricted was tricky. For this reason, it was soon carried out an operational, fast survey with a smaller type of laser scanner, which gave most interesting outcomes (see Figure 36) in less than half an hour. It was possible to assess immediately that the closure of the area was not sufficient and fenced area had to be enlarged.

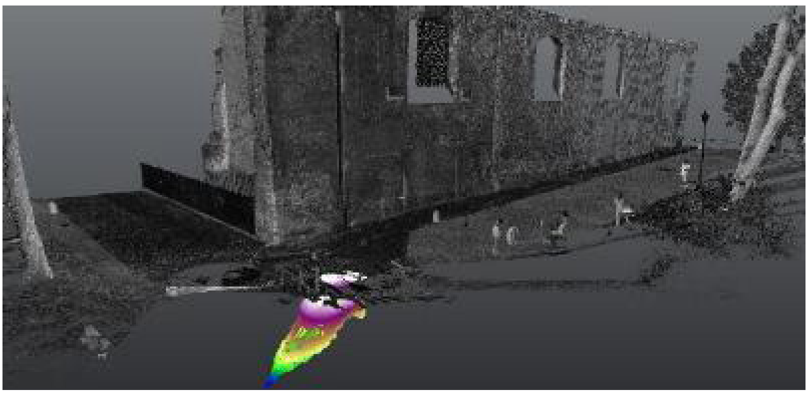


Figure 36. 3D point cloud imaging the crater in the Baths of Diocletian garden.

Laser scanning and photogrammetry are well-known and consolidated methods for the documentation of CH. Their use in the framework of STORM project has been extended in a research and experimental approach so as to produce a solid workflow capable of creating comparable results across time.

When possible, data was acquired also with the use of RPAS, as it was the case in difficult-to-reach monitored items in Fortezza of Rethymno (Greece) or in the Mellor archaeological assets (U.K.). This approach ensured also that high-resolution imagery could be captured, allowing much higher detail in the outputted imagery for the advantage of site manager, surveyors and volunteers to better assess the damages while they are still small-scale.

The easily perceivable differences, results of comparisons of digital elements (whether raster-to-raster or cloud-to-cloud) constitute a powerful tool for the understanding of the 'life' of an artefact. Below is an example of changes visualization to highlight the spontaneous vegetation growth in specific areas of the façade. Looking and data in further detail and filtering out extreme values corresponding to extruding object (namely vegetation) one can distinguish the loss of material (possible stone erosion or collapse) in specific spots of the wall (Figure 37).

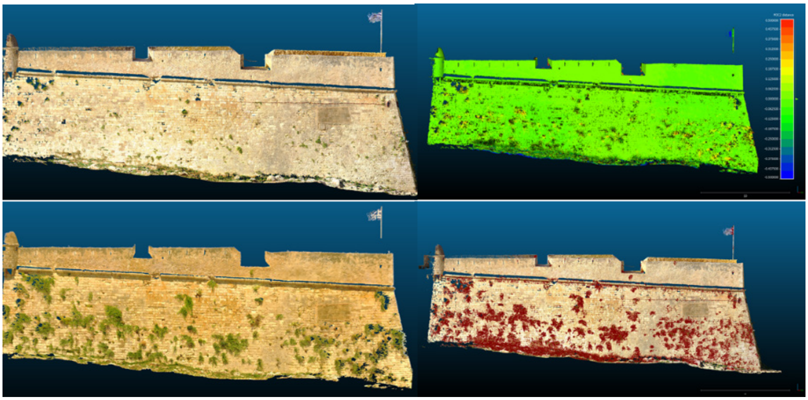


Figure 37. Fortezza Fortress, Rethymno (Greece). Frontal view of point-cloud from June (top left) and October (bottom left) 2017. On the right, two representation of dataset comparison: colour scale proportional to distance difference (top right) and statistical outlier in red (bottom right).

It is important to note that the method employed for change detection, called with the acronym M3C2 (Lague, Brodu, and Leroux 2013; James, Robson, and Smith 2017), is far more accurate than traditional cloud-to-cloud (C2C) or cloud-to-mesh (C2M) comparisons and can encompass (differently from other algorithms) for the aforementioned shadowing effect (Figure 38).

In particular, the algorithm has been implemented in a freely distributed software (CloudCompare: Girardeau-Montaut 2012; CloudCompare 2018) where users have the possibility to set parameters such as the Normals and the Projection diameters together with the registration error. All these three parameters are essential for the estimation of point-clouds' differences and the calculation of the statistically significant values.

The proposed approach demonstrates the possibility to use methods and procedures to obtain quantitative and qualitative data of a given artefact. Such information, although still in need of manual (human driven) data analysis, can provide unique information for the state of monitored buildings and

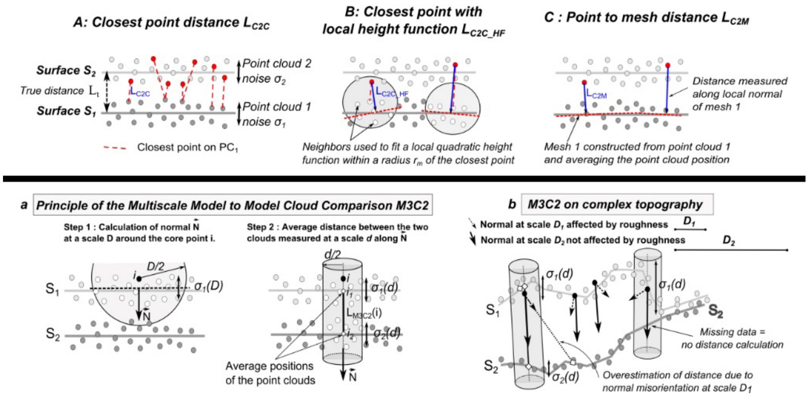


Figure 38. Schematic representation of traditional approach for point-cloud change detection (above) and M3C2 approach with visual explanation of main parameters to be set for optimal results. (Image edited from Lague, Brodu, and Leroux 2013, Figures 2–3).

can as well strongly contribute to the identification of potential issue e relative solutions. Even if the time span of the project could not grant sufficient datasets to explore long-term changes, the STORM approach showed the capabilities of detecting millimetric or centimetric changes (see the vegetation growth at Fortezza Fortress in Greece) that could drive to major damages to surfaces if not counterbalanced. Indeed, if changes are matched with vegetation growth, the availability of a difference-map can help local authorities to target counter-intervention for the preservation of artefact or to minimize potential damages derived from spotted problems. In other cases, no specific damages could be related with a particular natural event; yet, a wider timespan and further analysis in the same direction will contribute for the specific assessment of changes driven by natural events.

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4.
Data management for situational awareness enabling efficient monitoring and preservation of CH sites

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Introduction

STORM provides the tools and services to help cultural heritage sites maintain and monitor their assets. The use of these tools and sensors will help sites conduct on-going STORM prevention and mitigation plans which in turn will form a STORM conservation management plan, in which site will be required to conduct surveying and sensing activities utilising the technologies developed.

This chapter will outline the selected technologies that will aid the STORM users to conduct their surveying and diagnosis efforts. The technologies will consist of novel (e.g., utilising social media, and tailor-made acoustic sensors) and inexpensive (e.g., amateur automatic weather stations) to help sites develop enriched situations from the raw data, and enabling the site to act when such a hazardous situation occurs. The enriched situations are built on a basis of historic event detection and correlation rules. Past events have been studied, and the effects of these events have created matrices highlights cause/effect relationships. In terms of meteorolgoical events, these situations may be developed using historic events, but they also will use thresholds that are well documented and the standard in their field.

The chapter focuses on four technologies and services that have been utilised in the STORM project. The use of Automatic Weather Stations and the data analysis that has been conducted at the Mellor Pilot Site. The assessment of earthquake damage on CH assets in the pilot site of Ephesus. The novel use of event dectection utilising the social media website Twitter, extracting events from tweets posted close to the site and making use of key-word detection. Along with the use of novel acoustic sensors that will be deployed across many of the STORM pilot sites, and assess noises close to the CH assets to determine when an event may occur.

1. Detection of weather events close to cultural heritage sites

1.1. Introduction

Archaeological significant sites form a large aspect of the Cultural heritage (CH) assets participating in the STORM pilot. Notably, the UK and Portuguese pilot sites are ongoing archaeological digs that are run by either local business or charities. These remains are protected from the elements well up until the point they are excavated, become exposed and undergo degradation as a result of meteorological conditions. In the British site the archaeological remains are heavily effected by rainfall, cold spells and wind. Precipitation can either directly erode the asset, or during heavily rainfall events or rain when the ground is already saturated can lead to flash flooding which induates the archaeology. Wind again can directly erode and degrade the Archaeology, especially when considering the Shaw Cairn Area of the Mellor site. This exposed archaeological asset is located on top of Mellor Moor and windspeed can be high. Across all of the Areas there is a risk to the archaeology from nearby trees and other objects and structures being dislodged or collapsing on top the remains and causing damage. At the Mill site in particular, cold waves are of concern. Prolonged periods of cold weather are likely to lead to freeze-thaw action as the archaeology remains wet throughout the year due to its location. Freeze-thaw action will severely impact the masonry and brick work that still stands today, and such erosion is evident throughout this Area of the British pilot site.

Weather is defined as the current meteorological conditions over a small geographical area and a short temporal scale and so it is possible to monitor it directly. Climate on the other hand is the average of weather conditions over a larger geographical area and longer temporal scale, making it more difficult to monitor. The micro-climate is small changes to weather over very small spatial scale owing to local weather forcings such as topography and elevation.

Climate change will alter the meteorological conditions on long timescales. It is not possible to make an assessment on the result of climate change on archaeological remains in real-time, as climate change is something that needs to be monitored over a long period of time, for example over multiple decades. However, as weather events will be augmented, or reduced in their severity, as a result of on-going climate change, beginning to monitor the weather close to archaeological sites is vital. It is only with measurements of weather data, that future stakeholders will be able to assess the changes that occur in the next 50-100 years. For the UK pilot site, STORM has helped start this process, where the University of Salford have integrated the monitoring of weather events close to heritage into their programme, and have taken steps to ensure that the data will continue to be collected into the future.

1.2. Automatic weather stations

For the UK pilot site there was a determined effort by the site, and the University of Salford to ensure that the three areas of the Mellor pilot site, which due to their relative locations all have unique micro-climates, could be monitored. For this, three weather stations were selected and sited; one in each of the pilot site areas ensuring that information gained from the weather stations were unique to their relative area.

A key objective of the STORM project was to select novel and inexpensive tools to help monitor hazards and survey CH assets. Automatic weather stations do not fall into the novel category, although STORM has utilised many modern environmental sensors that arguably do.

One such sensor is the Environmental Sensor Network which is a set of individual nodes connect via IoT to a base station that are capable of communicating over a large geographical area. The idea with such sensors is to assess the ground temperature across the Mellor pilot site to analyse how homogenous the temperature distribution is in and around the archaeological remains.

That said, automatic weather stations are available in many price ranges and currently form the basis for the majority of weather sensing networks globally, ranging from scientific use to home and amateur use. The cost of the more sensitive and accurate equipment is constantly falling, meaning good quality weather stations are being affordable even for the most amateur of weather enthusiasts. To meet the aim of the STORM project, the weather stations that have been selected are all within the low-cost off the shelf price range. The reason for selecting the less expensive stations was to ensure that archaeology sites, especially those that are small and in the private sector would be able to purchase these sites in future roll outs of the STORM service.

One such station is the Davis Vantage Pro2 weather station. It is relative low cost, whilst retaining the accuracy and precision of some of the more expensive scientific weather stations. However, the lower costs do bring some disadvantages. Namely, the precision of the instrument may not be as good as would be expected, for example, if the precision is 1 °C then the measurement taken will be within +/- 1 °C. Furthermore, accuracy of the data will be reduced when compared to the more expensive equipment. That considered, it must be understood that for the use case described here those downsides are understandable and reasonable; the data are not needed to be extremely accurate to detect issues that may damage the CH assets and structures. Other issues with such weather stations is that they usually are packaged sensors in a single unit. Meaning air temperature, rainfall and sometimes windspeed will be measured at the same location and altitude. This is not ideal when considering sensor siting, as World Meteorological Organisation guidelines (WMO, 2008) recommend air temperature to be measured at 2 m above the ground, rainfall at ground level and windspeed at 10 m above the surface.

For the scope of this pilot site the issues were considered reasonable to deal with; the data did not need to be 100% accurate, but they needed to be relative to the area of interest. Measuring rainfall at 2 m above the surface is bad when comparing to other weather stations where rainfall is measured at ground-level (Campbell Scientific 2019), but in this study rainfall was only being compared to other measurements of rainfall at the same station. An allowance was made for the fact the weather stations siting could not be perfect.

1.3. Threshold calculation

Once the weather stations had been selected and sited as required, the stream of data from the weather stations would pass from the online database to the STORM cloud where basic pre-processing and data analytics can be performed. This analytics is critical to the function of STORM. Taking measurements of the weather conditions is one thing, but understanding when the owners of CH sites should act is another matter. The owners of CH sites often are not weather enthusiasts and are not experts in understanding what the data are showing. To overcome this a set of thresholds were selected that the platform would use to define when a hazard may be occurring. If the thresholds were overcome, the site manager would receive a warning that an event could be occurring and that they should take steps to check and react as defined in their STORM risk management strategy plan.

On the one hand, such thresholds are based on indices from the Expert Team on Climate Change Detection and Indices, who defined various parameters to capture climate and climate variability. One example, used in STORM to describe intense precipitation is for example a 'heavy precipitation day', which is defined as a day with a daily rainfall sum of 10 mm or more.

However, such thresholds do not take the local conditions into account. When considering out of the ordinary, extreme events, a statistical approach is needed as well. This is best illustrated looking at an example: what is considered an extreme temperature in Mellor (UK) might not be extreme in Ephesus (Turkey) at all. To take such regional differences into account, the thresholds used in STORM are not only based on absolute values, but also determined using statistics based on meteorological observations taken in the vicinity of the site to define values that are considered extreme for the pilot site location. Using e.g. the 95th percentile of daily maximum temperatures, a threshold may be set for high temperatures (23.1°C for Mellor vs 35.1°C for Ephesus).

In order to obtain proper statistics, long-term records (ideally 30 years or more) of meteorological observations are needed for such a derivation. As generally such long time series have not yet been recorded at the CH sites, data from other stations in the vicinity of the site may be used. In the Mellor case, data from the UK Met Office Ringway station for the time period 1971-2000 were used.

In Table 1, the different meteorological hazards as well as the suggested threshold definition are outlined.

Table 1: Different meteorological hazards as well as the suggested thresholds. The value of the statistics-based threshold is added in the final column. Ringway data courtesy of the UK Met Office.

Hazard / warning	Threshold definition (based on the existing long-term 1971-2000 time series/absolute values)	Threshold
Extreme temperature (high)	95th percentile of maximum temperature (tx)	23.1°C
Extreme temperature (low)	5th percentile of minimum temperature (tn)	-1.9°C
Heat wave - unusually many summer days	90th percentile of summer days (su)	17.0 days
Heat wave – unusually long heat wave	90th percentile of yearly maximum consecutive summer days (csu)	7.0 days

Cold wave – unusually long cold wave	90th percentile of yearly maximum consecutive frost days (cfd)	14.3 days
Frost event	Day with daily minimum temperature < 0°C (fd)	-
Freeze event	Day with daily maximum temperature < 0°C (id)	-
Freeze-thaw event	Day during which the maximum temperature > 0°C and the minimum temperature ≤ -2.2°C (ftd)	-
Intense rainfall – heavy precipitation day	Daily precipitation sum ≥ 10 mm (r10mm)	-
Intense rainfall – very heavy precipitation day	Daily precipitation sum ≥ 20 mm (r20mm)	-
Intense rainfall – Extreme maximum 1-day precipitation amount	90th percentile of yearly RX1day (maximum 1-day precipitation amount)	38.8 mm
Prolonged wet period	90th percentile of yearly maximum consecutive wet days (cwd)	14.0 days
Prolonged dry period	90th percentile of yearly maximum consecutive dry days (cdd)	24.3 days
Strong wind	See e.g. the TORRO scale and set threshold(s) as needed based on damage description (https://en.wikipedia.org/wiki/TORRO_scale)	-

1.4. Event Detection

At the time of writing, the integration of the data analytics component had not been completed within the STORM service. This section will therefore, discuss some of the offline analytics that have been conducted on the weather data by the UK team at Sparta and Mellor Archaeological Trust to illustrate what type of information may be gathered from the basic data analytics that will be conducted within STORM.

Once a threshold had been breached the platzform will send a notification that an event may be occurring. But this is in real time. The analytics can be conducted in a way that assesses for example, the number of times certain thresholds have been breached. This would be useful to assessing the state of seasons or years, help drive comparisons between years and understand how year-on-year changes may be evolving. The following analysis was conducted throughout the period 2016-2018 with the summer of 2018 being notably dry and warm across the UK and much of western Europe.

Utilising the R programming language (R Core Team, 2013) some basic data analysis have been conducted as to show how the data will be useful to site owners of CH using the STORM platform. Using the aforementioned thresholds, the weather data were analysed to show how often the thresholds were overcome, and in those instances could this be correlated to real, reported hazards at the site itself.

R is a statistical programming language built for data analysis. There are a plethora of packages which are a set of functions written by the large user community. The packages can be installed on the fly, as the R scripts are run, and as the corresponding function is required. R is a scripting language. The XTS package is extremely useful when dealing with time series data. This package brings function to convert data frames into XTS objects and the weather station timeseries are manipulated this way.

```
dat.summerday.xts <- xts(data.m$Temp, as.POSIXct(data.m$Date.Time))
```

here, the dataframe “data.m” which consists of two columns, air temperature and date and time, are converted from a data.frame (R’s standard table format) to a XTS object.

Utilising the aforementioned variables and thresholds that were selected for STORM, the simple R script is capable of analysing the data, outputting the number of times throughout the timeseries these events have taken place. For example, frost days (defined as a day where the minimum temperature dropped below 0°C) have occurred 59, 86, and 48 at Shaw Cairn, Mellor Mill and Mellor Old Vicarage respectively. The script could also illustrate the number of times that such events occurred over five or more consecutive days: 3, 3 and 2 for the same sites.

Example lines from the data analysis script can be found in the below:

```
#####
dat.frostday.xts <- xts(data.m$Temp,
                as.POSIXct(data.m$Date.Time))
ends <- endpoints(dat.summerday.xts,‘days’,1)
frostdays <- period.apply(dat.frostday.xts,ends, mean)
frostdays <- data.frame(date=index(frostdays), coredata(frostdays))
frostdays <- subset(frostdays, frostdays$coredata.frostdays <=0)
#####
```

The above lines aggregate the data into daily averages, then a subset of the data; selecting a subset of data where only those datapoints where daily average air temperature is, in the case of frost days, equal to or less than 0 °C.

The analysis was conducted on measurements between 1 December 2016 to 24 July 2018. Thus encompassing large weather events like ex-Hurricane Ophelia (October 2017), the ‘beast from the east’ (Feburary 2018) as well as the start of the 2018 prolonged summer heatwave (June-August 2018). Each of these events brought different hazards to the Mellor pilot site (High winds for ex-Hurricane Ophelia, Prolongued coldwave during the 'beast from the east', and dry spells for the summer drought of 2018).

The following lines then calculate the number of times the event has taken place for five or more consecutive days, the program then prints the answer. The threshold can be altered on the fly, as well as the counter for number of days.

```
on_trot_dat <- function(x, n){
 counter1 <- 0
 counter2 <- 0
 y <- list()
 for(i in 1:(length(x) - 1)){
  if(abs(difftime(x[i], x[i+1], units = "days")) == 1){
   counter1 <- counter1 + 1
     } else{
   y[[i]] <- x[i-counter1:i]
   counter1 <- 0
     }
 }
   print(paste("The data exceeded the treshold value on", n, "consecutive day(s)",counter2, "times"))
 y <- return(y)
}
```

This type of analysis proved very useful to experiment with and test the sensor usefulness, the archaeologist at the University of Salford could compare the results of the analysis to real situations that they documented for example, in the aftermath of ex-hurricane Ophelia. This cursory analysis highlights the usefulness final STORM package as such analyses may be available through the platform utilising the data analytics component once it is available. An extract of the data analysis discussed in brief here is illustrated in Figure 1.

The next stage will be to integrate the data analytics discussed in this chapter with into the STORM platform, this combined with the thresholds that have been defined in the project will enable the service to simple and complex event and in turn generate sitatuions for which the site managers of CH will be able to react to, pottentially preventing or mitigating the damages caused.

Mellor Pilot Site Weather Data

Date range: 1 December 2016 to 24 July 2018
Total Number of Observation Days 601

Shaw Cairn

	Number of Days	Instances of 5 Consecutive Days or more
Summer Days	12	0
Frost Days	59	3
Dry Days	219	8

Oldknow's Mill

	Number of Days	Instances of 5 Consecutive Days or more
Summer Days	26	1
Frost Days	86	3
Dry Days	229	7

Mellor Hillfort

	Number of Days	Instances of 5 Consecutive Days or more
Summer Days	22	0
Frost Days	48	2
Dry Days	215	10

Figure 1. Mellor Pilot site weather data summary for the period 1 December 2016–24 July 2018 (Nevell *et al.*, 2019).

2. Earthquake emergency response and rapid damage assessment for historical buildings

2.1. Introduction

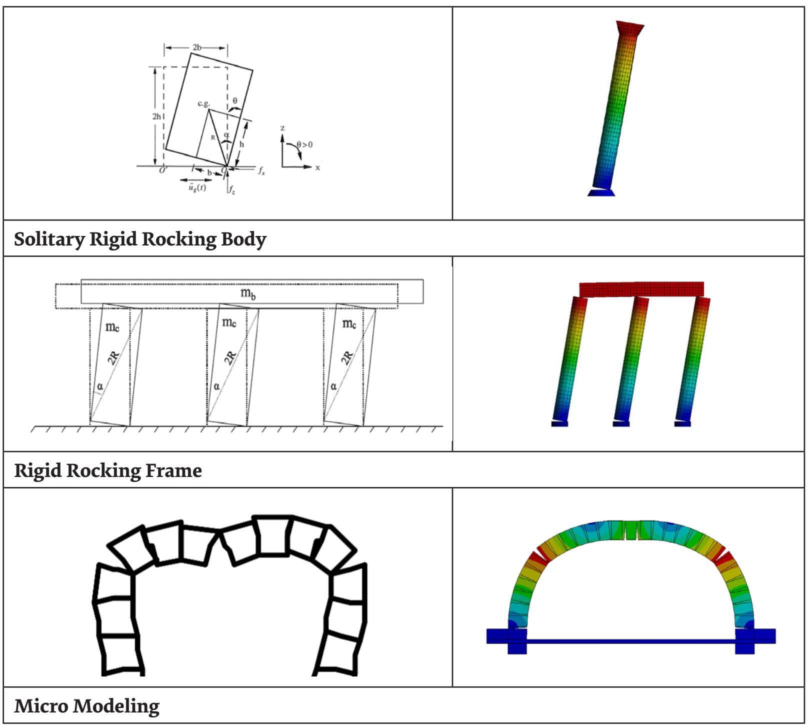
The damage to cultural heritage assets during past earthquakes (L'Aquila 2009 and Emilia 2012), showed the high vulnerability of historical structures. The earthquake performance of historical structures during earthquakes is a challenge regarding not only structural and architectural components, but also movable (paintings, statues, libraries) and unmovable (frescos, stucco-works, pinnacles, battlements, banisters, balconies) artistic assets contained in it (D'Ayala, Lagomarsino, 2015). Emergency response for CH structures considers a critical situation which should involve the recovery, restoration or maintenance actions for the protection of the asset. The STORM project, which is being implemented in this context, aims to develop an integrated platform for the monitoring and control of environmental and human-induced risks of historical structures at pilot sites in Europe.

The emergency response approach for STORM makes use of mainly two sources of information, pre-earthquake engineering and post-earthquake-operational. Before the earthquake, the numerical model of the structure is developed to determine the performance-based building damage threshold levels of the structure. For this purpose, three main performance criteria are considered, namely, artistic, architectural and structural. For the post-earthquake respond, a structural health monitoring system is constructed. In case of an earthquake, the system will automatically collect and process the actual data coming from the site and compare it with the threshold value of the Engineering Demand Parameter (EDP) in question and provide preliminary information about the extent of the damage in the CH structure. In this way, the authority would be able to determine if it is safe to enter and use the structure. The possible damage to the architectonic and artistic features will be analyzed in the next few seconds and a warning message will be sent to authorities by short SMS message. The platform will also provide a resilient communication to ensure that the acquired data is safely transferred from the source to the user during and after disasters. The system architecture of the STORM platform is flexible so that it can be updated under the light of new information and data for new sites. It is therefore, particularly useful for the quick damage assessment and emergency response of CH structures and determination of triage especially in geographically dispersed sites after earthquakes.

The earthquake risk strategy for CH aims to develop a structure specific risk strategy to improve risk preparedness (ICCROM 1998). The structures of architectural heritage present a number of challenges in diagnosis and restoration that limit the application of modern legal codes and building standards. ICOMOS, 2003 indicates that no action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in cases where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g. after seismic damages); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way. Preservation principles for seismic retrofit projects indicates that historic materials should be preserved and retained to the greatest extent possible and not replaced wholesale in the process of seismic strengthening. New seismic retrofit systems, whether hidden or exposed, should respect the character and integrity of the historic building and be visually compatible with it in design; Seismic work should be 'reversible' to the greatest extent possible to allow removal for future use of improved systems and traditional repair of remaining historic materials. Considering all these restrictions and the huge amount of CH structures to be retrofitted, it is obvious that most CH structures will remain vulnerable to earthquakes. Therefore, it is important that the disaster risk management strategy for CH structures should not only address engineering (retrofitting and strengthening) but also operational aspects, such as stabilization, preservation, conservation and first aid.

Quick Damage Assessment: Immediately after the earthquake, the site manager would like to know the answer to the question "who will do what?". QDA aims to provide operational information to authorities about the level of earthquake damage within a few minutes of the earthquake. It will therefore be useful to help develop emergency response plans for the preservation and recovery of historical items that may be exposed to public particularly for sites in remote regions.

Numerical modeling: The seismic performance of a structure depends on its geometrical, materials and structural properties. The determination of the seismic behavior of historical structures is difficult to obtain by the use of common engineering methods. Masonry structures are composed of sub units that have different shapes and materials, which have different properties. Thus, numerical modelling is the most preferred method for masonry structures. In order to solve the engineering problems correctly, it is essential that the numerical model is established correctly. There are several different modeling approaches used today for this purpose (Figure 2).



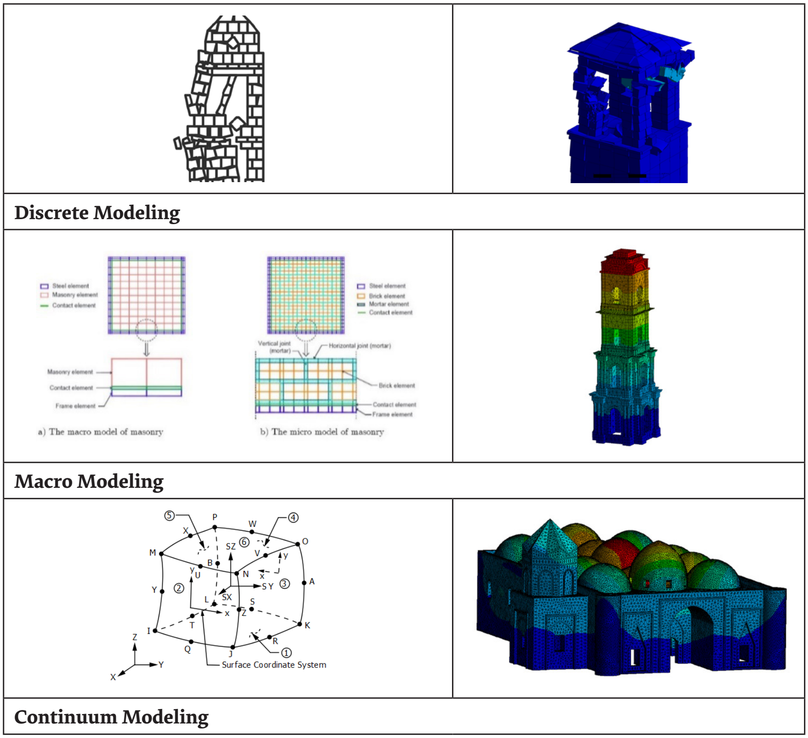


Figure 2. Modelling techniques for different types of historical structures (Cakir *et al.*).

2.2. Use in the STORM Project

The Ephesus amphitheater was chosen as the pilot site in Turkey. The north entrance of the Ephesus theatre was considered as the most vulnerable part of the structure since there is no load bearing system, hence structural integrity is lacking. Therefore the response of the system is unpredictable and complex.

Four different earthquake levels, DD1, DD2, DD3 and DD4, are selected (Table 3) and the analyses are conducted on the simplified model of the north entrance of the theatre.

Table 3. Description of selected earthquake levels based on the Turkish Building Earthquake 2018 regulations.

Earthquake Level	Description
DD1	The earthquake, which is defined as DD1 (Earthquake Level 1) represents the strongest earthquake in the direction of the earthquake. This proves that the earthquake might happen once in 2475 years. It is a rare and a big one.

DD2	The earthquake, which is defined as DD2 (Earthquake Level 2) is the earthquake seizure based on the design earthquake. The probability of exceeding this earthquake in 50 years is 10%.
DD3	The earthquake with DD3 (Earthquake Level 3) represents the earthquakes that are frequent. The repetition period is 72 years. However, in the case of the most recurrent period of 2475 years, the most frequent earthquake occurred in 72 years.
DD4	DD4 (Earthquake Level 4), which is the earthquake period of 43 years. The repetition is repeated very often.

Nonlinear numerical analyses were performed to calculate the expected damage forms of the north entrance of the theatre for different earthquake levels.

Structural Health Monitoring (SHM): Digital signal processing (DSP) is a useful tool to analyze the vibration data provided from sensor locations. The sensors can be located at different positions, but most typically, at the base and top of the structure. As a result of this it can be possible to detect changes in the structural properties, hence, to identify the characteristics of the structural system. In cases when vibration data is not available at the top of the structure it can be calculated analytically by referring to the vibration record at the base of the structure.

Matlab applications: Two Matlab alghorithms were developed for online processing of the measured vibration data for the two different types of structures: Ephesus theatre and ancient pillar. For the stone blocks of the Ephesus theatre the peak acceleration of the structure was considered as the damaging parameter. Four threshold damage levels (D1-D4) were considered. During the course of the project, a rigid rocking body (near the Celsus Library) was also studied. Real time sensor data was not available from the structure. Therefore, a Matlab code was developed to calculate the response of the structure to the recorded ground motion in near real time. Details of the procedures will be provided in another paper.

3. Event Detection from Social Networks

3.1. Introduction

Social Networks are nowadays frequented by many millions of people providing a huge amount of information of various kinds. Processing of data coming from social platforms has attracted attention during last years due to the widespread availability of data and the ease to access to them. These data can be extracted and analysed to detect relevant information and identify several kind of threats in different contexts. Among Social Networks, Twitter is one of the most popular and a blogging service able to provide relevant information for situation awareness and decision making support. Herein is presented a novel approach for detecting dangerous events affecting the STORM heritage pilot sites analysing real-time data incoming from the Twitter stream. An approch based on tweets semantic analysis, rule classification, and time-space detection models has been implemented and applied to the STORM heritage sites for detecting hazardous natural events (e.g. earthquakes, storms, fires) and related consequences (e.g. transportation system failures, lifeline failures, structural failures).

The process of gathering information from the field requires an infrastructure able to retrieve data from multimodal sources and process them in order to detect events. Advanced emergency management systems aim to provide these functionalities producing situation awareness and supporting decision making during the critical situation. In this context, online stream data processing has become an important technology for many applications, such as trader behavior evaluation in financial markets, patient monitoring in health facilities, surveillance and protection of critical infrastructures and areas (e.g. train stations, airports, world heritage protected areas in historical cities) and so on. In all of these applications, the amount of data being generated requires online processing and immediate reaction in order to be managed in an efficient way.

By means of the possibility to easily link persons, facts, events and places through a large quantity of online geo-referenced data, users are the real producers of current information about social phenomena and dangerous events as 'human sensors' providing qualitative, and sometimes quantitative, information.

Among social networks, Twitter (Twitter 2018) has recently received much attention for its particular characteristics such as services portability, communication immediacy, ease of use, and the possibility to access the user data stream. Twitter is a fastest-growing microblogging (Java 2017) with online social networking services. Microblogging is a broadcast medium that allows users to exchange small digital content such as short texts, links, images, or videos. On August 2017, Twitter has been the most popular and fastest-growing blogging service, with more than 328 million users producing over 500 million tweets per day, (Statista 2017) (Omnicore 2017)[5]. Messages posted on Twitter (tweets) report from people daily-life stories, to the latest local and worldwide news (Hurlock 2011). Event detection from Twitter stream introduces several challenges: i) the huge amount of data in twitter stream may affect event detection time preventing the proper timely reaction; ii) twitter stream contains large amounts of meaningless messages and polluted content (Castillo 2011) which negatively affect the detection correctness. Furthermore, the presence of large amounts irregular and abbreviated words, grammatical errors and improper sentence structures, implies that traditional text mining techniques are not suitable for tweets classification.

Processing of data, retrieved from Twitter and sensor networks deployed on the field, allows identification and detection of dangerous events in a specific application domain. Such online approach enables the recognition of a critical situation when it happens.

3.2. The Twitter event detection in STORM

Event detection from Twitter cannot be performed analysing the content of the single tweet, but a mechanism of real-time analysis of the tweet stream should be used in order to select relevant information from tweet groups and analyse them respecting precise time and space requirements. In particular, the process of detecting events from the Twitter stream in STORM is made up by four steps: i) extraction of relevant domain tweets; ii) classification of domain tweets; iii) tweets frequency evaluation; iv) localisation of events.

Very briefly, the Twitter data extraction has been performed accessing to the Twitter stream using the Twitter Streaming API (Twitter Developer, 2017). Such API, applying a set of relevant keywords related to the STORM hazards, provides tweets containing the specified keywords. Keywords have been be accurately selected in accordance to a measure of relevance for the specific STORM hazards. The keyword relevance measure used in this approach is keyness (The Grammar Lab 2017). Keyness provides an indicator as a content descriptor and it has been automatically evaluated analysing a very large collection of texts, written in natural language, in which topics related to the STORM hazards are discussed.

Once that the domain tweets are extracted from the stream, they have to be classified. Each class corresponds to an event: if a tweet belongs to a certain class, it is related to the corresponding event. Classification is performed by a set of rules applied to the text of the extracted tweets. The application of the rules consists of checking in the tweet text the existence of precise words combinations. Each class is associated to a rule, if the tweet verifies the rule, the tweet belongs to that class. Each rule is expressed as a logic function, whose terms are represented by keywords selected by the experts and logical operators.

The event detection method is an empiric method based on the examination of the stream behaviour during the occurrence of the events. Studying the frequency of tweets both during 'normal' conditions, when no events are in progress and in 'alarm' conditions, when an event is occurring, it was noticed that: when an event occurs, the frequency of tweets related to that event grows so as to produce spikes. The intensity of the spikes is variable according to the differences between the observed phenomena. These behavioural differences imply that events cannot be recognized using constant thresholds on the tweet frequency but it is necessary to adopt variable thresholds able to adapt to different situations.

The process of tweeting as been modelled with a mathematic model called homogeneous Poisson process [19]. The Poisson process is a simple and widely used stochastic process for modelling the times at which arrivals enter a system [29]. It is usually used in scenarios where the occurrences of certain arrivals happen at a certain rate, but completely at random (without a precise structure). Using this model the probability that a classified tweet is relative to an event occurrence can be evaluated in real time, hence it is possible to detect STORM hazard occurrences.

The last step for the event identification is the localisation where the hazard occurs. The process of localisation has been performed through adopting two different approaches: i) the identification of the locations of interest in the tweets text that are the STORM pilot sites; ii) the GPS localisation based on the distance between the GPS coordinates of the tweets, and the coordinates of the identified location of interest. During the experimentation it was noticed that only about 2% of the tweets are GPS located by the Twitter users and for this reason, the text analysis localisation proved to be more effective then the GPS localisation.

3.3. Implementation and experimentation results

The methodology described in the previous section has been implemented in the (Twitter Event Detector) TED tool that has been integrated in the STORM platform as an event source toghether with the phisical sensors deployed on the field. Information produced by the TED, active 24 hours per day, is correlated with information coming from the phisical sensors in order to produce the situation awareness.

The TED graphical user interface allows the user to enable the rules and set the parameters used for identifiyng hazard occurrences.

Herein the results of the experimental campaign performed from October 9th 2017 to May 23th 2017 are described. This experimentation permitted to: i) validate the TED using a huge amount of collected data, ii) tune the tool configuration for improving the level of precision in detection of useful info, iii) execute a sensitivity analysis on event detections varying the extraction keywords. This experimentation has been performed on the Baths of Diocletian italian (BoD) site.

The following set of events has been identified for the BoD: i) Fires ii) Lifeline Failure (e.g. blackout, lack of gas or water), iii) Structural failure, iv) Telecommunication System Failure, v) Terrorism, vi) Thunderstorm, vii) System Transportation Failure, viii) Vandalism.

The experimental campaign has been divided in four sessions. Each session is a period of time in which the tool has worked with a specific set of extraction keywords. For each session, useful info detected have been analysed and the correct detections have been separated from the fake detections. Furthermore, during the experimentation keywords have been extended for each session considering the obtained results.

The detection rules for tweet classification and event detection have not been changed compared to those decided by the end of the first phase.

During the period of this experimentation 11628 tweet bursts (set of tweets regarding a specific hazard) have been detected by the tool. Among these bursts, 645 events involving the BoD have been detected. Details on data collected for each session are shown in Table 4.

Table 4. Details on Collected Data for the Experimentation.

Session	Period of Time	Total Useful Info Detected
1	10/09/2017 – 11/21/2017	145
2	11/22/2017 – 01/21/2018	188

3	01/22/2018 – 03/07/2018	171
4	03/08/2018 – 05/23/2018	141

Output of the TED has been examined for each session in order to evaluate detection precision. For each session Figure 3 reports, on the left part, the number of the correct detections together with the number of the fakes. This is done for each class of useful info related to a precise hazard. On the right part of the figure, the precision of the detection is depicted. For each hazard detection is reported the relative precision.

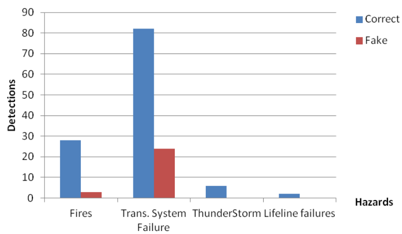


Fig. 3a. Results in Session 1.

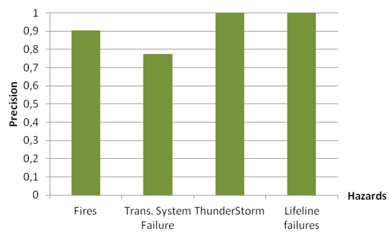


Fig. 3b. Results in Session 1.

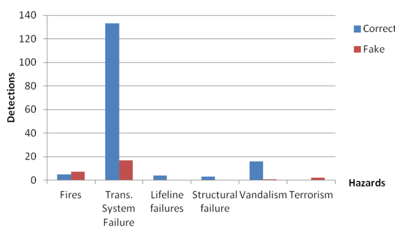


Fig. 3c. Results in Session 2.

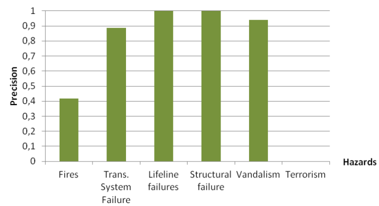


Fig. 3d. Results in Session 2.

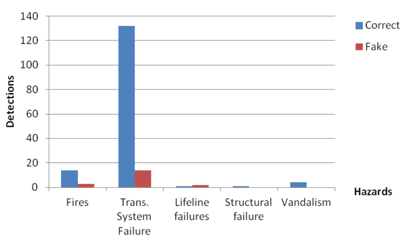


Fig. 3e. Results in Session 3.

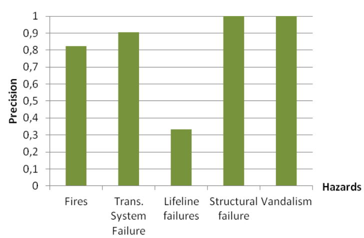


Fig. 3f. Results in Session 3.

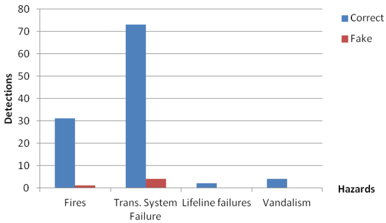


Fig. 3g. Results in Session 4.

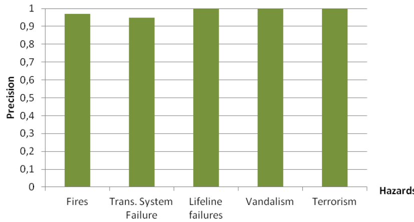


Fig. 3h. Results in Session 4.

Figure 3. Experimental Campaign Results of the TEE.

It is important to remark that precision grows with the application of different extraction keywords through the sessions. This result is better highlighted by Figure 4 showing the trend of overall precision through the different sessions.

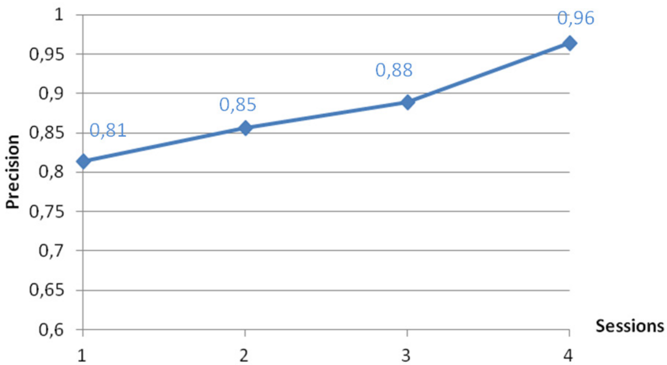


Figure 4. Precision evaluated in the four Sessions.

However, it has to be considered that at the beginning of this campaign, the tool configuration of was already well set up by the first experimentation. This is the reason why the result of this second campaign is already good since the first session.

Table 5 reports the extraction keywords used in the last fourth session. Actually, as for the BoD, Italian words have been used for getting a huge amount of tweets. However, in order to provide an easy comprehension, keywords have been translated in English from Italian.

Table 5: Extraction Keywords applied to the BoD.	
Alert (useful info)	**Keyword Set**
Thunderstorms/ Lightning	lightning, thunder, storm, clouds, loud, bolt, thunderbolt, rumbling, thunderclap, crack, rumble, roar, crash, boom, thud, fork lightning, sheet lightning, colour, sound, rumble, weather, severe, storm, hail, rouse, sky
Structural failure	crack, cave, structural failure, collapse, fail, crack, victim
Fires	fire, flames, smoke, burning, burnt, plume, spreading, hot, heat, flaming, red hot, inferno, combustion, bright, firefighter, safety, bang, engineering, extinguish, wood, bomb, barn, first responders, wildfire, fire preparedness, fire protection, rescue, risk, burning
Transportation system failure (e.g. train/aircraft crash and major road accident)	connection, transport, congestion, traffic, urban, tilt, stop, block, interruption, train, car, railway, railroad, truck, road, highway, accident, derailment, practicability, driveability, municipal, work, collision, crash, no entry, close, vehicle, hospital, circulation, overturn, die, dead, grow, caution, centre, transit, passage, stretch, severe, direction, victim
Telecommunication system failures	interruption, internet, failure, telephone, communication, interrupt, stop
Lifeline failures (e.g. electricity and gas lines)	electric, power, supply, distribution, water, gas lines, area, methane, failure, blackout
Vandalism	vandal, chavs, scaly, wasters, stealing, thieving, robbed, stolen, thief, destroying, lifting, ruining, hoodie, spate, crime, thriller, mystery, t-shirts, sensible, crime scene, fire, badboy, writer, scally, crime story.
Terrorism	terrorism, dead, terrorist, attack, bomb, explosion, islamic, jihad, victim, massacre, kill, killer, assassin, terroristic, fear, threat, risk, alert, allah, disaster, injured, disaster, isis, islam, alarm, aggression, police

These experimental results highlight that improving the set of the extraction keywords the correctness of input data grows leading to a better detection of the events. Precision reached the value of 96% during the last session of the campaign, however the tool will be also improved during the STORM platform testing phase.

The TED have been applied on the five STORM heritage sites. Better results have been collected using the laguage spoken in the country in which the site is located, as for Italian for the Baths of Diocletian in Rome or English for the Mellor site in Manchester. In particular, during July 2018, the TED have detected several events related the big fire that affected the woods near Mellor threatening the site.

5. Event Detection using Wireless Acoustic Sensor Nodes (WASN)

5.1. General

Classification of environmental sounds has attracted significant research attention due to its linkage to economic growth and environmental protection (Michener et al., 2001; Karsten et al., 2012). Among others, this fact is also reflected in relevant directives of the European Commission as well as periodical reports of USA state and federal agencies (EU, 2002; Sueur et al., 2008; Joo et al., 2011; Tatlas et al., 2015). A key task during the initial stage of the STORM project deployment was the comprehensive state-of-the-art survey of the most current sound classification techniques, with the goal of building upon it and delivering an efficient yet portable acoustic classification platform that would meet the project requirements (Mitilineos *et al.* 2015; Mitilineos *et al.* 2018). Sound classification relies on the designation of a series of carefully selected sound features that collectively represent essential information about the sound sample and are able of being used in order to discriminate between samples. As an example of a sound feature, consider the zero crossing rate (ZCR) which is the number of times that a given time-series crosses the zero line. Given that a sound sample is in essence a time-series of samples acquired over a period of time, it arises that similar time-series features may be calculated for each sound sample and then fed to an appropriately designed classification tool. The selection of sound features directly affects the performance of the classification procedure. A variety of sound features have been proposed in the literature in order to perform environmental sound monitoring.

On top of the already mentioned ZCR, there is a long list of features that are based on the time-domain representation of the signal, such the signal linear prediction coefficients (LPC), signal energy, volume etc. As long as the frequency-domain representation of the signal is concerned, there are the pitch, bandwidth, fundamental frequency, spectral peak, track, brightness etc., mel-frequency cepstral coefficients, short Fourier coefficients etc. There are also many statistical features like the variance, skewness, kurtosis, median, mean value, as well as various complexity measures (entropies, information) of the signal; more spectral features used include the 4-Hz modulation energy, percentage of low frames, spectral centroid, spectral roll-off point, spectral frequency, mean frequency, and high and low energy slopes (Mitilineos *et al.* 2018).

Nevertheless, neither time nor frequency domain features per se do provide any information about the temporal evolution of the signal. Thereupon, time-frequency (TF) features have been introduced in order to capture the spectral variation with time. TF features are effective for revealing non-stationary signal aspects such as trends, discontinuities and repeating patterns. The usual approach is to extract spectral features for each frame, allowing a certain percentage of overlap between adjacent frames, and then concatenate spectral features in order to produce a new time-series of spectral signal content versus time.

As an example, one may consider spectrograms, scalograms, or even MFCCs and Fourier coefficients over time. Furthermore, various techniques have been proposed in order to reduce the arising high TF features' dimensionality, including flux modeling. After extensive search, we adopted the Gaussian Mixture Modeling (GMM) technique for TF feature dimensionality reduction. Furthermore, after careful consideration and overview of the available literature, we chose to use the following features in our platform: zero-crossing rate, pitch, bandwidth, MFCCs, spectrogram coefficients, and a variety of statistical features, namely different complexity measures (Shannon, Tsallis, wavelet and permutation entropies). In order to capture the temporal variation of spectral features we calculated the GMM of each one of them. Our goal for this selection of features was to keep a high level of performance and robustness while maintaining ease of implementation and low complexity.

A short discussion on wavelet denoising and the adopted GMM technique follows; for more information, the interested reader may refer to (Mitilineos et al., 2018) and references therein.

5.2. Wavelet denoising

One way of reducing the noise contaminating a signal is to decompose the latter into a number of components (decomposition levels) using the discrete wavelet transform (DWT) and an appropriate orthogonal wavelet basis (Mallat 1989) and then to reconstruct it using only the components that correlate to the useful signal. This is possible by (hard or soft) thresholding that reduces those components' coefficients that correspond to noise (Donoho 1995). Herein, both the decomposition and reconstruction processes were performed using Mallat's fast algorithm (Mallat 1989), resulting to a good time resolution at high frequencies (low scales), and good frequency resolution at low frequencies (high scales).

5.3. Gaussian Mixture Modelling (GMM)

A mixture model is used in statistics in order to represent the presence of data subpopulations within an overall population without the need to identify such subpopulations explicitly. We are using GMM in order to statistically fit MFCC and spectrogram coefficients evolution over time to a probability distribution function (PDF). GMM essentially dictates that the empirical PDFs of these coefficients are the weighted sum of Gaussian PDFs of different mean values and standard deviations. With the proposed platform, the user selects the number of Gaussian PDFs to configure the GMM and the Expectation Maximization algorithm is used in order to calculate their parameters. The PDF of a GMM is defined by

$$p(x) = \sum_{i=1}^{G} w_i g(m_i, \sigma_i) \quad , \qquad (1)$$

where is the total number of Gaussian PDFs participating in the GMM, is the weight of the Gaussian PDF, and is a Gaussian PDF of mean and standard deviation.

5.4. Proposed platform functionality

An overview of the proposed sound classification platform's functionality is available in Figure 5 (Mitilineos et al., 2019); (Mitilineos et al., 2018). First, the captured sound signal is optionally denoised using the wavelet analysis procedure that is described in the previous sub-section, while silent parts of the captured signal are cropped prior to feature extraction. The recomposed signal is normalized and its features are calculated. After applying GMM for reducing the dimensionality of the TF features, the corresponding GMM parameters are passed over to a number of fully connected and independently optimized Artificial Neural Systems (ANSs). Following the independent ANS outputs, there is a fusion module that implements an ensemble learning approach and essentially provides a final sound estimate that is more accurate and robust compared to the average ANS output. The final sound class estimate is forwarded to the STORM cloud through the WASN infrastructure and archived for future reference. A set of rules is also expected to be applied at server-side to the incoming sound event notifications and possibly trigger further action from the stakeholders' part. Details about the implementation of the proposed ANS architecture may be found in [Mitilineos et al., 2019].

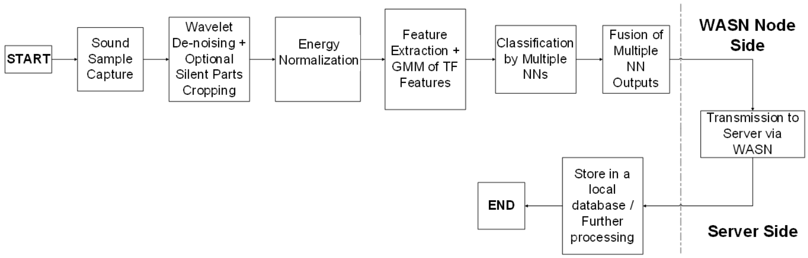


Figure 5. Proposed platform functionality.

The key part in combating noise and leveraging the performance and robustness of the proposed platform is the introduction of a number of fusion rules upon the ANSs' outputs. Regarding the ensemble learning approach that we introduced in [Mitilineos et al., 2019], we proposed that when combining multiple neural networks we can define fusion rules for obtaining equal or better accuracy, in a manner that is more robust and for a larger range of negative signal-to-noise (SNR) values compared to mere optimal ANS selection. The ANS metrics that are used in order to evaluate the performance of each ANS and its voting weight in the final ensemble outcome are (a) the number of epochs needed for convergence during offline ANS training (b) the accuracy percentage of the network upon the entire offline dataset (c) the accuracy percentage of the network upon the offline training dataset (d) the accuracy percentage of the network upon the offline validation dataset and (e) the accuracy percentage of the network upon the offline testing dataset.

In this context, we propose 5 different fusion rules that are tabulated in Table 6. The first rule is to linearly combine the weighted outputs of all networks, with the weights being directly proportionate to each network's number of epochs needed for convergence (fusion rule #1). The second rule is to obtain the linear weighted combination of all networks' outputs with the weights being directly proportionate to each network's performance accuracy upon the entire offline dataset (fusion rule #2). The next three fusion rules are also linear weighted combinations of all networks' outputs with weights being directly proportionate to each network's performance accuracy upon the offline training, validation and testing datasets (fusion rules #3 to #5, respectively). Weighted summing is herein defined as the weighted vector sum of the output of all networks; the sound class estimate is calculated as the vector element with the larger value, similar to majority voting.

Table 6. Fusion rules used for sound classification.

Fusion Rules
Fusion Rule #1:
Weighted sum of NNs; each weight is directly proportional to the respective network's number of epochs needed for offline convergence
Fusion Rule #2:
Weighted sum of NNs; each weight is directly proportional to the respective network's accuracy upon the entire offline dataset
Fusion Rule #3:
Weighted sum of NNs; each weight is directly proportional to the respective network's accuracy upon the training offline dataset
Fusion Rule #4:
Weighted sum of NNs; each weight is directly proportional to the respective network's accuracy upon the validation offline dataset
Fusion Rule #5:
Weighted sum of NNs; each weight is directly proportional to the respective network's accuracy upon the testing offline dataset

5.5. WASN nodes

The proposed Wireless Acoustic Sensor Network (WASN) consists of nodes able to log and transmit audio and/or processed data from the area of interest to the STORM cloud. Local data processing is optional and may consist in extraction feature but also classification within the node. In this respect, data transmission may refer to either original recorded data or their compressed equivalents. Each WASN node falls within one of three different node groups: the Integrated Peripheral Unit (IPU), the Central Network Unit (CNU) and the Intermediate Network Unit (INU). The CNU is connected with a back-end system for further processing and archiving. Depending on the trade-off between processing power, network bandwidth, battery life and audio fidelity, features may be extracted at the IPU level and/or the data may be compressed prior to transmission to the CNU. The INU receives data through the 802.11b/g network and then repackages them for retransmission on a wireless WAN. Although more advanced options exist, a GPRS/EDGE/UMTS (UMTS will be used for short) network is used, showing well-balanced characteristics between hardware and software availability, bandwidth, power consumption and cost. Moreover, backward compatibility to GPRS is mandatory to be able to set-up the network at areas where there is only legacy cellular network coverage.

Every WASN node is based on the OMAP L132 embedded processor and Digital Signal Processing (DSP) platform by Texas Instruments (TI) (OMAP, 2019). The main goal was to create a flexible hardware for the WASN in terms of one generic platform that can be the basis of all three units (IPU, INU and CNU). This is achieved by designing a modular system that contains a data processing unit and has several add-ons for the various functions of the system, such as the digital microphone, WLAN and/or 2G/3G subsystem that is interfaced directly to the embedded processor. A modular architecture is selected, according to which a main board with extension capabilities using appropriate daughter boards is developed. The daughter boards establish the required 802.11b/g and UMTS communications links but also offer the flexibility to further extend the communications and processing capabilities of the node with extra options.

The OMAP L132 platform includes an ARM core and is equipped with onboard DDR2 and flash memory and was selected mainly due to its state-of-the-art characteristics in terms of processing power, DSP capacity, and overall performance and life-of-cycle service requirements. A crucial factor for the processor choice was the trade-off between performance and power consumption. Maximum speed of operation would require a processor capable of running in high frequencies (GHz range), while portability dictates reduced frequency operation. Also, a floating point DSP can offer an accuracy that is considered being indispensable for almost any audio application. Furthermore, specific processor interfaces for the application are desirable in order to connect to audio sources. All of the above are requirements are fulfilled by the selected platform (Tatlas *et al.* 2014).

The 802.11b/g and UMTS daughter boards are installed at the lower and upper right of the main board respectively. The remaining daughter boards in are the main board that includes the processor/DSP, the LAN connectivity sub-module and the SD memory, and then the digital audio, LoRa, environmental sensors, Z-Wave, ZigBee and Bluetooth boards. The processor/DSP and digital audio boards are essential for the node operation whereas the remaining boards may be added or excluded according to the needs of the specific WASN at hand. It is considered that the UMTS and WiFi boards will be mostly used. Nevertheless, a multitude of different low power network connections are included in case there is the need for collecting data from additional wireless sensors or advanced remote control capabilities. Also, a LoRa board is included in order to offer a backup solution in the case of a remote site with no UMTS coverage. In such cases, and since LoRa throughput cannot withstand audio data transmission, it is considered that only a small fraction of processed data will be transmitted to the STORM cloud for further processing.

5.6. Classification test results

Classification results are presented herein in terms of achieved accuracy of the proposed classifier. The achieved accuracy is defined as the ratio of successful classification outcomes vs. the total number of sound samples fed to the classifier. We used a sound dataset that is a subset of the "505 Digital Sound Effects" database (LaserLight 2006); this subset is carefully selected in order to include sounds that correspond to anthropogenic, animal or environmental activity. More specifically, there are 3x16 samples of airplane, car and pistol sounds (a total of 48 anthropogenic sound samples), 21 samples of dog sounds, 16 samples of snake sounds and 18 samples of crow bird sounds (a total of 55 animal sound samples), as well as 3x16 samples of fire, gale and waterfall sounds respectively (a total of 48 environmental sound samples). Each sound file was normalized with respect to its energy content and random samples corresponding to white or pink noise were added; the final generated dataset consists of 9 sound classes that correspond to 151 sound samples. With white or pink noise added and SNR values ranging from -20 dB to +12 dB with a step of 1 dB, the resulting dataset includes a total of 9966 sound sample files.

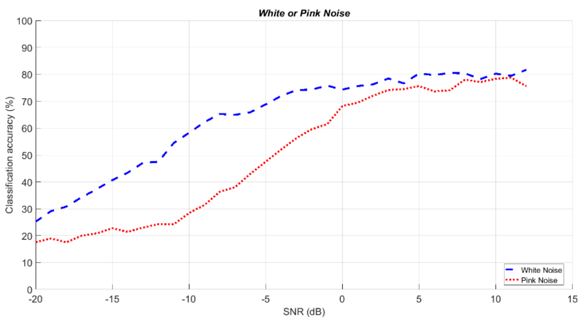


Figure 6. Average classification accuracy for SNR values ranging from –20 to +12 dB.

Figure 6 demonstrates the average classification accuracy for SNR values ranging from -20 to +12 dB. It is evident that pink noise is affecting the achieved accuracy more seriously compared to white noise. Furthermore, it can be concluded that accuracy drops for lower SNR values, as expected. A more detailed description for the STORM reference Architecture can be found in Deliverables 3.1, 3.2 and 3.3 (STORM Consortium 2017).

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5.
Decision making for risk mitigation based on collaborative services and tools

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1. STORM Collaborative Decision Making Dashboard (Collaborative and Operative)

1.1. Collaboration and Knowledge-Sharing Infrastructure

The current world is increasingly supported by a knowledge-based economy, where technological, economic, political, social and cultural changes modify the nature of human relationships. The Information and Communication Technologies (ICTs) revolution along with the spread of different and faster channels have become important driver to disseminate knowledge and information. In this changing landscape, knowledge is considered one of the most valuable assets able to generate growth and competitive advantage. It is fundamental to develop an infrastructure able to manage knowledge and, most specifically, to foster knowledge creation and sharing in order to create economic and social value, to remain innovative and perform better, to be updated and to enhance sustainability.

According to Martensson (2000), in a knowledge-based economy, having access to the right data at the right time is viewed as a prerequisite for higher productivity and flexibility. Managing knowledge involves either the processes of knowledge creation and knowledge sharing as two opposite side of the same coin since knowledge is valuable if it is shared and knowledge sharing implies knowledge transformation and, therefore, creation of knowledge.

Knowledge sharing constitutes the whole process of exchanging knowledge regarding information, skills or expertise through people, communities or organizations. It is an intrinsically human and cooperative process, directly related to the environment's features that must be conducive to collaboration. The creation of a favourable environment for communication, collaboration, knowledge sharing and transfer has become essential and technology plays a crucial role as a key part of this changing environment (Ramesh Babu, Gopalakrishnan 2008).

The current innovations in ICTs facilitate activities involving knowledge exchanges among people and organisations. In order to be really effective, the implementation of a collaboration and knowledge-sharing framework should be not confined to technology solely but has to foster the creation of an environment able to allow collaborative work. Specifically, IT support can be classified into the use of proper repository for storing and sharing knowledge and the use of channels for communicating and facilitating the sharing of knowledge amongst individuals. Upon the implementation of IT tools, the access to information becomes much easier, cheaper and more efficient.

1.1.1. The importance of Collaboration and Knowledge-Sharing during disasters

Knowledge sharing plays a central role during emergency, allowing the access to and the availability of critical information regarding risks and disasters. According to Hackbarth (1998) and Davenport and Prusak (1998), a Knowledge Management System (KMS) can support an organisation in planning for and dealing with crises.

The lack of effective knowledge sharing during crisis can be identified as one of major reasons behind the unsatisfactory performance levels of current disaster management practices. The lack of a continuous and efficient coordination among all the stakeholders involved in preserving and securing the cultural heritage assets is one of the main concerns raised during crisis.

All these highlight the importance of embracing knowledge management within the context of disaster management. Crisis response management is a collaborative activity which requires a highly cooperation among all the involved actors in order to face and recover from the risks of crisis and disasters events. It should be a critical need to gather and access critical real-time information, and share knowledge resources in order to make faster and more informed decisions.

Information is vital for early warning, planning, rehabilitation and reconstruction. Lack of information complicates the efficient management of catastrophes and makes the decision making process a difficult task (Puras, Iglesias 2009).

Anyway, a knowledge sharing process alone is not the solution because, during emergency, the real actors are people involved whose role is to make the best decision. Communication and decision making during disaster must occur in a compressed timeline since faster response than usual is needed to stabilise a dangerous situation, prevent further losses, and begin reconstruction. Collaborative emergency management requires a networked co-ordination, collaboration and partnerships in crisis, disaster and emergency.

In such complex situations, a collaborative and dynamic environment allows the actors to interact with each other and join their efforts in order to cooperate and make collective decisions. Making fast and efficient decisions needs supporting tools allowing a prompt situational picture and critical information sharing and this is based on the effective use and coordination of resources, people, and information, where information and knowledge are distributed.

From this variety and large volume of data and information, decision makers need to obtain the most relevant and accurate ones, having a clear view of the situations in order to make the right judgments. An effective toolbox with the aim to assist in responding to an emergency situation, supporting communications, data gathering and analysis, and decision-making is an imperative. The goals of such a system are to facilitate clear communications, improve collaboration among users, improve the efficiency and effectiveness of decision-making. Moreover, the decision making is more about facilitating the communication and implementation of those decisions, and allow the access to the correct knowledge and information.

For this reason, STORM aims to build a *Collaborative and Decision Making Dashboard* where, at any moment, the relevant actors can have a clear situational picture to better act in the prevention phase to mitigate the effect of climate phenomena and intervention phase when a disaster occurs. In the context of STORM, the proposed tools vectored through technology are expected to enhance collaboration, co-ordination and to support decision making amongst stakeholders.

This will be a resultant of having faster access to information and knowledge increasing the chances of the right people making better and right decisions in disaster situations. Furthermore, sharing the right information and knowledge with the right people is crucial for collaborative performances amongst stakeholders. Collaborative knowledge sharing will be advantageous to STORM by speeding up response times where the right people with the relevant skills are identified more quickly and disaster events dealt with in a more timely manner.

A more detailed description can be found in Deliverables 7.1, 7.2 (STORM Consortium 2017, 2019).

1.2. STORM integrated solution: a toolkit of collaborative and decision making services and tools

Existing knowledge (e.g. best practice, guidelines, lessons learned, operative procedure and processes, etc.) related to natural disaster risk and impact can help in making the decisions and new knowledge (e.g. from the situational picture, risk assessment and data analytics) can be shared by team of experts in order to identify the best and most urgent recovery.

STORM proposes an integrated solution, namely STORM Collaborative Decision Making Dashboard where collaborative and operational environments are strongly interconnected each other. The platform aims to be the enabler (and at the same time supportive) tool for the development of a collaborative environment. STORM Collaborative Decision Making Dashboard provides a quick view of the main parameters coming from a systematic analysis, assessment of data and facts, according to the user's interests and needs. The opportunity to have a customizable prompt dashboard, mapping the current situation in a synthetic way and gathering the most relevant information, is an imperative for supporting an efficient and effective decision making. Moreover, users can share knowledge and opinions using the set of collaborative and knowledge sharing tool. The set of services and tools belonging to the respective environments, support the knowledge sharing, coordination of involved stakeholders and the decision-making process.

The following Figure 1 shows the STORM Collaborative Decision Making Dashboard main home page, underlining the specific collaborative and operative services coming from the two interconnected environments, the *Collaborative and Operational enviroments.*

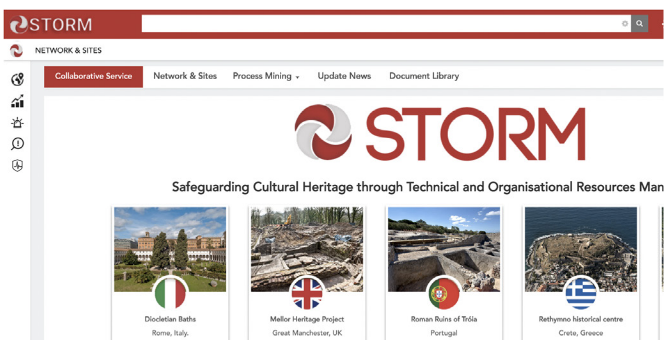

Figure 1. STORM Collaborative Decision Making Dashboard: Home page.

1.2.1. STORM Collaborative and Knowledge Sharing Services

The basic principle of collaborative work is the concept of a working group, a set of individuals interacting with each other with some regularity, in the knowledge of being dependent on each other and sharing the same goals and tasks, in which each has a specific and recognised role, based on the circularity of communication.

The **Collaborative Working Environment** (CWE) provides a set of services that encourage, capture, organise free and open interaction among actors to create and exploit the collective knowledge. These services support several actions and operations related to information and knowledge management (e.g., creation, research and extraction, organisation and analysis, interaction), offering a set of customisable features.

Specifically, a set of collaborative services is provided in order to enable the CH and emergency stakeholders to collect, contribute and share data and information as well as the knowledge on the potential threats, vulnerabilities, risks, along with the actions to be performed to manage, in a suitable way, the critical situation when it occurs, putting in the loop both their own experience and skills.

The available data and information related to the disaster (threats, vulnerability and risks) and how have to be managed (operative procedures and processes, best practice, lessons learned, etc.) are collected, managed and shared among different community stakeholders (emergency operators, first responders, citizens, public authorities, etc.). This allows users to establish a virtuous mechanism of using, elaborating and releasing new knowledge that becomes a valuable asset during the decision-making processes. One of the objectives of the STORM platform is to support users in carrying out part of their daily activities and their work.

The specific **Collaborative and Knowledge Sharing services** featured in the collaborative environment are the following:

1.2.2. User Profile

Every user registered on the platform has its own profile and access to a set of specific site he belongs to and the roles assigned. *User profile* gives each user a complete visibility into how other users manage knowledge and their activities.

Moreover, it shows user's relevant roles and responsibilities so each user knows who is responsible for each relevant area, procedure and task. The type of users and the level of involvement and interaction in the platform depend on the users' respective roles and responsibilities in a certain process management area.

1.2.3. Semantic Search

The *Semantic Search* service is a functionality featured as an intelligent information retrieval. This approach tries to understand the intent and the context around a query in order to retrieve the most pertinent resources, related to the particular information request. It delivers the user a better match to queried content and information.

Different knowledge and information are uploaded by users in the Document Library service and, using the Semantic Search, it will be easy to find the right knowledge. For this reason, fast, efficient, simple, configurable and intuitive search and retrieval service is required in order to retrieve and find such information.

The service is able to identify, process and, if necessary, store existing relationships among all the available information in order to deliver aggregated results, expose and motivate the link between the user query and the proposed results, enrich the results suggesting, in addition to textual and multimedia resources, people, team, skill, etc., available in the platform. By definition, semantic search reaches out beyond keywords and seeks to understand the semantics of the search query. It improves search accuracy by looking at both data and their connections.

1.2.4. Network & Sites

The *Network & Sites* is a way to organise activities among all the members belonging to the same site. In this way, it is possible to avoid sharing of data, activities with unwanted receivers.

Using Network & Sites service is possible to choose a specific Network Site that represents a private area in which users are able to share documents, news, and activities related to a particular site. The documents and all the activities performed in a specific site are not available to those users who are not part of it.

1.2.5. Process Mining

The *Process Mining* STORM collaborative service supports site managers and CH professionals during the STORM Quick Assessment process, covering both the phases of feeding and using the system, before and after a hazard. The STORM Quick Assessment process consists of some fundamental phases.

In particular, four different **procedural phases** are considered, namely:

1. **Data Collection**: The first phase is before the hazard happening and, at this stage, the process involves a "Feeding Activity" where the system is fed with all the relevant data and information useful to build a database containing the detailed multimedia knowledge concerning the site of interest, such as historical and technical data, material details at three different levels: site, area and item. Data Collection represents the first step and means the gathering of all the data to be entered in the STORM system. In STORM, this activity is done using the **Description forms** available on the platform through the Process Mining collaborative service. The data, in accordance with the required fields in the Description forms for each Site, Area and Item, are filled in the dashboard knowledge base (Des site; Des area; Des item).
2. **Preparedness**: The second phase has been identified, as Virtual Hazard, with the aim to plan actions and resources in order "to be prepared" prior to the emergency. Related to an in-depth analysis and processing of the collected knowledge, and starting from this, a simulation has been launched for each single expected hazard. This moment is characterised by the events simulation and emergency interventions identification that will support the Preparedness. Many heritage assets are further damaged by inadequate emergency interventions because urgent responses may lead to emergency measures and interventions that are insensitive to CH. The preparedness covers the whole quick assessment phase, including the evaluation of interventions in case of first aid, by organising both the processes of safety, possible materials needed and means which are necessary for the interventions. A simulation is conducted in relation to a virtual disaster in order to locally assess the disaster-affected areas and the needs, to design a prioritized plan of action based on those needs, namely the preparedness in order to be ready during a real disaster. Preparedness involves the activities related to the team formation, identification of the professional features of involved personnel and the minimum means requested during response phase. This improves the quality and speed of response during a real hazard. The purpose of this simulation is to conduct a detailed assessment of the disaster and basic needs of the in order to identify priorities and required resources. In STORM, the **Preparedness Forms** give all the information required in order to be ready to face future real disasters. In particular, the main information given through the Preparedness forms are about people training, contingency plans to guarantee accessibility to the site, securing and first

aid minimal materials and hardware ready to be used, identification of key people to be involved during the emergence, number of people needed, availability of information and so on. Preparedness forms are available at the three levels: Site, Area and Item.

3. **Response (First Aid)**: This phase takes place immediately after the occurrence of an emergency. The first aid corresponds to practical actions made by trained personnel, with specific skills based on an intervention scheme identified in the simulation phase. The process involves the real operative use of the system and the execution of the actions during the critical situation. The system has to retrieve the data entered during the simulation and preparedness phases, which are useful for the operators, helping them to take decisions. After using the system, when the real hazard happens, the service supports users to update the information inserted during the simulation phase (in the Preparedness Forms) in order to give better guidelines and a more detai of the Item Preparedness form is dedic led and concise information. A specific section ated to the First Aid, namely section **Response (First Aid)**. During the real emergency, the information inserted during the feeding and preparedness phase are of great importance and they probably will be update if necessary. Regarding the intervention on the field, when a real hazard happens, a dedicated mobile application has been designed to give users recommendations and guidelines in real time and on the site. This phase takes place after the hazard and, at this stage, the process involves the real operative use of the system, where the related activities are securing and first aid ones. The first aid corresponds to practical actions made by trained personnel, with specific skills based on an intervention scheme identified in the simulation phase. In STORM, the First Aid is used during the real hazard through a mobile application and is currently available for item. In particular, First Aid details are inserted in the Item Preparedness forms. Regarding the simulation on the field and the intervention when a real hazard happens a dedicated **mobile application** has been designed to give users recommendations and guidelines in real time and on the site regarding the tasks to be done and supporting work. All actions planned during the preparedness and tested in the exercise will be activated. A full diary of event is kept for further documentation and use.

4. **Debriefing**: The assessment and the evaluation of what have been done during the emergency. A more detailed description for Process Mining can be found in Deliverable 6.6 (STORM Consortium 2019).

1.2.6.Update News

This service allows members of a site to share particular news. In this way, tacit knowledge on strategic issues arises. The service allows community users to add blogs, categorise and associate them to other contents on the platform.

Every news can be voted and notified to specific user. News create instant feedback loops. Moreover, all contributions are tagged with the contributor's name and contact information to know exactly who to contact for more information.

Different actions can be performed when visualising a news such as: *Like*, *Follow*, *Share*, *Notify* and so on. This service allows people to share knowledge and communicate in an easier way.

1.2.7. Document Library

The *Document Library* is a service that supports document management (upload, view and download documents) among users. Each user can organise documents by grouping them into specific folders so that everyone can easily consult them. The service allows users to add a new folder in order to upload one or more documents at one time.

This service represents a valuable support for document sharing that allows knowledge sharing among users that work and collaborate for a common purpose.

STORM users collect and gather all the available data and information related to threats, vulnerabilities, risks, operative documents, best practice, lessons learned, etc. A knowledge archive further helps to distribute relevant information more effectively, simplifying the search for adequate information and providing the decision makers with the needed information to set the right strategies at the right time.

The quality and quantity of information received can have negative impacts if it is not managed correctly. In order to assure the usability of all the data about the cultural assets, all the relevant information is grouped into folders in order to more simply find the right data, in the right place, at the right time. The identification and listing information and knowledge linked to site, area and items is an important requisite. For this reason, specific folders at site, area and item level are essential to store CH information. All the available information helps to reconstruct the evolution in time and consequently to design a correct approach. A more detailed description for Collaborative and knowledge-sharing services can be found in Deliverables 7.1 and 7.2 (STORM Consortium 2017, 2019).

1.2.8. STORM Operative Services

The **Operational Working Environment** (OWE) provides some operative tools, services and application for a collaborative decision making.

The development of the Operational Working Environment is not intended to replace any existing participation methods but rather to act with innovative practices and techniques for the community. Hence, it is not aimed at substituting the decision makers' responsibilities, but rather to assist in making decisions by providing additional supportive information and tools.

The opportunity to have customisable prompt solutions mapping the current situation in a systematic way and gathering the most relevant information is an imperative for supporting decision making. The operative tools assist decision makers to enhance understanding and management of a critical situation in a collaborative and shared manner.

General information (e.g. guidelines, reports, etc.) related to dramatic events (e.g. flood, earthquake) are made available, shared and dynamically adapted in near real-time by an *ad-hoc* team of experts to identify the most urgent actions called for by the unforeseen emergency. The operational environment provides a quick view of the main parameters coming out from a systematic analysis and assessment of data and facts according to the user's interests and needs. Stakeholders need to make informed and consensual decisions working together, sharing information and the best available data.

A set of operative tools, services and applications help, during all the Disaster Risk Management phases, to:

- generate the current situation to be analysed giving all the necessary information to identify decisions that need to be made;
- recognise the right processes/tasks to be selected and people (and their specific role) to be involved for each of them;
- evaluate the measurements and options to make better decisions;
- collaborate with other involved stakeholders;
- gathering the most relevant information in order to detect anomalous events;
- evaluate the decision taken.

Moreover, to enable an effective decision making process, users need a complete overview of the critical situation that means, in terms of data and information, an integration of current (real-time) and past knowledge of critical evolution to help decision making leading actors to better understand the situation in progress.

The Operational Working Environment integrates operative tools, services and applications, to support decision making in extreme or high pressure environments, establishing necessary and useful functionalities for representing the critical situation and providing information for decision making support.

1.2.9. Sensory Map

The *Sensory Map* service shows the monitoring areas and the position of the installed sensors. The icons are the locations which need to be monitored because they have been affected by main hazards.

Specifically, the service shows the position of the installed on-line sensors connected to the On-line Data Sources and the results coming from the off-line sensors, connected to the Off-line Data Sources.

The On-line Data Sources generally consist of one or more nodes capable of hosting one or more sensors, and an aggregator or base station capable of collecting data received by several nodes and send them to a data gathering module for their collection, storage and management. When the user selects each of the sensors highlighted on the map, several sensory information is shown in a concise form on the map and, further data are showed in a specific section (the last measures for each sensor and data provided by sensors through charts are presented).

The Off-line data sources are used for scientific surveying activities that can be implemented periodically or after a natural hazard event, to monitor and assess damage. The Off-line Data Sources results come from Induced Fluorescence, Terrestrial and aerial Photogrammetry, Laser Scanning, Electrical Resistivity Tomography, Ground Penetrating Radar, Infrared Thermal Imaging, x-Ray Diffraction and Fluorescence, Spectral Camera. Their results, are identified on the map, providing both a form with brief information and a detailed section with the specific measurement information details as an image, 3D model, etc., can be shown.

1.2.10.Visual Analytics

The *Visual Analytics* service gathers sensor network data and other relevant information from disaster-affected areas and presents them to the user of the system. Data are processed to provide easy to understand representations considering both past events and the current situation at STORM sites.

This feature is essential to identify risks and to monitor their evolvement, starting from the analysis of the current and historical data. This information could be visualised on appropriate charts and maps. The users can visualise the analytics using various features, according to the selected type or to the particular event. For each chosen type, a view of the current trends and evolvement of the situation is showed, with a list of the current recorded events.

Specifically, information provided should include: i) type of the threats and their characteristics (e.g., wind or rain, intensity, direction, occurrences, time-frame, etc.); ii) maps of hazardous events occurred on the site; iii) monitoring of specific measures relative to assets (e.g., humidity, temperature, volume); iv) historical data monitoring of natural events; v) historical data monitoring of specific measures relative to the assets and evolutionary trends.

In the Visual Analytics service the home page is presented as a map in a WEB GIS layer where it is possible to select the preferred site/area/sensor node in order to visualise the associated analytics. Data analytics is used to improve understanding of the situation and support the end user in effective decision making via various data visualisations.

1.2.11. Diagnosis Reporting

The STORM Collaborative Decision Making Dashboard detects hazardous events or identifies relevant threats starting from the useful information extracted by processing and analysing data from STORM On-line and Off-line Data Sources.

The detection of a damage caused by a hazardous event previously occurred or the identification of some threats that could increase the exposition or vulnerability of an asset against specific hazards can be notified to the platform. Potential damages, events and threats detected by an expert user analysing the results produced by an off-line Data Source could be added into the platform directly using the *Event Manager* service.

Events manually inserted in the platform will be added along with those produced by the continuous monitoring through the On-line Data Sources. The Event Manager service provides a set of functionalities for managing (add, delete, update and show) all the STORM events both produced in an automatic and continuous way by the system and manually by an expert user.

1.2.12. Risk Assessment and Management Tool

Risk Assessment and Management Tool supports the derivation of appropriate risk management strategies developed in the context of STORM. The Tool aims to help the site managers and experts to assess the level of risk in different areas of the site and determine site-specific strategies to mitigate the risk associated with natural hazards and climate change.

Further details about this tool will be explained in subchapter 3 - STORM Risk Assessment and Management (RA&M) Tool.

1.2.13. Situation Awareness

Situation Awareness services provides a detailed view of maps with all the indicators and parameters essential to take under control the situation and assist decision makers. A clear picture of the situation with all the details about vulnerability and risk areas, hazardous events, and other relevant information are visualised in a thematic map in order to identify the impact on CH site, areas and assets. In this way, users can understand the current situation status, having a real-time monitoring on how the situation evolves and enabling a kind of common operational picture.

Situation Awareness service is organised in different views describing dangerous situations that arise when determined STORM events, detected by the system, happen.

All the dangerous situations are listed along with their criticality level, status and date. Moreover, the current situation is available both *on-Map* and *on-Time*, respectively focused on the geographical or temporal dimension.

The user has a detailed view of the current situation through the Web GIS service described in subchapter 4 Web-GIS tools and services for risk assessment and situational awareness, making use of specific icons for each relevant information to be shown. In this way, for each dangerous event, is possible to take under control the situation on the map. All the fundamental information is provided to the user, namely a description of the specific damage, the status, the affected site, the temporal range.

Moreover, a process list is visualised illustrating the specific hazards, the involved assets, a brief description and the user that manages the situation, if already established. Otherwise, the site manager can choose to assign a specific process to a user. A more detailed description for Operative services can be found in Deliverables 7.1 and 7.2 (STORM Consortium 2017, 2019).

1.3. Benefits of STORM Collaborative Decision Making Dashboard

The main purpose of the STORM Collaborative and Decision Making Dashboard is to inform and assist the stakeholders involved in the formulation and selection of risk reduction measures based on available risk information and stakeholders' needs. The main features and consequent benefits of the STORM Dashboard:

- The creation of an interactive environment would not only provide opportunities for an exchange of information among users of the system but could also facilitate the establishment of closer links;
- A more effective collaboration between the different actors by interactively involving them in the decision making process;
- Enhancement of the general coordination between actors involved and assist in the selection of the most efficient strategies and measures depending on available information and resources;
- Supports the collaborative interactions among stakeholders in a better-informed and transparent decision-making environment, rather than provide the collaborative decisions itself;
- Speeding up response times where the right people with the relevant skills are identified more quickly and disaster events dealt with in a more timely manner.

2. Surveying and Diagnosis Mobile Phone Application

2.1. Challenge

Surveying and diagnosis and the wider prevention strategies for CH should consider not only what risks and hazards exist at present, but also those that may be an issue in the future. Prevention measures and treatment intend to avoid adverse impacts of hazards, vulnerability conditions and exposure, which is a process that is not feasible in many scenarios and for such mitigation measures are more effectively implemented, since expresses the actions towards the lessening of the potential adverse impacts of hazards. An adequate implementation of prevention and mitigation processes must be supported by a set of priorities previously defined in the scope of a project. These terms are defined in detail in the *STORM Frame of Reference*, namely, *STORM Project Glossary of Terms* (STORM Consortium, 2017a) and *Heritage Disaster Risk Reduction phases*, *Conservation intervention processes & Relevant Actors: Definitions within Project STORM* (STORM Consortium, 2017b).

This is one aspect of the STORM project that brings novel, useful, surveying and diagnosis methods and processes that the five STORM pilot sites did not consider prior to the creation of STORM. For example, STORM not only considers current risks like meteorological risks such as freeze-thaw, droughts, sea-level rises, etc., it also considers how such a risk may be augmented by anthropogenic-led climate change into the future. Therefore, STORM prevention and conservation considerations are unique in answering the question: *would one expect the number of freeze-thaw events at the Mellor pilot site to increase or decrease by the middle of the 21st Century?* This additional information means that conservation management plans that are produced utilising the STORM prevention and mitigation process will take the answer to such questions into consideration, and the subsequent surveying and diagnosis techniques will be implemented and adapted appropriately.

STORM has adopted a prevention and mitigation process involving tasks that must be undertaken by owners of CH assets that should be developed in a **Conservation Management Plan** supported by the STORM service. These tasks include *Conservation planning*, *Monitoring planning*, *Maintenance planning*, *Team building and training*, *Cost-effective analysis*, and *Execution*. Specifically, the *Monitoring planning* stage of the STORM prevention and mitigation process will be addressed within this deliverable. Monitoring planning is a key aspect of the STORM Surveying and Diagnosis service. Therefore, Surveying and Diagnosis services play a critical role in the STORM prevention process.

In the case of Mellor Archaeological Trust's 2013 Conservation Plan, there were 41 aims and objectives set out as policies for the owners, current and future, to follow. Only two of these policies are centred on monitoring plans. The two monitoring aims were also only one-time events: a topographical site survey of the Mill and a survey of the Mill's fabric (archaeological survey). Both of these aims have been met, with Greater Manchester Archaeological Advisory Service, and the University of Salford undertaking these surveys. As part of these reports, detailed surveys would have been conducted using GPS data in CAD and GIS software, as well as high-resolution 3D scans of the site utilising laser scanners. Unofficially, the only other inspections to be conducted at the Mill site were visual inspections that were sporadically completed most commonly before and during community events at the site.

Prior to STORM, maintenance was inefficient and irregular at the Mellor site. As with monitoring tasks, maintenance was only conducted before and during public events at the site or on an *ad hoc* basis. Furthermore, as the trust is volunteer-led, maintenance has often, and understandably, been seen a low-priority task. Taking the above points into consideration, Mellor has adopted regular maintenance of waterways/drainage at the site. At the Mellor Mill site specifically, new and improved drainage has been installed and now a plan will be adopted with volunteers that ensure regular inspections of this system. Any necessary maintenance will be conducted, to prevent drainage from getting blocked; otherwise, such an event would lead to flooding of the site during heavy storm events. Similarly, a task force of volunteers has been selected to conduct regular cleaning and biological control. The timeframe has yet to be decided – the Surveying and Diagnosis component will provide the site with a tool for setting such frequency rules and significantly adhering to them. This task force of volunteers, will visit the site and make use of new equipment to keep the green areas of the site pruned and remove weeds that begin to encroach on the footpaths and archaeology.

STORM has led to the creation of new methods and processes for surveying the assets at the Mellor pilot site that were not previously being conducted. Such methods include:

- Aerial photogrammetry;
- Terrestrial photogrammetry;
- Laser scanning;
- Near infra-red photography.

Alongside the above, old processes such as visual inspections and specialised inspections of the surrounding vegetation will be continued but with a new process to ensure that these inspections are conducted at regular intervals.

There was a need, therefore, for STORM to provide a tool to enable sites, such as the Mellor Pilot Site to ensure that the monitoring objectives set out in the **STORM Conservation Management Plan** are completed on time and correctly. Moreover, it is vital that there should be some feedback ability within this service. For example, during the surveying activities it should be possible for the user of the service to report issues that are present.

2.2. Surveying and Diagnosis Component

STORM has created a solution to the above mentioned problem. STORM provides tools to support experts in the establishment of the best process in terms of the type of treatment to be applied. Procedural approach is supported by the *STORM Collaborative Decision Making Dashboard* described in subchapter 1 and, in particular, using the Process Mining service and the related forms. For each site, area and item, specific forms are filled in in order to gather the necessary information. For Prevention and Conservation process, for each site, area and item when a slow hazard occurs, it is necessary to mitigate the risks caused, establishing the treatment to be done along with the related features. The *STORM Preparedness Forms* allow to make this choice. The preparedness phase, as a fundamental part of the quick assessment, includes the evaluation of interventions in case of First Aid, by organising the processes of safety, possible material needed and means which are necessary for the interventions. Specifically, the preparedness involves the following activities:

- People training;

- Contingency plans to guarantee accessibility to the site;
- Securing and first aid minimal materials and hardware ready to be used;
- Identification of key people to be involved during the emergency;
- Number of people needed;
- Availability of information (both STORM collected and traditional ones).

In particular, the *STORM Item Preparedness Forms* allows to schedule the specific treatment to be done on a specific item. The Item Preparedness Forms are categorized as prevention process, which in itself has a number of tasks to be performed by specific resource group/personnel.

The restoration treatment service scheduling is based on the following steps:

1. During the process of filling in the Item Preparedness Forms, it will be possible to define, and insert in the system, a series of *treatments*, aimed at mitigating the risk caused by a slow hazard;
2. It must be possible, for each treatment, to program a *start and end date* and a *frequency* of the interventions (daily, weekly, monthly, and so on);
3. It must also be possible to select one or more *people* (already registered in the system) who will be responsible and have to monitor the status of the interventions made.

In particular, the fundamental information that can be filled in are related to the establishment of the specific treatment, the starting and end date and the frequency of the treatment itself along with the responsible people. The responsible users are designated, and they receive a notification to their own mobile phone, in order to do the assigned treatment and to monitor the treatment status. STORM adopts the concept of active participatory conservation of cultural heritage that involves the involved members to become active actors and collaborators in the preservation/restoration process of cultural heritage items.

To the end user (i.e., site manager/employees) there will be a mobile phone application that will alert users when activies need to be conducted and what specific activity should be conducted alongside a deadline for which the activity should be completed.

The Surveying and Diagnosis mobile application (Figure 2) will assist STORM users in conducting and timing their prevention aims and objectives. It will do this by reporting to the user, in most cases the pilot site manager, when surveying and diagnosis techniques, along with other conservation processes, need to be conducted and enable the site manager to first, act on the advice and conduct the relevant methods as well as provide the ability to check off the task once it has been conducted. The frequency and due date for tasks will be set in the prevention forms on the platform and this information alongside the prevention processes will form the basis of the *to-do list* style application. The application will alert the site management when a task is due to be completed with a notification on their mobile device. The receiver then has two options, the first a simple 'snooze' function which where the alert will be rescheduled, for example, the task may be delayed by 1 day. The second option is to open the task. If the user selects to open the task, the mobile phone application opens, and the user is presented with a list of complete and incomplete tasks. The most critical being at the top. The user can then open the task by clicking the card relevant to the task that is due – and the task window will open. Here, the user will see the current task and its description, followed by a list of the items for which the task should be conducted. A map showing the position of the item will be displayed.

Once the user clicks on the item for which the task needs to be completed, a new screen will load where the user can list any observations; these observations can be part of the task directly or simply other observations that are made at the time of conducting the task. If no observations are made, or new observations are included, then the user will return to the previous screen where they will be presented with a button to resolve the task, once they (or the experts) have conducted the relevant work. For example, in restoration tasks, this button would only be used after the conservation experts have conducted their work and the site manager is happy that the work has been conducted in line with the STORM conservation and prevention aims. Once all ongoing tasks are complete, the user will return to the home screen, where the list will reflect completed tasks only.

The app will provide a menu, where the user can select and see a calendar view of upcoming tasks. Once selected, the user will be able to sync the STORM surveying and diagnosis calendar with any third-party calendar application on their device. Included is the ability of the service to link multiple tasks into processes. Processes will reflect multiple tasks, although not all tasks need to be part of a wider process. For example, one process may include the tasks: Photogrammetry survey, Laser scan, Damage detection analysis, and conservation works. When the tasks are part of a wider aim and need to be done in quick succession.

Figure 2. Example of the Surveying and Diagnosis Mobile Phone Application.

2.3. Conclusion

STORM's surveying and diagnosis service will make it simpler for sites to monitor their CH assets through the **STORM Prevention and Mitigation Processes** and the associated **STORM Conservation Management Plan**. The mobile phone application and associated scheduler should aid STORM sites in not only conducting surveying and diagnosis methods on time, but it will also draw on expertise to ensure that the site conducts relevant and neccessary methods suitable to their situation, hazard, and site. The ability to report issues within the app whilst conducting the surveying activities will prove to be useful, especially the ability to link any issues to site areas and specific assets. The usefulness of the service and app will be throughlly testing in the STORM experimentation phases with results being presented as part of the deliverable 9.2 and 9.3.

3. STORM Risk Assessment and Management (RA&M) Tool

The STORM Risk Assessment and Management (RA&M) Tool has been implemented according to the Risk Assessment and Management Methodology (STORM project: D5.1, 2017) developed in the STORM project. The STORM RA&M Tool aims to help the site managers and experts assess the level of risks in different areas of the site and determine site-specific strategies to mitigate the risk associated with natural hazards and climate change. The STORM RA&M Tool will enable the site managers and experts to identify and analyse the natural hazards affecting a heritage site, assess the value of areas of the site, analyse the vulnerability of the site, measure the level of risks in different areas of the site, and finally determine site-specific strategies to mitigate the risk associated with each hazard.

The Risk Assessment & Management (RA&M) Tool is composed of three main modules that enable the STORM's risk assessment and management methodology to be implemented in a systematic and understandable way. The main components of the RA&M Tool, are as follows:

- Site Hazard Assessment: Site Hazard Identification and Site Hazard Analysis;
- Risk Assessment: Hazard Analysis, Exposure Analysis, Susceptibility Analysis, Capacity Analysis, Risk Identification, Risk Analysis, Risk Evaluation;
- Risk Management Strategies: Risk Treatment Strategy and Prioritisation.

The Site Hazard Assessment module is comprised of a Hazard Identification step and a Hazard Analysis step regarding a specific pilot site. The Hazard Identification step allows the user to quantify the relevance of each hazard (whether sudden-onset or slow-onset disasters) to the pilot site. The Hazard Analysis step enables the computation of an overall ranking according to a set of ranking factors defined in the RA&M methodology in order to identify the hazards of interest.

The Risk Assessment module provides a more thorough assessment per site area. In this module, the user can add any number of areas to the site and then create a risk assessment for each of those areas. The Risk Assessment module is composed of the following steps: Hazard Analysis, Exposure Analysis, Susceptibility Analysis, Coping & Adaptive Capacity Analysis, Risk Identification, and Risk Analysis. Each of those steps conforms with the same defined steps of the Risk Assessment methodology.

Finally, the Risk Management Strategies module categorizes each site's area per level of priority concerning a specific hazard. The prioritisation is based on the output of Risk Assessment module. In this step, users have the possibility to prioritise items, which have been defined for each area in the STORM platform, according to their values and sensitivity to different hazards. The tool enables the user to define risk treatment strategies and associated measures in response to each hazard.

Each page of the tool is supplied with an Informational tab that provides the user with the required information, such as definitions, assessment indicators, and ranking scales, to facilitate conducting the RA&M steps. Apart from the semi-quantitative and qualitative ranking scales, a colour coding system is also applied in the assessment process to better illustrate the priority levels.

Concerning the technical specification, the back-end part of the RA&M Tool is essentially composed of three logical layers, the Data Layer, the Database Middleware Layer and the Application Layer that interact in order to provide the required services to the platform. The lowest layer, the Data Layer, consists of a MySQL relational database containing information for evaluating the Vulnerability Score and the Risk Score related to a specific hazard and the involved heritage asset (i.e. a site, an area, an item). The Data Layer contains also information for providing the STORM Risk Management Guidelines as mitigations of sudden-onset as well as slow-onset disasters. The database has been designed to contain information regarding both the Risk and vulnerability assessment and the Quick Damage Assessment service tools. However, this document focuses on the RA&M Tool implementation and on the relative functional aspects with the software requirements specification provided in the following.

Front-end development of the tool involves a collaborative effort between multiple STORM partners. The task is mainly split into defining the workflow and user interaction through the production of a mock-up solution and coding work. The tool is developed as a web interface, served from the STORM main platform. The user will mainly be domain experts and site managers; therefore it is crucial to make the interface as user-friendly as possible. Also, one of the main features of this tool is to cover the risk assessment for multiple pilot sites – namely Troia (Portugal), Mellor (England), Diocletian Baths (Italy), Rethymno (Greece) and Ephesus (Turkey) – and a number of separate areas and items for each site. For that reason, the tool needs to have clear and separate functionalities for these different workflows so the user is fully aware of which site or area the current assessment is for.

By utilizing the Risk Assessment (RA) tool exposed API, STORM web-GIS interface (described in subchapter 5.4) is capable of providing risk maps for each pilot site, along with all the associated information. The implemented API of the RA tool is analysed in order to specify the necessary requirements for developing and updating the corresponding web-based GIS services. STORM web-GIS services are able to provide hazard, exposure, and vulnerability levels and overall risk scores, for each pilot site area, as GIS layers and maps. In each use of the associated RA tool, the corresponding site area results and associated information are sent and stored in a dedicated geodatabase (PostGIS) of the STORM web-GIS infrastructure (GeoServer). Hence, hazard and risk maps associated with each pilot site area will be updated and be available through the STORM platform.

Overall, the STORM RA&M Tool has been developed to provide the targeted stakeholders, heritage conservators and risk experts, and the trusts of the pilot sites with a user-friendly instrument to manage the risks of natural hazards and climate change. The Tool will provide a shared understanding of the risk data and assessment processes among the multiple stakeholders engaged in the protection of cultural heritage sites to facilitate the decision-making process. In the context of the STORM project, the tool will provide some other components of the STORM Platform with the necessary data, for instance, GIS services to generate and update hazard and risk maps for each pilot site.

4. Web-GIS tools and services for risk assessment and situational awareness

4.1. Introduction

The STORM web-GIS infrastructure has been designed so as to support the management and visualization of geospatial data related to hazard risk assessment and situational monitoring processes for the Cultural Heritage sites that were included as pilot studies in the project. A set of web-based GIS services, aiming to successfully address all geographical information management, processing and visualization requirements for the STORM project, has been developed to support the specific infrastructure. The design of these services has been based on existing, open-source web mapping server and client API solutions. Specifically, the most promising and widely used web-based GIS mapping tools have been studied and evaluated with the scope to identify the most effective and appropriate solutions that could be adapted and extended to support the STORM use case scenarios for each pilot site.

STORM web-GIS services are able to manage geospatial data to support STORM risk assessment analysis and modelling, as well as STORM monitoring and situational awareness services. They are designed for interoperability and make use of OGC (Open Geospatial Consortium) standards to publish geospatial data which are accessible to authenticated end-users. The overall design of the STORM web-GIS infrastructure is based on available *open-source* web-based GIS tools, including the use of a plug-in architecture and data abstraction layer that allow extension of its core functionality.

The core functions of the STORM web-GIS services operate on a client-server architecture. The architectural schema for the provision of efficient and effective STORM web-GIS services is formed by a set of free and *open-source* components; *GeoServer*[1], an open-source web map server, connected to a *PostGIS*[2] geodatabase for storing spatial datasets and *OpenLayers*[3] web mapping client API, for visualizing geographical information on a dynamic and interactive web map interface. GeoServer is a free and open-source solution of a web-mapping server that can provide access to geographical information through web services that support openly documented standards and protocols (Deoliveira 2008). OpenLayers is also a free and open-source, JavaScript based, web mapping tool for designing dynamic and interactive web maps, offering spatial visualization and manipulation tools to simplify the development of rich web-based GIS applications (Gratier, Spencer and Hazzard 2015). Spatial information is stored on the server in the form of raster or vector data type files, which act as *static* GIS layers in the corresponding web map services. *Dynamic* GIS data layers supporting the respective spatial information changes over time are also stored in a PostGIS geodatabase.

Besides data management services that are able to support a number of different spatial data formats, the STORM web-GIS infrastructure provides web map services for visualizing geographical information of the areas surrounding all STORM cultural heritage pilot sites. This information includes sensor node locations (installed and deployed on-site), site areas and item locations that need to be monitored, topographical (elevation, aspect, slope) data, as well as geological and hydrolithological information available from local, regional, national or other available EU open sources. Most importantly, STORM web-GIS services are able to support the functionality of other platform services and tools, such as the Risk Assessment and Management (RA&M) tool, Surveillance and Monitoring (S&M) and Quick Damage Assessment (QDA) services, by providing associated information as thematic map layers through the STORM dashboard. Thus, users of the STORM platform are provided with accurate situational awareness services and are able to effectively manage and monitor current critical situation events, their development and effects.

1 *http://geoserver.org*.
2 *https://postgis.net*.
3 *https://openlayers.org*.

4.2. Risk Assessment web-GIS services

STORM hazard and risk assessment effective services provision for cultural heritage monuments and sites is based mainly on the processing of geographic information and the analysis of their spatial association. Web-GIS services support the visualization of hazard related data sets, such as landscape topography and geology, together with the corresponding outcomes of the spatial analyses that provide direct images (maps) of the related risks or damages, which are caused by the associated hazards. In this way, Cultural Heritage operators, planners and decision makers are offered with valuable services assisting them to efficiently plan hazard and risk preventive actions.

The implementation of the above required the initial identification of the primary natural hazards and threats (sudden-onset/slow-onset) for each STORM pilot site area. The quantitative or qualitative analysis of them leads to the definition of the associated severity, exposure (significance value) and vulnerability (susceptibility and lack of coping and adaptive capacity), as well as an estimate of the overall risk assessment. The above were provided as a corresponding web map service to be further utilized by the STORM integrated platform. An example of the Risk Assessment web - GIS services results visualization through the STORM dashboard is illustrated in Figure 3 below.

5.4.3 Situational Awareness web-GIS service

In the STORM context, simple events, representing physical events, phenomena, damages or human activities are able to be identified, processed and ultimately provided in the form of a critical situation image depicting the heritage assets under threat. A dedicated web-GIS service was developed to support spatial (overlay) analysis for understanding the scope, complexity, and severity of critical situations, by identifying the affected heritage assets and structures, assessing their potential damage and establishing prioritization for restoration or recovery actions. The respective Web-GIS map service is further utilized by the STORM integrated platform in order to visualize critical situation events and associated hazards severity as corresponding "situational picture" map. An example of results visualization of such a situational awareness web-GIS service is illustrated in Figure 3.

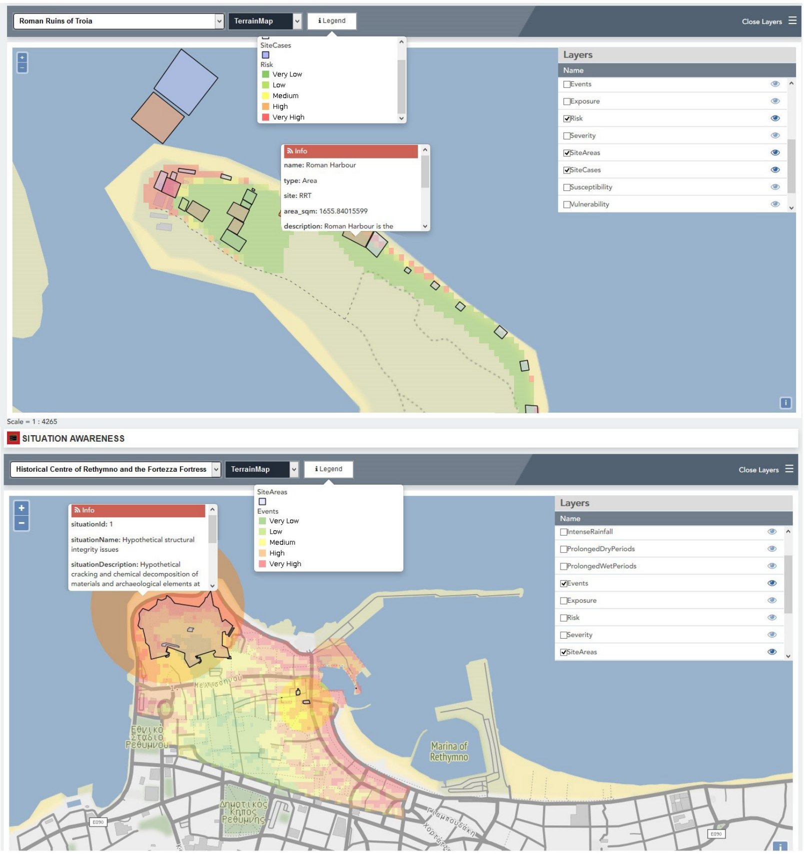

Figure 3. Two examples of STORM dashboard: the risk assessment web-GIS services for the "Roman Ruins of Tróia" pilot site (above) and the situational awareness web-GIS service for the "Historical Centre of Rethymno" pilot site (below).

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6.
Taking advantage of the cloud for efficient use of ICT resources and sensory data

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1. Cloud Computing technologies

The rapid growth of virtualization technology during the last two decades led to the mutation of legacy datacenters to synchronous cloud environments.

Virtualization technology enabled the management of computational resources (i.e., vCPUs, Storage, RAM) for supporting multiple different and isolated application.

The cloud computing nowadays is one of the basic technologies used in the industrial but also in the research areas for developing innovative products and technologies.

Cloud environments follow three different types of model architecture, regarding the services they provide and their user's characteristics, which are the following:

- the Infrastructure as a Service (IaaS);
- the Platform as a Service (PaaS); and
- the Software as a Service (SaaS).

The IaaS model offers computation resources, such as virtual CPUs (vCPUs), RAM, storage and networking, images of Operating Systems (OSs) to the users of the cloud in order to deploy their software.

In this layer, the user of the cloud has full control over the Virtual Machine (VM) provided by the cloud as he is fully aware of the underlying software of the VM and can perform changes in the environment of the VM (i.e., install software, change configuration files).

In the PaaS model, the cloud provider offers a platform ready to accept the code off the user in order to develop a software solution.

The freedom of the user is restrained in PaaS as the user has no control over the underlying software and is able to make some changes only where the Cloud Provider (CP) allows it.

Finally, at the SaaS layer, the CP offers a software application ready to be used by the user for performing experiments and simulations, while the user has no control over the underlying software and is not able to make changes in software level.

However, a cloud environment is not characterized only by the service model it follows but also to the audience it is referring to.

There are four main categories in which the clouds are divided to: the Public clouds, the Private clouds, the Hybrid clouds and the Community clouds.

The Public clouds are available for the general public which means that it can be accessed by individuals, students or even companies (e.g., Amazon)[1].

On the other hand, private clouds are used by companies or institutions for their own needs (e.g., OpenStack)[2].

The creation of a private cloud can be performed on-premises or even off-premises, depending on the strategy of the company or organization which owns it.

The Hybrid cloud is a combination of a Private and Public cloud and demands at least one Public and one Hybrid cloud.

In this scenario these two clouds are bound with technologies that enable the data portability among them.

The Community cloud is usually a federation of clouds belong in several organizations and follow the same policies and therefore they form a community used for common goals and purposes.

[1] S. Mathew, *Overview of Amazon Web Services*, 2018. Available online at: *https://docs.aws.amazon.com/aws-technical-content/latest/aws-overview/aws-overview.pdf*.

[2] A. Abdelrazik, G. Bunce, K. Cacciatore, K. Hui, S. Mahankali, F. Van Rooyen, *Adding Speed and Agility to Virtualized Infrastructure with OpenStack*, 2015. Available online at: *https://www.openstack.org/assets/pdf-downloads/virtualization-Integration-whitepaper-2015.pdf*.

The STORM project, after assessing the above models, the nature of the Cultural Heritage (CH) safeguarding services and the needs of the involved partners, follows the Private cloud IaaS solution in order to deploy and host the required services.

2. STORM Cloud Architecture

STORM uses a cloud-based infrastructure for the collected data to be stored, accessed by registered users and processed to determine useful information that can be translated to events that require the administrator's attention and, possibly, call for actions.

The Cloud architecture in STORM exploits STORM's Open Cloud Framework which provides a set of standard APIs (e.g., use of RESTful APIs) for the communication between its modules and the external world.

In addition, the Open Cloud Framework describes an hierarchical architecture based on a tree approach and consisting of two layers: the Core cloud at the root of the tree and the Edge clouds which communicate with the Core using the aforementioned set of APIs.

The Core cloud is considered as the main layer of the STORM architecture and there is only a single instance of it (root), while there are several Edge clouds (leaves) supporting each of the participating cultural sites.

Figure 1 illustrates the tree-based cloud architecture; its main components, Edge Cloud Connector (ECC), Core Cloud Connector (CCC), and Cloud Broker are explained in detail in the later sections.

Some of the key advantages that led as to follow the architecture below were:

- The isolation among clouds;
- The multitenancy of the systems which is maintained;
- The decrease of system's vulnerability;
- The increased scalability considering that all clouds could be clones of a generic cloud configuration.

The Core cloud plays an important role in the STORM architecture and is, mainly, responsible for:

- Collecting information from the Edge clouds;
- The generation of events based on the received information;
- The communication with the STORM Edge clouds and;
- Hosting of visualization services.

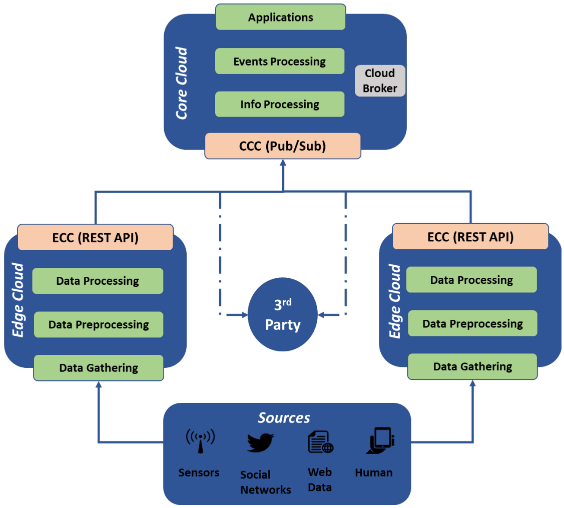

Figure 1. STORM tree-based Cloud Architecture.

In addition to this, the Core cloud is not only responsible for controlling the communication between itself and an Edge cloud but, also, for administrating the communication between two (or more) Edge clouds by playing the role of a broker for this purpose.

Part of playing the role of a broker (mainly for the communication between the Edge clouds) includes to indicate which types of data are offered by each Edge cloud, facilitating the discovery of the data needed to satisfy a request.

At the same time, the Core cloud is also responsible for monitoring the status of the Edge clouds and their services that are running on virtual instances.

Software services (e.g., Web-GIS service), also, run on the Core cloud interacting with an Edge cloud and retrieving data and information related to the existing sensors.

The Edge clouds are at least as many as the number of participating sites in the project and, most of them, are located near the sites in an effort to optimize the network's performance and to provide for most efficient support of their functionality.

Each Edge cloud is responsible for collecting, storing and processing the data that are gathered by the sensors, which are deployed in the sites of interest; these data can be raw or pre-processed (i.e., by the gateways) and are gathered by services which operate inside the virtual instances running on the Edge cloud.

The development of custom data processing services has been promoted to serve the different needs of each partner and each Edge cloud, based on the type of sensors that are deployed in the area and the different dangers and/or needs that must be monitored in every site.

At the same time, the information collected from each site should be available to every Edge cloud that requests it and be displayed through the Core cloud, communicating using the designed APIs, as has been described above.

To this end, each Edge cloud could differ not only on the content, but also on the services that it provides and the processes that run to it, based on the different demands that should be met[3].

The use of specifically designed RESTful APIs ensures that the communication between each Edge cloud and the Core cloud is standardized, as is the type of data that will be transferred to address the system's needs, based on the designed STORM standards.

2.1. Implementation framework

The implementation of the aforementioned architecture is based on the selection of a cloud computing software for the deployment of cloud infrastructures.

Nowadays there are several opensource cloud computing solutions offered for the creation of private IaaS clouds.

Some of these are the OpenNebula, the CloudStack, the Eucalyptus and the OpenStack.

In the STORM project the OpenStack cloud solution was the most preferable as it is a well-documented cloud solution with a very large community.

In addition, many research institutes, such as CERN, are using the OpenStack software; OpenStack was initially developed by the National Aeronautics and Space Administration (N.A.S.A) and Rackspace Inc.

Today, OpenStack has met a rapid growth and has been adopted by huge organizations such as PayPal.

The OpenStack cloud software uses the Kernel-based Virtual Machine (KVM) hypervisor in order to introduce the virtualization technology and manage the computational resources.

[3] STORM Consortium, *D5.1 Risk Assessment and Management*, Project STORM - Safeguarding Cultural Heritage through Technical and Organisational Resources Management, 2017.

The usage of KVM automatically enables the processor virtualization, memory virtualization, storage virtualization and network virtualization.

Nevertheless, the management of those resources and the whole cloud environment is based on the OpenStack, which presents a large number of services[4] used for several purposes, but for the implementation of a functional cloud there are some core services which need to be implemented.

These core services are the following:

- Identity service, codename Keystone;
- Compute service, codename Nova;
- Image service, codename Glance;
- Networking service, codename Neutron;
- Block storage service, codename Cinder;
- Dashboard service, codename Horizon.

Keystone provides a single point of integration for managing authentication, authorization and service catalog services, as a result other OpenStack services use the Keystone service as a common unified API.

In addition, services that provide information about users but that are not included in OpenStack can be integrated into a pre-existing infrastructure.

All the other services need to be compatible with Keystone, and when an OpenStack service receives a request from a user, it checks with the Keystone service whether the user is authorized to make the request.

The *Glance service* accepts API requests for disk or server images, and metadata definitions from end-users or OpenStack Compute components.

Additionally, it supports the storage of disk or server images on various types, including OpenStack Object Storage.

Also, a number of periodic processes run on the *Glance* to support caching. Replication services ensure consistency and availability through cluster and other periodic processes include auditors, updaters, and reapers.

The *Nova service* is used to host and manage cloud computing systems and its main modules are implemented in Python.

Nova interacts with Keystone for authentication, it also interacts with Glance for disk and server images and with Horizon (dashboard) for the user and administrative interface.

[4] O. Khedher, *Mastering OpenStack: Design, deploy, and manage a scalable OpenStack infrastructure*, Birmingham: Packt Publishing Ltd, 2015.

Image access is limited by projects and by users. Nova can scale horizontally on standard hardware and download images to launch instances.

Interface devices managed by OpenStack services to networks are allowed to be created and attached by the Neutron service, while plugins can be implemented to accommodate different networking equipment and software, providing flexibility to OpenStack architecture and deployment.

Using *Neutron* there is the ability to create virtual networks and virtual routers and control the communication between virtual machines.

The *Cinder* service adds persistent storage to a virtual machine and provides an infrastructure for managing volumes for instances, and also enables the management of volume snapshots and volume types.

The method in which the storage is provisioned and consumed is determined by the Cinder driver, or drivers in the case of multi-backend configuration; some of the available drivers are: NAS/SAN, NFS, Ceph and more.

Finally, the *Horizon* service (dashboard) is a web interface that enables cloud administrators and users to manage various OpenStack resources and services.

Concluding the brief analysis of the OpenStack services, it should be mentioned that all these services are controlled through the use of REST APIs, relying on an Apache web server.

The usage of IT automation software such as Ansible allows us to create a unified configuration which can be used in various datacenter environments for the deployment of an OpenStack infrastructure.

Currently the University of Greenwich has a fully functional cloud infrastructure based on a documentation which combines OpenStack and Ansible technology.

3. Registration mechanisms

3.1. Edge cloud registration and service authorization

The STORM cloud infrastructure ensures a secure and private aware access by using the STORM Authentication Server (SAS), which is based on the OAuth2 Client Credentials Flow[5].

[5] J. Sendor, Y. Lehmann, G. Serme, A. Santana de Oliveira, “Platform level support for authorization in cloud services with oauth 2”, in *Proceedings of the 2014 IEEE International Conference on Cloud Engineering, IC2E '14*, 2014, pp. 458–465.

According to this authentication process the users provide their service credentials (username and password) directly to the service, which uses these credentials to obtain an access token from the service.

The SAS is a token-based authentication server consists of the following entities:

- *Admin*, which is responsible for managing the Clients that are registered to the authentication service;
- *Client*, which represents the services that register to the Authentication Server in order to the authenticated to the Edge cloud and receive an access token, which will enable it to get authorized by other services;
- *Token*, which is a unique identifier string that is generated every time the client is getting authenticated by the server in order to get authorized by the rest of the Edge cloud services.

To register an Edge cloud, and subsequently its ECC, a Client must visit the Edge cloud registration page (*http://vm10.openstack.puas.gr/register/edge*), fill the login fields (Client ID and Client Secret) that has received from the cloud administrator.

Upon success a confirmation dialog appears. Afterwards, (s)he provides his/her the information in the registration form:

- *Owner*, the name of the partner that owns the Edge cloud (e.g., UWA);
- *Edge cloud name*, the name of this particular Edge cloud (e.g., UWA Edge Cloud);
- *Cloud domain*, an identification string that defines the Internet address of the Edge cloud (e.g., http://vm6.openstack.puas.gr);
- *Cloud tenant ID*, the OpenStack project (e.g, uwa_edge_cloud).

3.2. Node and Sensor registration

The STORM platform can be described as an Internet of Everything (IoE) platform that is based on cloud-hosted services to derive value from the incoming data sources.

As it is depicted in Figure 1, in STORM there are the following types of sources:

- *Sensors*, which are the monotoring devices and its nodes;
- *Web Data*, which are historic static climate data;
- *Social Networks*, which are data extracted from existing social networks;
- *Humans*, which are data provided by users of the STORM platform that can be CH experts or visitors.

However, in order to communicate with the STORM platform all of the aforementioned sources have to be registered to a STORM Edge cloud.

Sensors and sensor nodes unlike the other three types of sources they are not directly servitized (i.e., represented directly by a service) but are considered to be a standalone entity that has to be registered to an Edge cloud in order to transmit the data it produces.

Consequently, every Edge cloud provides an interface (i.e., web page) to enable the sensor node registration.

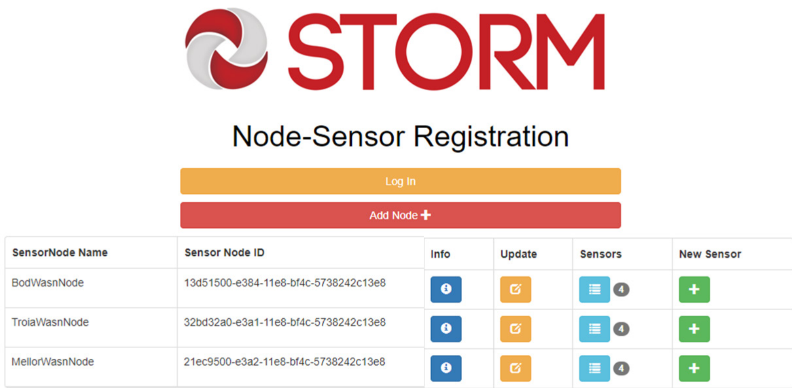

Figure 2. Node-Sensor Registration page.

Figure 2 presents the Node-Sensor page (*http://vm12.openstack.puas.gr/register*), where an authenticated user of the Edge cloud that is responsible for handling sensor data can insert a node firstly and afterwards add its sensors.

In particular, if a user wants to register a new sensor node, by pressing the Add Node button, (s)he has to fill the following fields:

- *Node Name*: the unique name of the node (e.g., Weather_Station_Node);
- *Identifier Type*: the unique STORM ID of the Node (e.g., WeatherStation_49387063D9374225);
- *Producer*: the manufacturer of the node (e.g., Libelium);
- *Model*: the name of the node's model (e.g., Waspmote Plug Sense 868 EU);
- *Serial Number*: the ID of node that is given by the manufacturer (e.g., 49387063D9374225);
- *Power Type*: the type of the power (e.g., solar, battery, etc);
- *Connectivity Type*: the network connection (e.g., wireless);
- *Technical Provider*: the STORM partner that is responsoble for the node (e.g., ENG, INOV, FORTH, UWA, etc);

- *Site*, a drop down list that inclued all the STORM sites and defines the location of the node (e.g. Mellor, Ephesus etc);
- *Description*, a short description (i.e., text) for the node;
- *Portable*, a boolean value that defines if the node is portable;
- *Status*, a boolean value that defines if the node is online;
- *End Point URL*, the endpoint of the Edge that will register this particular node (e.g., *http://vm12.openstack.puas.gr*);
- *External ID*, the ID that is assigned by the 3rd party IoT platform (e.g., SENTILO) if the node is registered also to another commercial platform (e.g., *SmartCitiesPro_40457863D9374218_PRES*);
- *Image URL*, the electronic address that presents the image of the node;
- *Longitude*, the geographic coordinate that specifies the east–west position of a point on the Earth's surface (e.g., 12.49897205655543);
- *Latitude*, the geographic coordinate that specifies the north–south position of a point on the Earth's surface (e.g., 41.904026569524675);
- *Altitude*, the height that the node is placed measured in meters (e.g., 2.24).

After editing the application form, the user can see the details of the node displayed in JSON format by pressing the Info button.

Moreover, the user is able to change the values of the nodes (s)he has entered by pressing the *Update* button.

Of course there is no added value injecting a node for STORM project without registering its sensors; this is done by pressing the *New Sensor button and filling the following fields:*

- *Sensor Name*, the unique name of the sensor (e.g., AirThermometer_1);
- *Model Type*, the name of the sensor's model (e.g., Waspmote Plug \u0026 Sense 868 EU);
- *Serial Number*, the ID of sensor that is given by the manufacturer (e.g., 49387063S9374228);
- *Sensor Type*, the type of the sensor (e.g., Air Thermometer);
- *Measurement Type*, the observation parameter of the sensor (e.g., Temperature);
- *Measurement Unit*, the unit of measurement (e.g., Celsius);
- *Description*, a short description (i.e., text) for the sensor;
- *Status*, a boolean value that defines if the sensor is online;
- *External ID*, the ID that is assigned by the 3rd party IoT platform (e.g., SENTILO) if the sensor is registered also to another commercial platform (e.g., SmartCitiesPro_40457863D9374218_PRES);

The details of a sensor can also be displayed in JSON format by pressing the *Sensors* button.

For example the following JSON shows the information of the temperature sensor that is attached to the Wireless Acouctic Sensor Network (WASN) located in the Baths of Diocletian:


```
{
"sensorNodeId": "13d51500-e384-11e8-bf4c-5738242c13e8",
 "sensorName": "BodWasnEnvTemp",
 "model": "",
 "serialNumber": "",
 "sensorType": "AirThermometer",
 "measurementType": "Temperature",
 "measurementUnit": "Celsius",
 "description": "",
 "status": "true",
 "extId": "",
 "owner": "Tk9UlieZsa1wokYlOPkCh17b",
 "sensorId": "5500bca0-e384-11e8-bf4c-5738242c13e8",
 "expose": {
        "topic": "uwa_SENSOR_1541701813",
        "option": true
 },
 "datetime": {
        "created": "2018-11-08T21:30:13.000Z" }
}
```


4. Cloud-based components

The cloud-based components are responsible for establishing the communication between the Core and the Edge clouds, between two Edge clouds, and between the Edge clouds and third-party providers[6].

In particular there are the following three STORM cloud components:

- Edge Cloud Connector;
- Core Cloud Connector;
- Cloud Broker.

[6] P. Kasnesis, D.G. Kogias, L. Toumanidis, M. G. Xevgenis, Ch. Z. Patrikakis, G. Giunta, G. Li Calsi, "An IoE Architecture for the Preservation of the Cultural Heritage: The STORM Use Case", in *Harnessing the Internet of Everything (IoE) for Accelerated Innovation Opportunities*, IGI Global, 2019, pp. 193-214.

4.1. Edge Cloud Connector

The ECC component is a RESTful webservice, deployed at every Edge cloud, that acts as an interface between the STORM Edge cloud and the Core cloud (see Figure 1).

The ECC is responsible for receiving real-time data, that probably have been preprocessed and validated, by the Data Preprocessing modules, or useful information that have been extracted using statistical methods and machine learning techniques, by the Data Processing (or Information Extraction modules).

The former are stored in a local NoSQL database (e.g., MongoDB) in order to create a pool of historical data, and forwarded, afterwards, in the Core cloud, while the latter are firstly validated with respect to their format and forwarded to the Core cloud's interface (i.e., the CCC).

All the HTTP methods that have been designed and implemented for the ECC are described in Table 1.

Table 1. Edge Cloud Connecotr API

End-Point	HTTP Type	Short Description
/<PartnerID>/post/create/node	POST	Publishes a node's attributes
/<PartnerID>/post/create/sensor	POST	Publishes a sensor's attributes
/edgecloudconnector/data	POST	Publishes sensor data values
/edgecloudconnector/update/node/<nodeid>	POST	Updates a node's attributes
/edgecloudconnector/update/sensor/<sensorid>	POST	Updates a sensor's attributes
/edgecloudconnector/nodes/list	GET	Retrieves a list of nodes
/edgecloudconnector/sensors/list	GET	Retrieves a list of sensors
/edgecloudconnector/nodesensor/list	GET	Retrieves sensors list grouped by nodes
/edgecloudconnector/sensor/list/node/<nodeid>	GET	Retrieves sensors list of a specified node
/edgecloudconnector/topics/list	GET	Retrieves a list of topics
/edgecloudconnector/node/<nodeId>	GET	Retrieves the attributes of a specific node
/edgecloudconnector/sensor/<sensorId>	GET	Retrieves the attributes of a specific sensor
/edgecloudconnector/sensor/<sensorId>/ data	GET	Retrieves the Data of a specific sensor

/edgecloudconnector/sensor/<sensorId>/ data/last/value	GET	Retrieves the last data value of a specific sensor
/edgecloudconnector/sensor/<sensorId>/ date/<date>/data/	GET	Retrieves the data values of a specific sensor from a date
/edgecloudconnector/sensor/<sensorId>/ from/<from>/to/<to>/data/	GET	Retrieves the data values of a specific sensor in a date span
/edgecloudconnector/sensor/<sensorId>/files	GET	Retrieves the files of a specific sensor
/edgecloudconnector/sensor/<sensorId>/ files/last/value	GET	Retrieves the last file of a specific sensor
/edgecloudconnector/sensor/<sensorId>/ date/<date>/files/	GET	Retrieves the files of a specific sensor from a date
/edgecloudconnector/sensor/<sensorId>/ from/<from>/to/<to>/files/	GET	Retrieves the files of a specific sensor in a date span
/edgecloudconnector/user/nodes/site/ <site>	GET	Retrieves a list of nodes of a specific site
/edgecloudconnector/user/sensors/ site/ <site>	GET	Retrieves a list of sensors of a specific site
/edgecloudconnector/site/<site>/nodes/ sensors/list/type/<type>	GET	Retrieves a list of sensors grouped by nodes of a specific site and a specific type
/edgecloudconnector/sensor/data/ type/<type>	GET	Retrieves sensors' files of a specific type
/edgecloudconnector/sensor/data/ type/ <type>/date/<date>	GET	Retrieves sensors' data of a specific type from a date
/edgecloudconnector/sensor/data/ type/<type>/date/from/<from>/ to/<to>	GET	Retrieves the data of sensors of a specific type in a date span
/edgecloudconnector/sensor/files/ type/<type>	GET	Retrieves sensors' files of a specific type
/edgecloudconnector/sensor/files/ type/ <type>/date/<date>	GET	Retrieves sensors' files of a specific type from a date
/edgecloudconnector/sensor/files/ type/<type>/date/from/<from>/ to/<to>	GET	Retrieves sensors' files of a specific type in a date span

The responses are retrieved in JSON format. For example, <domain>/*edgecloudconnector/sensor/952805a0-58f5-11e8-b621-99a2c75e8b0c/from/2018-08-28T03:15:00/to/2018-08-28T03:25:00/data/* GET method may return the following JSON:

{
"success": true,
"data": {

“site”:{ “heritageAsset”:”Basilica, South corner walls, Well”,
“siteName”:”Roman Ruins of Troia”},
“sensorNodeId”:”952805a0-58f5-11e8-b621-99a2c75e8b0c”,
“nodeExtId”:”rrt_weatherstation”,
“status”: true,
“location”:{ “point”:{“longitude”:”-8.88445526”, “latitude”:”38.4867774”} },
“sensorId”:”2baf6800-8043-11e8-be03-0b6fce77a5a1”,
“sensorExtId”:”rrt_barometer”,
“unitMeasurement”:”mb”,
“identifierType”:”Barometer”,
“measurement”:[
{ “value”:1016.3,
“datetime”:{
“created”:”2018-08-28T03:25:00”,
“transmitted”:”2018-08-28T03:25:02”,
“received”:”2018-08-28T03:25:05”,
} },
{ “value”:1016.5,
“datetime”:{
“created”:”2018-08-28T03:20:00”,
“transmitted”:”2018-08-28T03:20:03”,
“received”:”2018-08-28T03:20:05”} },
{ “value”:1016.38,
“datetime”:{
“created”:”2018-08-28T03:15:00”,
“transmitted”:”2018-08-28T03:15:02”,
“received”:”2018-08-28T03:15:05” } }] }
}

4.2. Core Cloud Connector

On the other hand, the CCC component is based on the Publish-Subscribe (Pub/Sub) pattern and, exploits the Apache Kafka framework[7]; it consists of the following four entities:

- *Producers* (i.e., Publishers), they send (produce) the messages, which contain data records or information, and are forwaded through the ECC to the broker;
- *Consumers* (i.e., Subscribers), they receive the messages from specific topics that they have subscribed to;
- *Topics*, they are pools of specific messages (e.g., weather topic);

[7] J. Kreps, N. Narkhede, J. Rao, “Kafka: A Distributed Messaging System for Log Processing”, in *Networking Meets Databases Workshop (NetDB) workshop*, 2011.

- *Kafka Broker*, it acts as a bus, which is known by both the producer and consumer, and distributes them accordingly (i.e., based on their topics).

It should be noted that in order to achieve low latency, the CCC utilizes the Kafka Cluster, which is consisted of several Brokers, enabling the use of more than one Broker for handling the incoming request in parallel.

Moreover, Kafka uses the Apache ZooKeeper framework to manage the Cluster and coordinate the topology of the Brokers.

As a result, the CCC uses three Kafka Brokers, and each of them categorises the incoming messages in one of the following types of topics:

- *sensor_nodes_topic*, where updates on any sensor node are published;
- *sensors_topic*, where updates on any sensor are published;
- *measurements_topic*, where each measurement (data records) notified to the Edge Cloud Connector are published;
- *useful_information_topic*, where each Useful Information Extractor component publishes its results to be consumed by the Information Processing components.

An example of an information message that is produced by an Information Extraction module, which is deployed in the Edge cloud owned by ENG, and provides details about freezing temperatures near the Baths of Diocletian site is the following:


```
{
"category": "http://demo-storm.eng.it/ontologies/ENG_UI#freezingtemperature",
"severity": "LOW",
"startTime": "2018-01-26T13:42:23.000Z",
"endTime": "2018-01-26T13:42:25.000Z",
"location": {"point": [12.4984, 41.321]},
"data": [
      { "description": "",
      "url": "",
      "created": "2018-01-26T13:42:23.000Z",
      "sensorDataPackage":
          { "sensorSource": {
                "providerId": "ENG",
                "nodeExtId": "WeatherStation_Terme01",
                "sensorExtId": "Temperature01".
                "sensorNodeId": "952805a0-58f5-11e8-b621-99a2c75e8b0c",
                "sensorId": "95e805a0-58f5-11e8-b621-99a2c75e8b0c"},
          "measurements":[
                { "created": "2018-01-26T13:40:23.234Z",
```

"received": "2018-01-26T13:40:23.334Z",
"transmitted": "2018-01-26T13:40:23.522Z",
"value": "4.0"},
{ "created": "2018-01-26T13:41:23.234Z",
"received": "2018-01-26T13:41:23.434Z",
"transmitted": "2018-01-26T13:41:23.522Z",
"value": "2.8"},
{ "created": "2018-01-26T13:43:23.234Z",
"received": "2018-01-26T13:43:23.334Z",
"transmitted": "2018-01-26T13:43:23.622Z",
"value": "2.5"}] } }],
"CHAsset":{"id": "BoD_Michelangelo_Chiostre", "type": "AREA"},
"additionalInfo": {}
}

4.3. Cloud Broker

The Cloud Broker is deployed in the Core cloud and hosts a RESTful API, which is responsible for the registration of the Edge Cloud Connectors that have been deployed in STORM Edge clouds.

The registration process depends on the STORM Authentication Server, and is executed through the Edge cloud registration page, which is a login form that requests from the user to add his/her Client ID and Client Secret.

Moreover, the Cloud Broker is not only considered to be the Core cloud administrator component, but also a mediator, since it is aware of the existing Edge clouds and can provide information about them to every registered Edge cloud that wants to consume historical data.

In particular, this is achieved by calling the *EdgeConnectorsList* method:

{
"success": true,
"edgeCloudConnector": [
{ "owner": "TEIP",
"edgeName": "TEIP Edge Cloud",
"edgeDomain": "http://vm12.openstack.puas.gr",
"edgeTenantId": "teip_edge_cloud",
"status": true,
"created": "2018-06-29T11:36:06.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
},
{ "owner": "ENG",
"edgeName": "ENG Edge Cloud",
"edgeDomain": "http://storm-edge-connector.eng.it",

"edgeTenantId": "eng_edge_cloud",
"status": true,
"created": "2018-07-17T11:11:40.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
},
{ "owner": "INOV",
"edgeName": "INOV Edge Cloud",
"edgeDomain": "http://stormedgecloudinov.cloudapp.net",
"edgeTenantId": "inov_edge_cloud",
"status": true,
"created": "2018-09-17T19:34:36.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
},
{ "owner": "FORTH",
"edgeName": "FORTH Edge Cloud",
"edgeDomain": "http://storm-edge.ims.forth.gr",
"edgeTenantId": "forth_edge_cloud",
"status": true,
"created": "2018-11-13T18:12:47.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
},
{ "owner": "BOGAZICI",
"edgeName": "BOGAZICI EDGE CLOUD",
"edgeDomain": "http://79.123.180.66",
"edgeTenantId": "BOGAZICI_EDGE_CLOUD",
"status": true,
"created": "2018-12-14T11:50:04.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
},
{ "owner": "SPARTA",
"edgeName": "Sparta Mellor Edge Cloud",
"edgeDomain": "http://35.246.75.192",
"edgeTenantId": "sparta_mellor_edge_cloud",
"status": true,
"created": "2019-01-21T10:11:06.000Z",
"lastOnline": "2019-02-08T15:51:29.000Z"
}
]
}

Finally, an important feature of the Cloud Broker is its dashboard; it is an administrator dashboard provided by the OpenStack framework that displays all the necessary details, in terms of VCPUs, Disk and RAM.

Figure 3 presents the current status of the VMs that are hosted by the STORM Core cloud.

Figure 3. Cloud Broker dashboard for the Core cloud status.

5. Conclusion

STORM platform enables the collection of both pre-processed (in situ) and raw sensor data, and the deployment of services, tools and applications.

In order to achieve this goal, STORM platform relies on the implementation of a cloud-based infrastructure, which follows the Infrastrusture as a Service (IaaS) model and supports the sensor data management.

To this end we used OpenStack, a free and open-source software platform for cloud computing, and adopted a tree-based architecture; it consists of several Edge clouds, used for data storing and processing, and one Core cloud that aggregates the extracted information to detect hazardous events.

The adopted distributed and scalable architecture is enforced with advanced security mechanisms and utilizes three cloud-based components; the

Edge Cloud Connector that is deployed in every Edge cloud acting an interface and as a database, the Core Cloud Connector that is the Core cloud' receiving real-time records and, finally, the Cloud Broker which is deployed in the Core cloud acting as an administrator and mediator for the Edge clouds.

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7.
A reference architecture: STORM project platform

Gabriele Giunta, Emilia Gugliandolo

1. The STORM System Architectural Design

The *STORM System Architectural Design* is inspired by a layered architectural principle, following an open and standard approach to build a modular and interdependent architectural schema for managing in a distributed, time-reducing and parallel way, the definition and the implementation of the different architectural modules.

The design of the architecture has been heavily affected by the identification and the definition of the case studies and the use case scenarios in the five STORM pilot sites, along with the specification of their main functionalities. Specifically, the definition of the use case scenarios has been built on a detailed analysis of the Cultural Heritage regulatory framework and on the particular profiles, needs and expectancies of the participant sites, as reported in *D3.1 – STORM Use Cases and Scenarios*.

Following this step, the requirements elicitation process has taken place, leading to the compilation of a system and user requirements analysis report, included in *D3.2 – System and User Requirements*, to successfully address the expectations and to optimize the overall experience and performance of the STORM system. To this end, a preliminary set of user requirements for the use cases have been listed based on their functionality, guiding the formulation of *functional* and *non-functional* requirements, covering both the requirements from the sides of the system and the users.

To this end, STORM requirements were divided in two categories:

a. *Functional Requirements* (FR) which relate to the system requirements (e.g., Source Integration and Data and Information Processing) and describe what the STORM platform should/ must do, and
b. *Non-Functional Requirements* (NFR) which relate to user requirements (e.g., availability, security, efficiency and user satisfaction) and describe how the STORM platform should/ must perform something.

For example, the need for monitoring the environmental conditions nearby the sites is a functional requirement, while the need of providing a scalable monitoring service is a non-functional requirement.

The FRs are composed of five main subclasses: a) Source Integration, b) Source Management, c) Data and Information Processing, d) Event Processing and Management, and e) Services, Tools and Applications.

On the other hand, the NFRs contain: a) Operational Requirements that define the criteria to judge the system's operation, such as Usability, Efficiency, and Scalability, and b) External Requirements that define the Legislative and Ethical requirements, which STORM system has to take into consideration.

These high level FRs and NFRs have been a guide for the design of the STORM abstract architecture, contributing to the definition of its conceptual layers. In that respect, the description of these requirements has been used as input to *D3.3 - System Architecture* that describes in detail the specifications of all modules of the STORM System Architecture along with the communication between them.

Following the requirements, the architectural pattern chosen is decided to be a Layered Architecture that identifies, per each logical layer, a specific set of logical functionalities. As a result, Source, Data, Information, Event, Service and Application Layer have been identified, according to the type of input received from and the output provided to the next layers.

The layered architectural style chosen to represent the STORM System Architecture offers benefits in terms of interoperability, understandability and reuse. In this style, each layer exposes an application programming interface (API) to be used by the layer above and below it.

Specifically, each layer acts, at the same time, as a server and as a client, respectively providing and consuming functionalities and services.

In an ordered sequence of layers, each layer contains a set of modules or components that are logically related among each other through software connectors.

A software connector is an architectural building block which aims an effective and regular interaction among the software modules.

Moreover, the layers allow a clear separation of concepts and functionalities, which in turn ensure flexibility, scalability, and maintainability of the entire architecture.

The STORM architectural layers are described along with their core modules in the following paragraphs.

1.1. STORM Architectural Layers

The STORM System Architecture, depicted in Figure 1, includes six main layers, namely Source, Data, Information, Event, Service and Application, that communicate data each other through a set of connectors where a specific set of logical functionalities are identified.

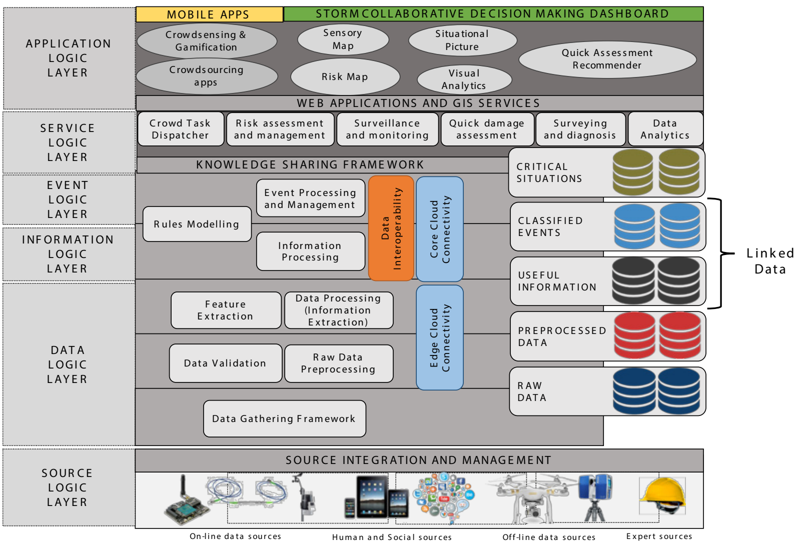

Figure 1. STORM Logical Architecture.

a. ***Source Logic Layer*** is the lower layer of the STORM Logical Architecture. It contains functional modules that manage the integration of the information sources into the STORM platform. Each information source provides raw data as structured and not structured data that are sent to the STORM cloud infrastructure to be elaborated and extract the relevant information for the CH domain. The STORM Data

Source types are the following: Web Data Source, Social Data Source, Human Data Source, Sensor Data Source, Static Climate Data Source.

b. ***Data Logic Layer*** contains functional modules that gather and process the data collected from heterogeneous information sources in the STORM system, using techniques of data pre-processing, such as cleaning, filtering, and segmentation to reduce the noise. The pre-processed data are then validated and further elaborated using data validation, processing, classification and enrichment techniques to produce useful information.
c. ***Information Logic Layer*** contains information processing and fusion modules that deal with the processing of the useful information, produced by the data analysis modules, to extract and generate from them classified events, according to the STORM hazard classification. In STORM, an event represents something that has happened or is related to something that has occurred in a specific place and time.
d. ***Event Logic Layer*** defines a set of modules able to analyse and process the classified events received as input from the Information Logic Layer, applying several operations such as validation, aggregation and correlation (Complex Event Processing techniques) to identify and generate critical situations. Moreover, the situations are further elaborated through threats analysis and risk assessment services for a better decision making.
e. ***Service Logic Layer*** defines the services used by CH experts to prevent, manage and mitigate the risk associated with natural hazards in the CH domain. A set of services has been defined with the following purposes:
    - *Risk Assessment and Management* services, allowing the assessment of all potential vulnerabilities and risks to specific cultural heritage sites and the definition of the best-fitting risk management strategies;
    - *Surveillance and Monitoring* services, allowing the CH users to be informed of critical situations and select how to manage them using the information retrieved from the field by physical sensors and human evaluators, exploiting both human cognitive ability and machine inference;
    - *Quick Damage Assessment, Surveying and Diagnosis* services, allowing the CH users to select the best actions or treatments of the intervention process to mitigate the possible consequences of the observed situation considering the known risks;

- *Data Analytics* services, allowing to enhance the understanding of the users before, during and after a critical situation to enable an effective and efficient response to it.

f. ***Application Logic Layer*** allows the end users to interact with the STORM services and tools using Web application technologies, GIS services and mobile apps for tablet and smartphone devices as well as crowdsourcing and gamification applications. In this layer, the GUI functionalities aim at an easy and intuitive access to the proposed services and tools through an operational and collaborative working environment for making decisions and sharing the CH knowledge. Collaboration among users is a key point of this tier.

2. The STORM Architecture Core Modules

An overview of the main architectural sources and modules is described in the subsequent sections, going through each layer to identify functionalities, dependencies and preliminary operations.

2.1. STORM Data Sources and Data Processing Modules

The STORM Data Sources are those elements of the STORM System, able to feed it with data and information to generate simple and complex events related to the current situation need to be mitigated.

2.1.1. STORM Data Sources

In STORM, the existing data sources along with the new proposed ones have been combined in a holistic approach to be able to collect and process data to make decision related to potential risks caused by environmental hazards. The following categories of data sources are proposed.

Web Data Source, represents a web source (e.g., a website).

Social Human Data Source, represents people that generate data during their interaction with the social network (e.g., Twitter). Social networks are integrated into the system using a set of APIs provided by the respective development support networks or third party.

Human Data Source, represents humans that implicitly or explicitly interact with the system through specific crowdsensing applications [reference to STORM Book Chapter or D4.3 - Report about capabilities of the implicit crowd sensing: screening]. Through the crowdsensing applications, the STORM System takes advantage of human perception and intelligence to detect hazards and assess risks that may affect cultural heritage site. In essence, people act as human sensors exploiting the *Human as a Sensor* (HaaS) paradigm to easily collect relevant data from the field through human interactions. This could be done either with an explicit involvement of the people, inviting them to make some observations and take some pictures on sensitive spots using specific mobile crowdsensing apps (explicit crowdsensing), or implicitly without any direct involvement of the users can play a game while they gather data through several kinds of (embedded) sensors installed in their mobile phones (implicit crowdsensing). The collected data have to be validated and processed by the crowdsensing modules to extract from them useful information on the domain specific hazards or threats.

Sensor Data Source, represents a generic sensor that may transmit data in real-time (e.g., weather station) or not (e.g. fluorescence sensor). As a result, in STORM there are two type of sensor sources: On-line Data Source and Off-line Data Source.

- *On-line Data Sources* are ground sensors that (locally) produce and collect real-time data (e.g., air thermometer, anemometer, barometer, acoustic sensors, weather and environmental stations, etc.) to be sent in real-time to the STORM System to be automatically processed for identifying useful information. Generally, the On-line Data Sources consist of one or more nodes capable of hosting one or more sensors; an aggregator or base station capable of collecting data received by several nodes and to send them to a data gathering module for their collection, storage and management.
- *Off-line Data Sources* are used for scientific surveying activities that can be implemented periodically or after a natural hazard event, to monitor and assess damages, for instance, in a monument. Examples are terrestrial and aerial photogrammetry, laser scanning, electrical resistivity tomography, ground penetrating radar, infrared thermal imaging, etc. Experts use special equipment and techniques to perform the surveying activities. The outcomes of the surveys are used for obtaining information about the status of an object. For instance, the photogrammetry is used for obtaining information about structural health of a build while a laser scanning survey for identifying the presence of invasive weeds on high walls. After the surveys have been completed, experts must post-process the collected data using workstations with specific installed software, mostly proprietary software, capable of applying the necessary algorithms and procedures for cleaning, processing and visualising the data. In several cases, these outcomes are

in the form of 3D models or raster images that will be further analysed by experts able to interpret them and extract useful information. The surveys must be conducted by expert people using special equipment. Differently from the On-line Data Sources, the data collected during the surveys need to be processed, but not in real-time, using proprietary software. Once the data collected have been processed, they can be uploaded in the STORM System through a dedicated service or application to make them available to other STORM modules and users, or for further data analysis.

Static Climate Data Source. In STORM, external data sources can be integrated into the system. Specifically, those related to the climate data can provide an important contribution to the risk assessment tasks. The climate data are available describing the climatic conditions in the past, based on the analysis of observations from stations in the pilot site regions (usually denoted as 'current climate') and the projected conditions for the future, based on simulations with regional climate models. The climate data can be used in combination with those collected from the weather stations for extracting the following information:

- Climatological information for temperature (minimum, maximum, mean) and precipitation could be shown in the background of a plot showing the weather stations temperature/precipitation readings. Users could be given the option to switch between current climate and future climate conditions to get a feel for how typical the weather on that day is compared to the long-year mean.
- Alerts can be set if the sensor observed values over a certain threshold determined from the climate data (such as for example, the 95^{th} percentile temperature/total precipitation sum for that day-of-year); if the temperature remains over 25°C for more than the climatic average (denoting a longer than average heat wave); if there more freeze-thaw events occurred in a winter than on average; if temperatures are below/above the 5^{th}/95^{th} percentile for that month (winter/summer); etc.

2.1.2. Data Gathering Framework and Data Processing

The *Data Gathering Framework* (including the Data Gathering Server) is the module responsible for the collection of raw data from the different STORM Data Sources. Specifically, it stores the received raw data and notifies the presence of new incoming data to the Data Pre-Processing Module. It supports a service of REST APIs with an end-point and provides infrastructure for any STORM compliant Proprietary APIs.

The REST end-point is generic for all the STORM Data Sources and accepts only a specific structure of the published data in order to facilitate the security validation of the provider as well as storing the data in the STORM Servers and Clouds.

The Proprietary APIs are platforms that a source may need in order to publish data to the Data Gathering Framework and acts as mediator between the STORM Servers and Clouds. They can then interact with their respective Proprietary Cloud Service and gain access to any services the Proprietary provider supports. These Proprietary APIs like OpenHAB and Sentilo provide tools and add-ons that are ready to use.

Another service it can support is a response to the publisher every time a data value or bulk of data values are sent, depending on the service and the provider needs. For instance, if there are any updates like a firmware update that the middleware should be aware to push it to the Data Source Modules or an on-demand service that needs to be triggered. Also, if required, it can provide a small-scale elaboration on the received data and in conjunction with the response service a communication with a source provider can be established to resolve any issues that might occur.

In STORM the Data Processing is a pipeline of modules able to validate, pre-process and process the collected raw data. The final processing step of this data processing chain includes the identification of useful information in the processed data. According to the type of raw data processed, there are two different kind of data processing: *Online Data Processing* – acoustic, Fiber Bragg Gratings, weather and environmental data, *Human and Social Source Data Processing* – tweets and explicit crowdsensing data; or *Offline Data Processing* – Photogrammetry (terrestrial - aerial) and Laser Scanning, Electrical Resistivity Tomography, Ground Penetrating Radar, IR Thermal Imaging, X-Ray Fluorescence Spectrometry, Spectral Camera and Induced Fluorescence.

A detailed view with further information of the main STORM Logical Architecture modules is described.

2.2. STORM Information and Event Processing Modules

This subsection provides a description of the logical architecture of the Information and Event Processing Modules, included respectively in the Information and Event Logic Layers of the STORM System Architecture.

The Information Logic Layer represents the entry point of the *useful information*, produced by Data Layer Modules. A *useful information* is a fundamental element of the information fusion process on which is based the methodology to detect and identify STORM threats and events. In STORM, *useful information* is any information, that could be extracted by processing or analysing the pre-processed or enriched data, that is useful for identifying natural phenomena or threats (e.g., water detection, rapid temperature increase, cyclic temperature, bird detection, etc.). These are threats that are considered dangerous for the monitored assets. The *useful information* always includes the following data:

- The *asset* (case, area or site) exposed to the identified phenomenon;
- The *time interval* in which the phenomenon is observed;
- The *location* where the phenomenon is observed;
- The *enriched data* that has been extracted.

Any *useful information* can be extracted following a double approach:

- Defining and implementing data processing techniques and methodologies. The selection of the best choice to be adopted depends on the type of data that needs to be processed and on the Useful Information to be extracted. In section 3, some significant examples with regards to the STORM data source are described.
- Monitoring of surpassing the thresholds related to specific measurements has been set up starting from the current practices and literature work, in addition to the domain expert involvement through collaboration. As a result, a set of first-level rules have to be provided by the domain experts, based on their knowledge of the phenomena and factors that have to be considered.

In this layer, set of *useful information* are processed and fused together for producing STORM classified events. A *STORM event, or simple event*, is the conceptual entity used for representing the physical event, phenomenon, damage, or human activity that occurs in a specific place and time classified as *STORM hazard*, producing tangible effects and damages on the material that make up the cultural heritage asset.

The Event Logic Layer contains the Event Processing and Management Module that is able to analyse and process (e.g., validate, aggregate and correlate) the classified events received as input from the Information Logic Layer. It then applies Complex Event Processing techniques to identify and generate sets of correlated complex events that can represent potential critical situations.

These sets of correlated events are sent to the Surveillance and Monitoring Module, included in the Service Layer, which is able to analyse them and identify new Critical Situation or update the old ones.

2.2.1. Information Processing Module

This module elaborates the useful information, provided by the Data Processing Module, executing the following operations:

- Validation and Completion (Syntactic Check): consistency and coherence of the *useful information* for finding inaccurate and missing information;
- Aggregation: *simple events* (i.e., already validated and completed useful information) are aggregated according to the same information (times and places);
- Correlation: *simple events* are correlated using spatial, temporal and causal relationships with each existent event. The sets, also formed by one single *simple event*, allow for the identification and generation of a *complex event* that must be sent to the Event Processing and Management Module for the further analysis. Analogously to the *simple event*, a *complex event* represents a conceptual entity that includes information coming from the surrounding environment in which the event has occurred, through aggregation and enrichment and can be also classified as a STORM Hazard, according to the STORM Hazard Classification.

2.2.2. Complex Events Management and Processing Module

This module receives the detected *complex events* sent by the Information Processing Module and store them in the Events Repository.

- Moreover, it retrieves the stored complex events and executes the following operations:
- Validation: consistency and coherence of the information contained in the complex events are validate;
- Fusion: Complex events validated and stored on the STORM Events Repository that share the same information are fused together to reduce both information complexity and computational power that needed for analysing them;
- Correlation: Complex events validated and fused are correlated using spatial, temporal and causal relationships with each existent event. The sets (also formed by one single complex events) of related complex events are stored in the STORM Event repository and sent to the Quick Damage Module for the further analysis.

The above operations are driven by the rules defined by CH domains expert. Its functionalities are supported by a STORM Events Repository used for storing the complex events data.

2.3. STORM Service Modules

The Service Layer Modules of the STORM Logical Architecture are described by illustrating the main functionalities, input and output received and provided, as well as, the dependencies with other modules.

The architectural aspects of the Service Layer, including modules able to prevent, manage and mitigate the risk associated with natural hazards in the CH domain are considered.

Specifically, the following service modules are considered:

- *Risk Assessment and Management* service that allow the assessment of all potential vulnerabilities and risks to specific cultural sites and the definition of the best-fitting risk management strategies;
- *Surveillance and Monitoring* service that allow for, the CH users to be informed and aware on critical situations and manage them using the information retrieved from the field by physical sensors and human evaluators, exploiting both human cognitive ability and machine inference;
- *Quick Damage Assessment and Surveying and Diagnosis* services allow the CH users to respectively select the best actions of the intervention and prevention process to mitigate the possible consequences of the observed situation considering the known risks;
- *Data Analytics* service, enhance the understanding of the users early through interactive visualisations, during or in the afterwards of a critical situation to enable an effective and efficient response to it.

2.3.1. Risk Assessment and Management Module

The Risk Assessment Module receives the *complex event(s)* and associates a set of hazards to each of them, which represents all the possible effects that each event may cause.

The risk related to the *complex event* is evaluated by the Surveillance and Monitoring Module as the combination of the hazard likelihood and the event severity, in order to be added to the critical situation in compliance with the STORM Situation Information Model.

The STORM Disaster Risk Assessment methodology (identification, analysis, evaluation) has been integrated in the Risk Assessment Module. Moreover, hazard assessment as well as exposure and vulnerability assessment of CH sites, areas, artefacts or assets can be facilitated by the domain experts with the support of the Disaster Risk Assessment tool.

Furthermore, the Risk Management Module defines a set of proposed actions in case of predicted emergency, as well as, a set of guidelines for the involved stakeholders, targeting the protection of the CH site or specific monuments on the site.

Such a task can be facilitated by the domain experts with the support of the Disaster Risk Management tool.

Finally, the available risk maps and visualizations corresponding to specific hazards are provided through the Web-GIS interfaces and services provided by the Web Application and GIS Services Module (§7.3.2.6).

Therefore, associated risk assessment values along with the corresponding proposed actions, guidelines, warnings and reporting information shall feed the Surveillance and Monitoring Module towards the generation of the overall critical situation in compliance with the regulations in force in the country where the CH site or asset is located.

2.3.2. Surveillance and Monitoring Module

The Surveillance and Monitoring Module oversees the STORM *complex events* processing based on its characteristics and its possible cause-effect relationship.

It produces afterwards critical situation, which provides the needed elements for situational awareness and decision- making support. In principle, it receives as input *correlated complex events* (already correlated events group through its time and spatial relationship) from the Event and Processing Management Module and tries to relate events in the group and other events from the STORM Event Repository through causal rules, provided in input by domain experts.

Once the events are correlated and aggregated, the Surveillance and Monitoring Module takes into consideration the risk rating associated with the event and builds up its critical situation interpretation, which is made immediately available to other dependent STORM modules, like the Quick Damage Assessment and Survey and Diagnosis Modules.

The Surveillance and Monitoring Module is composed of the following sub- modules:

- Causal Rule Manager Module is responsible for managing the causal rules edited by domain experts through the visual interface. The rules are used by the Complex Event Correlator Module.

- Complex Event Correlator Module is responsible for causal correlation of the events through the causal rules provided by the Causal Rule Manager.
- Situation Builder Module is in charge of building the situation data structure including all correlated situation events and assets information. The situation is composed of the correlated events incoming from the Complex Event Correlator Module with involved asset information.
- Causal Analysis Module evaluates the probabilities of the possible causes and effects of the critical situation in progress. This module receives in input the situation from the Situation Builder Module and produces as output the probabilities related to the possible causes and effects of the situation.

2.3.3. Quick Damage Assessment Module

The Quick Damage Assessment Module oversees: i) the analysis of the overall situation for producing the *quick response process* and ii) the delivery of actions and actors (role) to Mobile Crowdsourcing Task Dispatcher Module, waiting for feedbacks and data as input.

The Quick Damage Assessment Module receives as input the critical situation from the Surveillance and Monitoring Module and selects the proper *quick response process* for managing the emergency. As the Quick Damage Assessment Module receives a new input, it sequentially performs the following actions:

- Analysis of the received input;
- Evaluation of severity related to the damage/disaster;
- Selection of the proper process for managing the critical situation in progress.

The Quick Damage Assessment Module sends actions and actors (role) of the *quick response process* detected to the Mobile Crowdsourcing Task Dispatcher Module and manage the feedbacks. Then, the Quick Damage Assessment Module waits for another critical situation and restarts from the first step.

The Quick Damage Assessment Module is composed of the following sub-modules:

- Quick Responder Module is responsible for evaluating the severity of the damage/disaster and selecting the best process for managing the critical situation in progress;
- Situation Manager Module oversees managing the situation data structure including all correlated situation events, assets information and the processes for managing the emergency.

2.3.4. Surveying and Diagnosis Module

The Surveying and Diagnosis Module aims to provide a management service for the site managers to record all restoration resources, e.g. sensor devices, coordinate responsible actors' task, keep track of current status, set activity plan, etc.

With this information available, it helps in selecting proper restoration process for managing any incoming critical situation.

The service also allows the recording of information extracted from the processing and analysis of data coming from the experts surveying activities and annotation and characterisation of specific areas of site where damages have been diagnosed.

The Surveying and Diagnosis Module is composed of two main sub- modules:

- Restoration Resources Manager Module is responsible for managing all restoration resources. It then links to Process Builder to decide which resources are going to be affected with related process;
- Process Builder Module aims in selecting proper restoration process based on incoming critical situation data from Surveillance and Monitoring Module.

2.3.5. Data Analytics Module

Data Analytics Module accesses the STORM Repositories (e.g., data, information, event, situation, process repository) to execute the following operations:

- Historical comparison: Comparison of current situation with historical situations and related sensor data to analyse what caused the critical situation and how to prevent damages in future;
- Historical data summaries: Mean, standard deviation, quartiles, histograms, boxplots to understand the distribution and spread of the data;
- Data analysis representation: Representation of data analysis models to be applied to specific data types.

2.3.6. Web Application and GIS Services Module

The Web-GIS Service Module receives requests mainly from the Risk Assessment and Surveillance & Monitoring Modules providing support for the management and visualization of STORM spatial data.

The Web-GIS Service Module provides geospatial information through several web services, such as Web Map Services (WMS) that supports requests for map images (and other formats) generated from geographical data, Web Feature Services (WFS) that supports requests for geographical feature data (with vector geometry and attributes) and Web Coverage Services (WCS) that supports requests for coverage data (rasters).

Moreover, the Web-GIS module functionalities are supported by the STORM GIS data repository, while it serves spatial data using standard protocols (e.g., Open Geospatial Consortium specification).

2.3.7. Mobile Crowdsourcing Task Dispatcher Module

The Mobile Crowdsourcing Task Dispatcher Module is a message-oriented dispatcher service based on a mobile application; it provides to Quick Damage Assessment and Survey and Diagnosis services a way to reach and propose Task (Action or Request) to professionals and volunteers, as well as gather real-time information from the disaster site.

Due to the intrinsic asynchronous nature of workflow involving humans, Quick Damage Assessment and Survey and Diagnosis Services interact with crowdsourcing volunteers on a message-oriented paradigm basis.

A specific crowdsourcing mobile app delivers messages to registered users on a push notification mechanism basis.

Generally, the Tasks, are defined by three logic parameters:

- What (the action to be performed);
- Who (specifies the actor that should perform the action);
- Where (specifies the position where the action should be performed).

The Task Messages can be delivered to one or more users, according to the content of the Who parameter:

- Specific User;
- Specific Group of Users;
- Users with a user profile that matches specific roles and/or skills and/or users that are near a specific position.

The Task Assignment Management is based on asynchronous request-response interaction model.

The Crowdsourcing for Crisis Management application is supported by a Crowdsourcing Mobile App (user front-end) and the Mobile Crowdsourcing Task Dispatcher Module that is in charge of the message dispatching between the service layer, namely Quick Damage Assessment Module and Surveillance and Monitoring Module along with the mobile workforce.

The Crowdsourcing Mobile App interacts with the Mobile Crowdsensing Task Dispatcher Module on a client-server basis. Client interactions are solicited by push notification or by the user.

2.4. STORM Application Modules

The Application Logic Layer allows the users to interact with the STORM services and tools using Web application technologies, GIS services and mobile apps for tablet and smartphone devices as well as crowdsourcing and gamification applications.

In this layer, the GUI functionalities are implemented to have an easy and intuitive access using a simple http browser to the operational and collaborative working environment for making decisions and sharing the CH knowledge.

Two categories of applications are considered:

- STORM Collaborative Decision-Making Dashboard;
- Mobile apps.

STORM proposes an integrated solution, namely STORM Collaborative Decision-Making Dashboard (for further details please refers to the Chapter 5: Decision making for risk mitigation based on collaborative services and tools) where collaborative and operational environments are strongly interconnected with each other. Existing knowledge (e.g. best practice, guidelines, lessons learned, operative procedure and processes, etc.) related to natural disaster risk and impact can help in making decisions and new knowledge (e.g. from the situational picture, risk assessment and data analytics) can be shared by team of experts in order to identify the best and most urgent recovery actions.

The STORM Collaborative Decision-Making Dashboard provides specific set of collaborative and operative services coming from the two interconnected environments. The set of services and tools belonging to the respective environments, support the knowledge sharing, coordination of involved stakeholders and the decision-making process.

In order to motivate the end users, and trigger their participation in crowdsensing activities, the use of Gamification strategies has been selected.

Based on the particularities of each site, as regards operational, regulatory, cultural and technical issues, the use of Gamification employs different ways to encourage users to participate in activities under the general "human as a sensor" concept.

Regardless of the particularities existing in each site, a common set of requirements driving the design of a gaming application include:

- The adoption of easy to use practical interfaces taking into account the mobile/pervasive nature of devices, the use in exterior/interior spaces, the need for location identification;

- The deployment of both onboard sensors and linked sensor devices to the mobile terminals.

A game type that can be combined with crowdsensing is a Scavenger Hunt game. A scavenger hunt game is a game where a player has to complete a series of tasks (or stages) grouped in scenarios in order to win the game. Stages can ask the player to answer a question, go to a specific location, annotate a picture etc. By completing stages, the player earns points, while the player with the most points wins the game.

The game utilises a server where scenarios and details about them are saved, a web application for the creation and modification of games and lastly mobile applications for the two major platforms, i.e. Android and iOS, where the players can play.

When the player reaches a specific location, the stage continues to the next step.

When arriving at the stage's location, the player can continue to the next step which involves the player submitting about the environment in that specific location.

By using the device's camera, the player can send a picture or a video clip of the surrounding space. Also, with the device's microphone, the environmental sound and data from sensors can be submitted.

Sensors can include mobile device's sensors such as the ambient light sensor. External sensors can also be used like the ones from Techonia.

These sensors can connect to the audio jack of the device and can capture temperature, humidity, UV light and radiation.

By sending the above information, the stage gets completed and the next is presented where the player has to go to a new location and send other data.

The game finishes when all stages are completed.

The Gamification app could be integrated with a Smart Sensors module able to provide sensory data (both human recorded, such as pictures and audio, and sensor generated such as temperature, humidity, light, UV, etc.).

The mobile application supporting gamification has to be developed exploiting an open approach which allows even the introduction of third partner sensor hardware, connected using a standard wired interface (i.e. USB, audio jack or wireless).

The idea is to enable a user to voluntarily contribute sensory data through personal devices such as mobile phones.

The layers of the STORM Logical Architecture and the core modules have been described. In the following paragraph, the main interactions among architectural modules are described, namely the STORM Interoperability Architecture is presented.

3. STORM Interoperability Architecture

The STORM Interoperability Architecture is described to show the interactions among layers and their included modules.

The STORM Interoperability Architecture is made up by layers that interact with each other in order to enrich data extracted from the lowest layer, adding information up to the higher level.

The STORM Interoperability Architecture is shown in Figure 2:

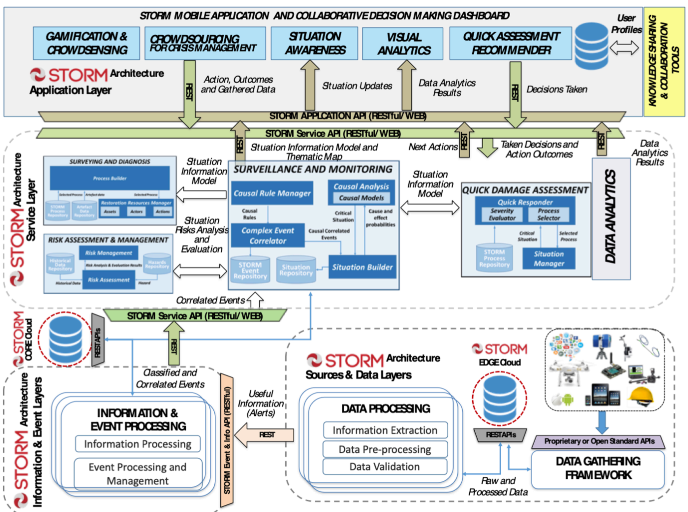

Figure 2. STORM Interoperability Architecture.

The layers of the STORM Architecture are described analysing the main interactions between architectural modules, showing the enrichment of the data from the single alert to the identification of the recovery processes.

At the Source and Data Layer, the modules are responsible for carrying out the extraction of data from the Source Data Layer, which is made up by physical sensors and applications for supporting the crowdsensing and crowdsourcing applications.

In this layer, the modules can pre-process and validate the collected raw data.

They also provide in output useful information that are the input of the modules at the upper level through the STORM Event and Info API (RESTful).

The upper layer of the Data Logic Layer is the Information Logic Layer.

At this level, the Information Processing Module is responsible to i) process the received useful information; ii) correlate and identify from these information new complex events and iii) send these events to the upper layer for their further processing.

At the Event Logic Layer, the Events Processing and Management (EPM) Module performs the validation, fusion and correlation of the received classified events from the lower layer and store them in the STORM Core Cloud so that these could be reused, in a successive step.

Therefore, these events are analysed for identifying spatial or temporal correlations and then sent in groups of correlated ones to the Surveillance & Monitoring Module, at the Service Logic Layer, using the STORM Service APIs (RESTful/WEB).

The Surveillance and Monitoring Service is responsible to i) identify causal correlations among correlated events received by the EPM and potential critical situations related to some dangerous events or a group of correlated events and ii) send the identified situations to the Quick Damage Assessment and Surveying and Diagnosis Module, respectively for managing sudden-onset or slow-onset disaster situations.

Once the critical situation has been identified, the Surveillance and Monitoring Service stores it in the Situation repository on the STORM Core Cloud and invokes the Risk Assessment and Management Module to obtain related risk information.

The information on the risk is used for evaluating the situation severity level and for building a clear situational map that are shared with decision makers through the Location and Situation Awareness application, which is located at the Application Logic Layer.

Moreover, the Quick Damage Assessment and Surveying and Diagnosis Modules are responsible for the identification of the most appropriate processes to manage the current critical situations.

During the execution of the processes, these modules interact with on the field STORM users (professionals and volunteers) through the crowdsourcing mobile application that dispatches them the required tasks and receives useful information (if any) from the operational site.

The crowdsourcing mobile application is logically located at the Applications Layer.

In addition, the Visual Data Analytics module is also included in the Application Layers and is responsible for producing and providing data analytics useful to the decision makers for analysing the current situations.

The STORM Interoperability Architecture is described according to a data-driven approach where aspects of the data interoperability among each architectural model have been considered, exploiting the STORM Open Cloud framework and a set of standard APIs, designed and developed in STORM.

All the data, as well as the useful information from heterogeneous information sources, can be archived in a cloud-based infrastructure.

Once the data have been stored in the STORM Cloud Infrastructure, they can be elaborated in order to extract the relevant data for the CH domain.

Cloud computing represents the technology that manages to address many of the features required for the STORM platform.

Cloud computing is one of the main technologies chosen in STORM, since a complex and modular architecture like that of STORM requires a careful choosing work of technologies and implementation methods that is used in its realization.

3.1. STORM Technologies and Implementation Methods

STORM technological solutions are chosen to minimize the loss of efficiency and responsiveness and possible failures typical of a modular and complex architecture.

Some technical guidelines and technical details that match requirements of the logical architecture are proposed.

The technical and implementation aspects of all STORM modules are described in terms of STORM Application Framework, STORM Platform APIs, and Open Cloud Framework.

3.1.1. STORM Application Framework

The STORM Collaborative and Decision-Making Dashboard is implemented starting from the Liferay Portal and its functionalities, in Software-as-a-Service (SaaS) mode, through Cloud Computing Infrastructure.

Liferay Portal is an open source enterprise portal, distributed under the GNU Lesser General Public License and written in Java.

Liferay Portal allows the usage and development of Web 2.0 Technologies including a built-in web content management system allowing users to build websites and portals as an assembly of themes, pages, portlets and common navigation.

STORM Collaborative and Decision-Making Dashboard uses the principal functionalities of Liferay Portal implementing also a suite of applications that provides high capability to manage and support the collaboration in a working group.

The built-in entities of the Liferay Portal such as Blogs, Discussion Events, Documents, Forums, Message Board, Questions and Wiki allows to define the Collaborative and Knowledge Sharing tools, enabling the users of the community to enter and enjoy data.

CRUD (Create, Read, Update, and Delete) operation of the data contained in these entities is carried out with the programming interfaces (APIs) made available by Liferay.

The STORM Collaborative and Decision-Making Dashboard allows grouping and displaying the contents of these entities using collectors classified according to the typology or custom criteria, encapsulating all the standard entities, on abstractions called Resources.

The STORM Collaborative and Decision-Making Dashboard supports plugins into multiple programming languages and simplifies the development of websites and portals allowing users to login personalized services or views.

The STORM Collaborative and Decision-Making Dashboard allows a concrete support to decision making in extreme or high-critical environments, establishing necessary and useful functionalities to represent the critical situation and provide information for decision making support.

STORM Collaborative and Decision-Making Dashboard is a dynamic dashboard whose features can be defined according to the user's interests and needs thanks to the adaptability of Liferay framework.

3.1.2. STORM Platform APIs

The STORM Platform has been designed according to the Service Oriented Architecture (SOA).

This is the best choice in case of system modularity, especially for STORM, where each module is developed by a different partner.

This approach allows the modules to communicate each other through specific APIs without accessing the internal implementation.

In the STORM Platform, every module has one or more REST Interfaces through which the other modules are able to exploit its functionalities.

In general, the term API refers to a set of well-defined methods that a module provides to other modules for communicating with it.

In STORM, every module provides at least one API that other modules can use for interacting with it and using its functionalities.

The STORM Platform APIs are the union of the APIs provided by every STORM module.

APIs can be provided using several methods and technologies.

STORM modules provide their APIs mainly on the WEB exposing REST web services.

REST is an architectural style and not a standardized protocol as SOAP or HTTP.

REST services are realized by taking advantage of several existing and widely adopted technologies as JSON (or any other data format) and standards as HTTP.

In general, the most adopted data format by REST APIs is JSON (JavaScript Object Notation).

The request-response pattern is the one on which the REST APIs are based.

REST APIs, in STORM, exchange message using the JSON message format.

These are universal data structures that every programming languages support.

This is the reason for which JSON is the most utilized data format.

3.1.3. Linked Open Data

Linked Open Data (LOD) transforms the World Wide Web (WWW) into a global database that is called the Web of Data.

In STORM, sensor networks are deployed within sites, with the aim of enhancing these areas of interest in terms of managing more efficiently key services, such as Quick Damage Assessment and Surveying and diagnosis services.

Exploiting LOD, STORM achieves large scale integration of data/information that enable the development of cognitive services for the protection of CH.

In particular, advanced STORM services use LOD, in order to empower the situational awareness in STORM platform and make sophisticated by exploiting the deductive reasoning of semantic rules.

In order to exploit the LOD, STORM translates the collected data/information to open data formats.

Specifically, the following resource/data formats and Semantic Web technologies are used:

- URI (Uniform Resource Identifier): it is a unique string of characters used to identify a resource. For example, in STORM, a specific URI defines uniquely an acoustic sensor deployed in the Mellor site;

- RDF (Resource Description Framework): it is a standard model for data interchange on the Web and is similar to classical entity–relationship diagram. RDF is based on URIs by making statements about them in the form of subject – predicate – object, known as triples. For example, using triple, in STORM, is possible to denote a specific sensor (subject) located (predicate) in a specific site (object);
- OWL (Web Ontology Language): it is a Semantic Web language that represents complex knowledge about things, groups of things, and relations between things by using an RDF/XML syntax. The STORM OWL documents, known as ontologies, are presented such as STORM Audio Signal Ontology;
- JSON-LD (JavaScript Object Notation for Linked Data): it is a method of encoding Linked Data using JSON in order to require as little effort as possible from developers to transform their existing JSON to JSON-LD. Since STORM architecture is SOA (Service Oriented Architecture), and its modules mainly exchange data through RESTful APIs using JSON format, JSON-LD is selected instead of other LOD publishing formats (e.g., RDFa and Microdata);
- Turtle / N-triples: they are two formats for expressing data (instances) in the RDF data model. STORM APIs expose data through JSON-LD and afterwards are automatically mapped onto Turtle / N-triples format with respect to STORM ontologies;
- SWRL (Semantic Web Rule Language): it is a language for the Semantic Web that expresses rules as well as logic. Experts define SWRL rules in order to empower situation awareness through deductive reasoning;
- SPARQL: it is an RDF query language, capable of retrieving or manipulating data stored in RDF format. STORM retrieves LOD based on SPARQL queries. Moreover, STORM provides public access of its data to experts and developers using SPARQL endpoints.

3.1.4. STORM Open Cloud Framework

The Open Cloud framework (for further details please refers to the Chapter 6: Taking advantage of the cloud for efficient use of ICT resources and sensory data) provides two hierarchical layers of cloud infrastructure: Edge Cloud and Core Cloud.

The two layers can communicate using tools and facilities provided by the STORM Open Cloud framework.

Moreover, the STORM Open Cloud framework provides services and specific instances of databases that make the data stored by each architectural module accessible to the other internal to the architecture, and even externally as Open Linked Data.

The Core Cloud is the main layer of the STORM Open Cloud framework and there is only a single instance of it.

The Core Cloud infrastructure is used for hosting the STORM Core Modules of the STORM Logical Architecture, while the Edge Cloud represents the sensing part of the STORM Logical Architecture, that consists of Source and Data Layer Module

There are several Edge Cloud instances and each one is used by one or more partners for hosting modules to monitor one or more pilot sites through the integration of several data sources.

The Core cloud can be described as a brokering system indicating which type of data each Edge Cloud offers, while the Edge clouds are cloud environments located in the sites.

The role of the STORM Edge cloud is the collection, storage, processing and analysing data gathered by sensors.

Therefore, each Edge Cloud instance can store data collected from several data sources and all the modules related to the Source and Data Layer (e.g., data source integration, data processing and management, etc.).

As a result, instances of Edge Cloud host every module needed for:

- Integrating and managing the data sources;
- Gathering data produced by these sources (raw data);
- Validating and pre-processing collected raw data (pre-processed data);
- Analysing pre-processed data (processed data) for identifying useful information and for providing these to the Information Processing Module hosted in the STORM Core Cloud instance.

Finally, the information of each site should be available to every Edge cloud and displayed through the Core cloud.

The aforementioned instances of Edge Cloud can communicate with the Core Cloud for notifying useful information and, similarly, every module hosted in the Core Cloud can access to the data stored in each Edge Cloud instance.

A relationship between the useful information and the processed data where the information has been extracted, needs to be stored inside the Edge or Core Cloud.

In case of Edge Cloud instance does not exist, the Source and Data Layer Modules along with the data they produce are hosted externally in a partner own proprietary cloud.

In this configuration, once a useful information is identified it can be sent directly to the Information Processing Module.

Accessing to the data, from which the useful information has been extracted cannot be possible.

The Open Cloud Framework is a key asset of the STORM cloud implementation as it describes the procedures needed for the creation of a STORM compatible cloud.

The usage of cloud computing technology in STORM is necessary for the storage, management and processing of large amount of data.

However, these procedures require the manageability of computational power, therefore a cloud computing solution following the Infrastructure as a Service model (IaaS) is needed.

The OpenStack cloud solution fulfils the criteria because it is open source cloud computing software with a very active community.

The implementation of an OpenStack cloud offers a fully functional IaaS cloud consisted of RESTful services and APIs.

One of the key functionalities of OpenStack is the creation of Virtual Machines (VMs), able to host many applications.

Additionally, the creation of fully customized instances, such as non-relational databases (i.e. MongoDB) which may easily communicate with other entities via RESTful APIs, makes it ideal for deployment.

An OpenStack cloud solution can be implemented following numerous deployment techniques.

Nevertheless, the Open Cloud Framework follows the Ansible deployment for the implementation of a STORM compatible OpenStack cloud.

The OpenStack Ansible uses the Ansible automated mechanism for the rapid implementation of a cloud.

One of the key characteristics of cloud is the multitenancy, which is also presented in the OpenStack solution.

As a result, the STORM cloud can be a project of the OpenStack cloud which means that it is isolated from the other OpenStack projects.

Additionally, the Open Cloud Framework is a guideline which describes the necessary procedures and actions for the implementation of a STORM cloud.

The Edge clouds are OpenStack clouds deployed following the OpenStack Ansible Deployment (OSAD) guide.

Edge clouds, are used for the storage and management of the data.

Incoming data can be pre-processed, processed or even raw under certain circumstances.

Key component for an Edge cloud is the Edge Cloud Connector (ECC), which is responsible for storing the incoming data and forward them to the Core cloud based on the Publish/Subscribe pattern or provide them by request using a RESTful API.

More specific, each STORM partner may create his own STORM Cloud Edge instance, by using automated scripts, or may use the Edge cloud features of another partner.

In the first case the partner is able to store and manage raw data in his Edge cloud but in the second option the data must be pre-processed or processed for capacity reasons.

Furthermore, each Edge cloud can incorporate any existing proprietary solution, or even directly interface it using proprietary interface implemented by the partner using this solution.

In example, the latter can be used for the photogrammetry case, with raw data belonging to the proprietary solution part and smaller scale data available over the Edge cloud through a REST API.

The Edge cloud also is responsible for the hosting of services related to pre-processed and processed data.

Finally, each Edge cloud provides information about the availability of computational resources which can be used by the STORM dashboard, hosted in the Core cloud.

The STORM Core cloud instance, however, is responsible for hosting event related data and services as well as the Core Cloud Connector (CCC) and the Cloud Broker.

The Core cloud is also an OpenStack-based instance and therefore it provides RESTful APIs.

The CCC is a Core cloud component that receives real-time data and information from the Edge clouds (i.e., through the ECC) and distributes them to the Core cloud services and tools based on the Publish/Subscribe pattern.

The Cloud Broker is a virtual machine (VM) hosted inside the Core cloud.

In the Cloud-based STORM architecture there is only one Core cloud which contains services and a dashboard, depending on the use of event data.

As it is clearly presented in the above architecture every cloud instance, Edge or Core, is based on REST APIs.

Therefore, all services and open data can be available by an Edge cloud that has announced its presence in the Cloud Broker.

Those services and data can be displayed in the STORM dashboard.

The Broker is also responsible for providing a dashboard for monitoring the resources of STORM clouds.

Finally, the architecture described above allows the integration of 3rd party solutions such as Sentilo, OpenHAB and others.

This can be achieved by the creation of virtual machines where 3rd party solutions can be installed and interact with other STORM services using APIs developed by the partner who uses that solution. A more detailed description for for the STORM reference Architecture can be found in Deliverables 3.1, 3.2 and 3.3 (STORM Consortium 2017)

4. Conclusion

Focusing on the implementation details inevitably the attention shifts to how the system works, before finishing the definition of how the system should logically implement its functionalities.

To solve this issue, the adoption of a design methodology that focuses primarily on how the system implements its functionalities (in a logical viewpoint) has been followed in order to define the STORM Architecture.

Once how the system functionalities are provided has been defined, it is then possible to focus on which technologies are used to realise such functionalities (i.e. implementation).

System Architecture must be flexible and adaptable to many possible changes that can occur during next periods, as for instance, the availability of new modules, the unavailability of other ones, the addition or removal of new functionalities and so on.

Any additional updates and modifications at the System Architecture, due to technological and implementation choices of complex systems like the STORM platform, are allowed.

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8.
Applications and services in a connected world

Ulderico Santamaria, Giulia Governatori, Maria Concetta Capua

1. Technology and everyday life

It is now clear that we live in a world that is completely surrounded by technology: any activity, as the subscription to a service, the shopping, or also a bank transfer can be done online, nowadays. Technology is actually overwhelming us at such a point that sometimes it replaces human beings; although this is often useful for speeding up a series of interventions and activities, we must not forget the importance of human connection nor eliminate human reflection. Only the thought of the specialist, applied to the available technology, in fact, can allow us to obtain valuable and effective results.

1.1. Technology and CH

Technology is actually changing also the Cultural Heritage's world, in many different ways, not only in monitoring, conservation and restoration work, but also in spreading culture and history for tourist and people who did not have a proper knowledge of it.

The importance of preserving the work of art, for professional figures dealing with cultural heritage, is a primary need, since this allows us to retrace the history of the civilizations of the past, or to know the thought and work of important artists. For this aim, it is essential to acquire data that allows us to 'communicate' with the work of art, in order to examine all the parameters that allow to understand the well-being of it and to promptly intervene, in order to prevent damage or material loss. In a connected world, every specialist has the opportunity to acquire the necessary data and to know the work of art's situation in advance, having the time to plan the right intervention to be carried out and to organize the needed activities with the due attention.

Also, technology can help in research works, in the last decades in fact, digital archives are born, this can be very helpful if a professional figures, but also a student, need to read documents that, otherwise, had to be found in archives or offices. Archives are usually very often full of a huge number of documents, that can be difficult to find and identify; this makes the research and identification of documents very complicated, enormously slowing down the process. Online archives, on the other hand, work like a real search engine that allows, by inserting one or more keywords, to view all the available documents, speeding up the process, a factor that can often be crucial, especially if working in emergency and needing to get information quickly in order to plan first aid interventions.

2. The usefulness of laptop, tablet, smartphone

Technology devices as computers, tablet and smartphones are nowadays extremely widespread and they are available for everyone. It is possible to say that anyone, from children to the elderly, can have them in their hands. Depending on the needs and the economic possibilities, obviously, these devices are different and have different functionalities or capacities, but the basic functions are almost the same for each one.

This instruments, that are very often criticized, above all for the excessive use that is made of them, especially among the youth, but also because of the difficulties in controlling the contents shared between the lower age groups, can actually be very helpful, if used in the right way. In fact the possibility of always being connected with everyone in any part of the whole world can allow us to share contents, news, updates and useful information in real time with anyone; but also to raise awareness of particularly delicate issues, to find, sometimes on the other side of the world , resources or solutions to problems of various kinds (i.e. medical centres specialized in treatments for very rare diseases).

All this, up until a decade ago, seemed absolutely impossible, but now it is literally in our hands. That is why we can really consider technic devices truly valuable instruments to be used not only for Enhancement, but also for Conservation, Monitoring, Protection of Cultural Heritage. In fact, they can create human contact between professional figures and tourists, visitors, helping them in sharing knowledge and information.

The most important thing to do that, is to integrate technologic devices in the real life, using them as an instrument that can enhance the contact between people, not the opposite.

2.1. Remote control of instruments and automatically data processing

During the last years several software for the remote control of devices and for their desktop sharing have been developed. These software, through the internet connection, creates a sort of bridge that allows the access, thanks to the network, to devices far from our workstation, simply by setting a user name and a password. The possibility of controlling remote instruments is certainly a great advantage for the monitoring of cultural heritage. Not infrequently, in fact, can happen that areas to be monitored are huge or quite difficult to be reached; this make extremely difficult the control the instrumentation and the possible maintenance of that. Maintenance is very important and it is an integration of the information and communication technologies (ICT) that can follow the new needs for innovative ways to collect data. In fact, is important that on board of the collection system can be developed new software able to transform automatically the data and produce an information about the Health of the monuments.

Automated data processing is possible thanks to software that automatically processes data including electronics technologies that can gather, store, manipulate, prepare and distribute data. The objectives of automated data processing is in real time process large amounts of information with minimal human interaction.

Furthermore, it may happen that the technical figures able to carry out the aforementioned activities is not numerous, making maintenance times even longer. For all these reasons, the possibility of connecting these instruments to a PC on the Internet and performing remote interventions can be extremely useful in the field of Cultural Heritage.

This was demonstrated, in the Storm experience, in Baths of Diocletian Pilot Sites. As already described in Chapter 3, the University of Tuscia has installed FBG with strain and wet/dry sensors in two areas of the Museum and sensors for the assessment of temperature, humidity, acceleration, stress, tilt. Being an experimental installation, the functioning had several problems to be solved, and a quite big number of interventions on the instrumentation had to be carried out. Most of these situations have been solved remotely, as well as data recovery and the installation of new software for data collection and analysis.

In Figure 1 and 2, it is possible to see how the Remote Control tool works; thanks to the Wi-Fi connection it is possible to see the screen of the computer were FBG interrogator Tool installed in Hall I of Baths of Diocletian is connected, to check if everything is working. In this way we always have data about the wall structures available. In particular is possible to process a large number of data to follow material and structure changes with high time-resolution. The analysis of these data normally is very time-consuming and, furthermore, it requires the days for process and understand what's happening. Inside STORM project we have a software system developed for automatic processing and analysis of large series of data on a peripheral personal computer. With this software the interaction of the professionals is limited to a definition of the processing conditions at the beginning of the data analysis and follow the maintenance of the system.

It is fundamental, though, to have a very stable Wi-Fi connection and a well performing computer in order to have a proper remote control of the instruments. During the Storm experience, in fact, several problems in the remote connection have been caused by the computer itself that, sometimes, needed to be restarted on place.

Figure 1. External wall of the Hall I, Baths of Diocletian Pilot Site, where is possible to see Rising Humidity, monitored by FBG sensors (almost invisible to a naked eye), connected to the computer inside the Hall, that can be remotely controlled.

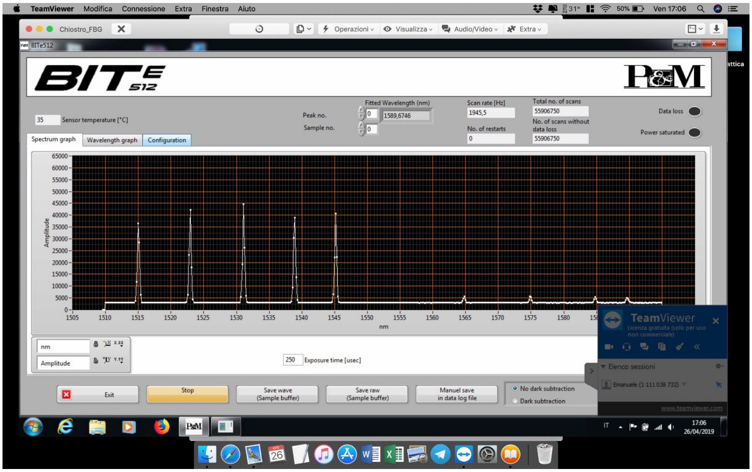

Figure 2. Remote control of the interrogator tool connected to the FBG sensors installed in Baths of Diocletian Pilot Site, Hall I, here we can see wavelenght registered by the nine sensors installed in the internal and external side of the wall.

2.2. Social Network and CH

The most used apps, in smartphones, are undoubtedly games, music apps and social networks: Facebook, Instagram, Twitter, Tik Tok, just to mention some of the most famous.

Although social media are mostly used as a hobby, to share light contents, it is not uncommon that they are exploited to raise awareness, make appeals, communicate important messages, often through the use of videos or images, and also to organize fundraising for charity. Sometimes even through social networks, alarms can be launched. This makes them a potentially useful tool for the enhancement, but also for the protection, of the cultural heritage. It is enough to consider all the ‘challenges’ that the word had to face in recent years. The tsunamis that affected tropical regions, the earthquakes that hit central Italy, damaging not only homes, but cultural assets of great importance, such as the Basilica of San Benedetto in Norcia, or the very recent fire that hit Notre Dame in Paris. Images, videos, cartoons and interviews of various kinds, about that topics, spread all over the Internet, becoming viral. In this way everyone who was connected to the network had the chance to know and see with his own eyes what was happening, and sometimes, have the chance to give help, to communicate an opinion.

2.2.1. The twitter appeals

Twitter was born as a service for sharing news and microblogging. Thanks to the possibility of using hashtags (words preceded by the symbol #) and tags (names of users preceded by the @ symbol) it is very common for users to make appeals or to request interventions on current issues, political or economic problems. Very often the hashtags become viral, allowing to give enormous visibility to the subject dealt with, which in this way sometimes succeeds in attracting the attention of important personalities, not only popular peoples such as singers and actors, but also politicians. This feature certainly makes Twitter an ideal 'place' to make appeals aimed at protecting, or safeguarding, cultural heritage (e.g. UNESCO Twitter profile, enhancing the importance of Cultural Heritage Protection, shown in Figure 3), as it happened, just to make an example, in Italy, when very strong rainfalls were seriously compromising Pompeii Archaeological area.

Figure 3. Unesco Twitter Account, 'tweet' about Cultural Heritage Protection.

2.2.2. Instagram and the images impact

Instagram is a social network born for image sharing, which allows users to share photos and videos and add them some captions and hashtags. Lately content sharing has expanded, allowing users to add polls and multiple-choice tests, options often used for advertising purposes, to Instagram Stories (contents that are available only for 24 hours). This social network, created to entertain users, has a great potential for enhancing and promoting cultural heritage. The strong impact of the images, which are disseminated and shared by different users, can undoubtedly be used to sensitize users to the protection or enhancement of our heritage; it is not rare, in fact, that museums, archaeological sites, public institutions or private heritage agencies have their own Instagram profile (as UNESCO or the Italian museums, as shown in Figure 4) by which they inform about initiatives, exhibitions, events.

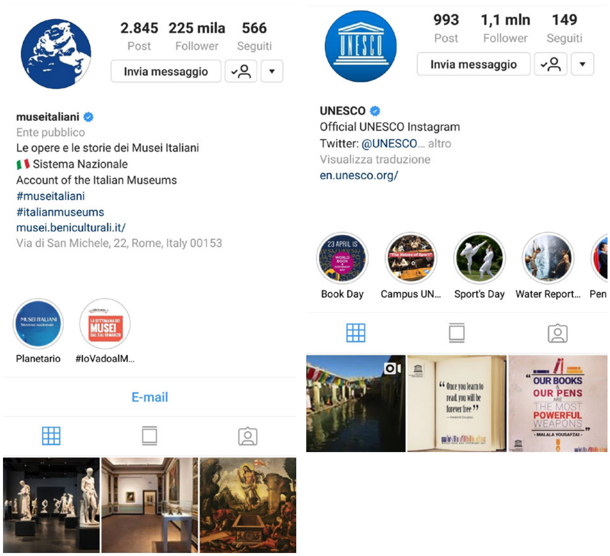

Figure 4. **Instagram Profile of Unesco and National Sistem of Italian Museums.**

Sometimes these official accounts can also inform and update their followers about damages, risks or disasters that, unfortunately too much often, affect cultural heritage. Recently, for example, an enormous number of videos and photos of Notre Dame de Paris, affected by fire, have been uploaded, focusing the users' attention on that disaster.

All this collection of images, of course, even though they are often amateur, can be a quite useful resource in time of crisis, if archives should not be available or easy to be reached.

2.2.3. Fundraising and social network, a resource for CH conservation?

Recently, fundraisings have been spread on the web, often on social networks, to support charities, to help individuals suffering from rare diseases, or to help young people carry out work or research projects. This kind of activities have been organized for decades now, initially asking to the interested people to call or send a text message to a dedicated number (in Italy, for example, there are many donations organized for Telethon, to help people affected by earthquakes or natural disasters, but also to rebuild / restore buildings damaged by catastrophes). In recent years, however, Crowdfunding is easily spreading through dedicated websites; often, directly from a social account, anyone can make a donation for the activities they are most interested in. In a world where the economic resources to be allocated to cultural heritage are never enough, where archaeological excavations continue to bring to light important pieces of ancient civilizations, in which often works of art deemed lost are found thanks to the work of the bodies the fundraisers can be really decisive. In fact, huge donations are not necessary, but every citizen can feel free to donate, simply with a click, the amount they prefer; this can allow to collect huge funds in very short time intervals.

3. Internet and data collection

Internet of Things (IoT) is a new term related to the objects connected to the internet. The meaning of IoT is well expressed if we consider important to know when a stated situation changes. IoT is gives alert when a Storm is coming. These are examples of IoT, that is of objects that, connected to the network, allow to combine real and virtual world. The term IoT ('Internet of Things') was used for the first time by Kevin Ashton, a researcher at MIT, Massachusetts Institute of Technology, where the standard for RFID and other sensors was found. Using IOT, the Internet of things, we can identify a set of technologies that allow you to connect any type of device to the Internet. The purpose of this type of solution is basically to monitor and control and transfer information and then perform subsequent actions.

3.1. IOT, Clouds for data storage

Things in IOT are represented by sensors, how in our case studies are devices capable of data collection in a manner according to a specific areas (equipment dedicated to detecting data related to the temperature, humidity, stress, etc.). We mean of sensors that detect information and transform it into digital data and send data and useful information to a cloud. Normally devices that in different forms and modes are interrogated manually or about a processing method of the data collection supported by a network to obtain the transition from sensors to the IoT. Internet of Things has then a series of steps that all refer to an important work on the data and that as Devices connected to the network - able to detect data and communicate data; Devices connected to the network - able to detect more types of data and transfer this data; Devices connected to the network able to carry out a first level of data processing; Devices connected to the network capable of collecting data, making a first selection level and performing actions based on information received.; Devices connected to the network capable of collecting data, selecting them, transmitting only those necessary for the projects in which they are involved, carrying out actions based on the information received and carrying out actions based on local processing capacity.

The word 'Cloud' in computer science is used to indicate a particular type of architecture. Cloud computing, as a source, has very distant roots, from the 1950s when the first server rooms were huge and full of giant mainframes that were shared by multiple users through connections. The word 'cloud' was chosen to indicate an enormous mass of individual units. Local computers no longer have to do all the work in running the applications that run at the network level. The only thing the user's computer needs to be able to do is interface software, which can be a program or, as often happens, a simple Web browser. As an example a cloud is shared between multiple organizations or organizations, a semi-public cloud limited to a certain set of institutions or organizations.

4. The crowdsensing app

The crowdsensing app developed within the Storm Project, as described in many other chapters of this book can be a very useful instrument for control and damage evaluation of Cultural Heritage. It allows greater control over the state of conservation and the presence of damage to cultural heritage and can be used not by specialists, someone who studied/is working in Cultural Heritage Protection, Management, Restoration field. The app can be used by everyone, not only by those working in CH fields figures of technical staff but by tourists. Entering the app it is in fact possible to make reports about all the situations that the user deems relevant, in order to generate some sort of alerts, which the site manager can control and evaluate. This app can be particularly useful especially in very large sites, where it is rather complicated to carry out a daily and regular check of the conservation status of the whole area.

5. The Storm Platform

The platform developed within the Storm project fully demonstrate how technology applied to cultural heritage actually represent a strength in response, quick assessment and first intervention procedures performed during an emergency or after a hazard occurred which caused damages to the whole site, an area or also a single cultural object. In the STORM project a clear process to facilitate procedures has been designed, as showed in Figure 5.

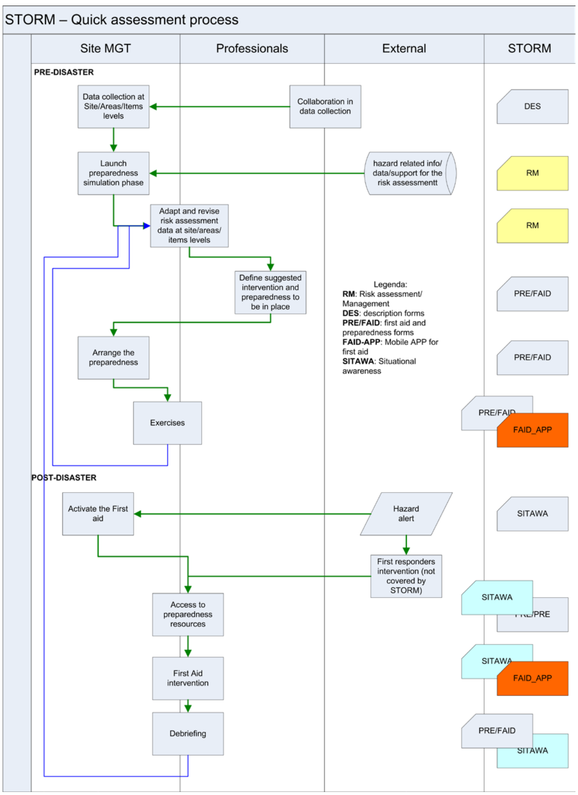

Figure 5. Storm Quick Assessment process.

Management forms provided in the platform, allow to have, descriptive information about the sites, areas and items, preparedness information about where warehouses and materials and resources for the intervention could be collected, first aid procedures to be followed including materials and protections to be used depending on the items structure, and actions guaranteeing quickest intervention based on a assessed preparedness. The team in charge of the first response operation could than count on a dedicated APP used on a tablet connected to the internet and access to a specific set of direction fed by the platform. The operator could get all the information previously entered, as already described in other Chapters of this book, in order to be able to coordinate more efficiently and fast, all the necessary operations which is some cases are carried out in cooperation with First responders. The strength of this system is also in the fact that all the information can be continuously updated; so, for example, if new procedures are put into practices or if new emergencies or hazards occur, during the debriefing phases, new information can be added in the forms, in order to always be updated and prepared for further risks.

Our experience lesson learnt indicated two main point to be addressed in the future one is the need to have a clear strategy defined at government level (as reported in a dedicated section of this book), and the proper allocation of funds to support capacity building at site manager level but also for professionals who are not used to follow this type of process. These action could really support a mitigation of damages caused by climate change hazard for all cultural heritage.

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9. Pilot practical experiences and achieved results

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1. STORM experimentation strategy

One of the main aims of the STORM project is to provide solutions that can be used in any Cultural Heritage (CH) context in Europe and over the world. Therefore, it was of the highest importance that the technologies, services and processes developed in the project could be tested in an appropriate number of different CH sites. The pilot sites have been carefully valued and selected in order to choose the ones which could be more apt to test the STORM solutions. The five selected sites, located in five different countries, are indeed

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one of the strengths of the project, as they are very different in location, size, historical period, as well as in the threats menacing them and in their conservation problems and needs.

In addition, each STORM pilot site has defined experimental scenarios and simulation activities according to the specific needs. The aim of the experimental scenarios is to validate the proposed solutions in relation to the three phases defined in the project, covering a comprehensive approach with ex ante planning and prevention, management and actions, and recovery activities, namely:

- Risk Assessment: Identification, assessment, and monitoring of disaster risks, improving prevention and real-time monitoring;
- Situation Awareness: improving management of crisis and disasters;
- First Aid: improving recovery activities.

STORM introduces a comprehensive approach that supports end users with transversal services as data analytics and knowledge sharing during all these phases. At the same time, the testing environments and scenarios validate three levels of STORM outcomes: technologies, services and processes.

2. STORM experimental sites

All the STORM pilot sites experimental scenarios have been planned to cover both slow-onset and sudden-onset hazards, involving multidisciplinary teams. Specific actors are foreseen for each experimental scenario, including several relevant stakeholders that have been actively engaged in the testing campaign.

2.1. Mellor Heritage Project

Challenges - The Mellor Pilot Site is a complex consisting of three individual sites: Mellor Mill – The remains of an industrial period Mill, Old Vicarage – a site with over 10,000 years of history and home to an exposed section of an Iron-Age defensive ditch, and a reconstructed round-house; and is Shaw Cairn, a Bronze-Age burial which has been excavated in recent decades and now remains exposed.

Mellor, therefore, provides a varied site to the STORM project. It covers a range of periods, and significant are the remains of Mellor Mill – industrial archaeology and cultural heritage is a very important part of the heritage of

North West England – Manchester specifically being the home to the industrial revolution. Mellor Old Vicarage is an interesting site, as it has been the location of a settlement for over 10,000 years and this continues to this day. Its importance throughout history is reiterated by it being home to Mellor's church in the present day.

Mellor also provides STORM with an interesting site in terms of meteorological hazards. This is because the Mellor complex and its three individual sites are located in very different "micro-climatic" conditions. Shaw Cairn is located on top of an exposed hilltop, Mellor Moor, and is therefore likely to be at risk from extreme weather conditions such as cold temperatures and strong winds. The Old Vicarage on the other hand is located on a hill side, with less exposure and more tree cover. This reduces the exposure of the archaeology to certain weather conditions, although the risk of falling trees during big storms, for example, might be increased. Mellor Mill was built in the 1790s at the base of a steep sided river valley – The River Goyt. The positioning of the mill was very important as the Goyt was used to power the water wheel and the operation of the mill. As a result, the mill site is fairly shaded, and protected from some of the extremes of weather. However, it is very damp and cold, therefore the largest risk to the CH here is from freeze-thaw events.

STORM will help the Mellor Heritage Project monitor the site, something that was not achieved prior to the project, by providing tools, services and expertise to help the site take action when hazards occur and protect, prevent and mitigate the hazards to the site.

Trial experiments - A series of experiments and trials have been defined specific for the Mellor Heritage Project. The three areas of the site have been divided into four use cases:

- MAT-01: Old Vicarage site – Iron Age Ditch
- MAT-02: Old Vicarage site – Reconstructed roundhouse
- MAT-03: Mellor Mill – Mill remains
- MAT-04: Shaw Cairn

From these use cases 30-40 items have been selected throughout the site, six of which are included below as a demonstration:

- Ditch bridge support
- Ditch cross-section
- Reconstructed roundhouse thatch
- Reconstructed roundhouse daub
- Mill boiler foundations – fire retardant brick

- Wellington Wheel Pit section

As the majority of the artefacts and areas at Mellor are immovable assets, it was difficult to select items so the work-around was to select items such as specific brick/wood/stone that is interesting archaeologically and suffering from a selection of different hazards. Items that have been selected at Mellor also cover modern day signage, statues and site infrastructure as the CH asset is everything from the archaeological remains on show to the signs for tourists and the bridges and footpaths for visitors to be able to view the CH at Mellor.

The experimental Scenario's selected for deployment at Mellor are:

- **Experimental Scenario 1 MAT_EXP1** – Environmental Monitoring through sensors;
- **Experimental Scenario 2 MAT_EXP2** – Meteorological monitoring through weather stations
- **Experimental Scenario 3 MAT_EXP3** – Monitoring the items material through laser scanning methods;
- **Experimental Scenario 4 MAT_EXP4** – Monitoring the items material through ground-based and aerial photogrammetry;
- **Experimental Scenario 5 MAT_EXP5** – Monitoring the vegetation growth through multispectral drone-based sensors;
- **Process Experimentation MAT_EXP6** – Process experimentation – Flooding;
- **Process Experimentation MAT_EXP7** – Process experimentation - Freeze-thaw.

The first 5 experimental scenarios are ongoing throughout the project and focus on testing the sensors and equipment's usefulness at the Mellor pilot site. The final two are process experiments, which will test the entire STORM process for two events, one slow-onset and one sudden-onset hazard at Mellor. These two will involve two periods of drills at the site to enact STORM processes in the event of flooding and freeze-thaw hazards occurring.

Herein, one scenario will be demonstrated in detail. **Experimental Scenario 2 MAT_EXP2** – Meteorological monitoring through weather stations. The data analysis and explanations can be found in Chapter 4 of this book; in this chapter we will describe how the results of such analysis can be used to highlight the usefulness of the inexpensive weather stations for CH sites in monitoring their assets. The specific objective of this scenario is the early detection of the direct hazards, such as heavy or prolonged rain, heat waves, freeze-thaw action, wind speed, etc., or hazards resulting from extreme weather events indirectly, such as falling vegetation, flash flooding, river flooding, etc. The expected impact is to provide detailed understanding of how localised weather is impacting the site items. This helps to correlate site item damage with meteorological data that are specifically relevant to the items at each of the Mellor pilot site locations, as well as warn site managers in case of the occurrence of extreme events. This is a superior solution to using, for example, the already available regional weather data (e.g. provided by the UK Met Office) as the regional data will not show localised weather events. In Mellor localised weather can vary greatly within a small area as a result of the surrounding topography. The context as described in deliverable D9.1 is as follows:

> At the Mellor pilot site there are three unique sites that all are influenced by differing localised weather patterns owing to the topography of the local area. As such it is important that weather stations were installed at the three different sites. Before STORM, the only way of assessing local weather was to use regional weather reports. This did not account for the more localised weather events that may be occurring at one site at a given time.
> The sensors that have been installed as STORM data sources (a selection of weather stations and environmental sensor networks) ensure that the pilot site is able to see a clearer picture of the current weather conditions at all times.
> What needs to be tested, therefore, during the experimental trials is how efficient the STORM set-up is in indicating to the site owner that a severe weather event is occurring, doing so in a timely manner that allows for the site to take action, ideally before the hazard has done too much damage. (STORM Consortium, 2018)

Achieved results - The following subsection of this chapter will describe the achieved results for the Experimental Scenario 2 MAT_EXP2 – Meteorological monitoring through weather stations. This will be the results so far in the project, but experiments are ongoing until May 2019, so final results will be presented in deliverable D9.2 and the conclusions will be thoroughly described in deliverable D9.3 both of which will be available at the end of the STORM project. From the experiment so far, it is clear that the choice of weather stations used at the Mellor pilot site (Davis Vantage Pro 2 weather stations and Davis Vantage Connect data logger) was good. The weather stations installed on-site have provided a regular stream of data that has proved useful to the site. Analysis has shown that some discrepancies between data from the UK Met Office operated weather station in the vicinity and the Mellor site are present. However, such discrepancies are to be expected, as the three Mellor sites each have a unique micro-climate.

Although the accuracy of lower-cost weather stations used in this project is not as high as that of weather stations operated by meteorological services, the work in STORM has demonstrated that it is possible to get useful information from inexpensive weather stations such as those used in the project. The weather stations have proved useful in warning about weather events requiring site management and archaeologists to visit the site and assess whether any damage has occurred.

On February 28th a drill was conducted at the Mellor pilot site for the Experimental Scenario 7. The drill was to test the response of the Mellor site to an emergency weather related hazard, in this case intense rainfall, and to test the usefulness of the STORM dashboard and the STORM crowdsensing application in aiding the site's response to the emergency. The drill was hugely successful, really highlighting the usefulness of the STORM and the improvements that can be achieved by such a service to a small site run by a charitable organization. The drill reenacted the response to intense rainfall, where parts of the site, specifically STORM Item number 6.1 "handmade bricks in the draft shaft area", had become inundated with rain water. The site responsible used the STORM service to follow the predefined STORM first aid and preparedness tasks to minimize damage and ensure the safety of the site and archaeological assets (Figure 1).

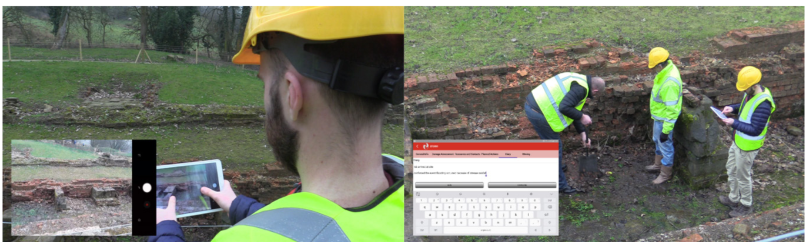

Figure 1. STORM services and first aid procedures in action during the Intense Rainfall drill at the Mellor site (February 28th).

2.2. Baths of Diocletian

The Baths of Diocletian (BoD), owned by the Italian Ministry of Culture, are an archaeological site also hosting, since 1889, a branch of the National Roman Museum. Built by the emperor Diocletian between 298 and 306 A.D., they are the biggest thermal complex of the Roman world. During the Renaissance, the Roman ruins were transformed to host a Charterhouse, projected by the elderly Michelangelo; after the reunification of Italy in 1870 the area became property of the Italian State, The Baths represent therefore a very complex site, where the conservation and the restoration of the ancient structures have to be integrated with the preservation and the exposition of the Museum items.

Challenges - The Roman Baths are located in the centre of Rome, just in front of the Central Railway Station of the city, in a very busy area. Vibrations due to the traffic of the adjoining roads as well as to the underground trains, passing very near to the roman buildings, are in fact among the most relevant hazards to cope with. Among the natural hazards menacing the site, the biological ones are the most prominent; increasing humidity both in the air and in the ground causes proliferation of biological infestations and mould growth, with consequent damage in the plasters and inside the walls, while the growth of invasive weeds can also cause structural damage and fall of materials. Pests in the area consist mostly in gulls and other birds, creating holes in the walls; also their wastes are corrosive and can cause great damage to the structures.

Other relevant natural hazards are temperature, heat and ice. Though the area of Rome has a relatively mild climate, in winter temperatures can fall below 0°C during the night for many consecutive days and then rise at midday up to 15-17 °C. In 2012, and again in 2018, snow storms hit the city and covered it for a whole week. On the other hand, temperatures in summer can rise up to 40°C. Water penetrating into the walls and then freezing can cause detaching and fall of materials from the walls; the same can happen because of the dilatation of the structures due to high temperatures and in case of sudden changes of temperatures.

Winds are another relevant risk. Dominant winds in the area are from the north and northwest, but southwest winds can also be fairly frequent. Strong winds from the west hit the Roman Halls I-II and IV, causing fall of materials and erosion of surfaces. Precipitations, particularly with wind-driven precipitations, also have an erosive effect on Roman walls and vaults. Rain acts in a very impactful way through infiltrations that can ultimately lead to fractures, particularly on the vaults of the Roman Halls. Storms (combination of high intensity wind and heavy rain) are affecting the area with increasing frequency and with serious impact on the archaeological vestiges: recent episodes (2018) include the opening of a chasm and the fall of a cypress tree over ancient items on display in the Museum Garden.

But probably one of the main challenges for the Baths, as for other archaeological sites, is the organization of the prevention and maintenance of the site. Before the STORM project this was demanded exclusively to technicians (archaeologists, restorers, architects, etc.) who periodically, or after an alert, performed inspections and assessment of the status of the site, but usually without the help of technologies or sensors, with the exception of a few, specific cases.

Trial experiments - Two areas were selected in order to test the STORM solutions against the main hazards menacing the site: The Hall I of the ancient Baths and Michelangelo's Cloister of the Charterhouse. In the Hall I Fibre Bragg grating (FBG) sensors were installed, and a Laser scanner campaign was carried out in order to check the stability of the structures and the humidity rising form the ground. In Michelangelo's Cloister FBG sensors were installed, and a weather station was also installed to gather and share meteorological data of the site. Moreover, the Baths of Diocletian, as every STORM pilot site, organized two experimentations to test both the prevention and the recovery processes, one in case of sudden-onset hazard and one in case of slow-onset hazard, which will be explained in detail below.

The **Sudden Hazard drill** was inspired by a real hazard, recently occurred in the Museum Garden area: in October 2018, an exceptionally strong wind caused a series of damages throughout the city, and the collapse of a cypress of the Museum Garden over a roman sarcophag and other ancient marble assets, luckily without causing great injuries. The drill, performed on January 28th 2019, reproduced a similar event, but simulating some damage in the marble assets, in order to understand how the procedures and the team work could be made quicker and more effective by the solutions provided by STORM, mainly by the STORM platform (Figure 2). The exercise simulated the first aid operations from the moment the strong winds rose up, causing the fall of the tree, to the moment the fallen tree was removed, the marble assets secured, and the damaged fragments moved in the storage for future recovery.

In the real event, the alarm was launched by the Museum keepers who noticed the strong winds and made a survey in the garden finding the fallen tree. Subsequently, the site responsible was contacted: she made a series of calls to summon the recovery team, interacted with them giving detailed instructions on where to get first aid instruments, where to recover the fragments, etc.

In the simulation, the STORM technologies and platform were instead used: as soon as the weather station installed in the Baths detected that the wind speed data exceeded the given threshold, the platform sends the alert for the related areas to the site manager. The manager starts the task on the STORM platform, that immediately sends the alert to the leader of the rescue team (names and cell numbers are already stored in the platform). The team leader contacts the other team members (an architect, an archaeologist, a professional restorer and a technical assistant), listed in the platform; after gathering information from the description and preparedness area of the platform, the team leader selects a meeting point and a way to secure the area, according to the conditions of the area as reported in the platform. The strategy to be applied is suggested by the STORM platform according to inputs given in the preparedness phase. The tools and materials previously selected for the first aid interventions and housed in the storage are brought in the area, and the activities are allocated among the professionals: with the help of the data stored in the platform they are able to compare the conservation status of the damaged items with the pre-disaster situation: a sarcophag lid has unfortunately been broken into pieces by the fallen tree. The documentation of the damaged items is uploaded in the platform through the quick damage assessment tool and the data are stored in the platform. Then the first aid operation starts, with the moving of the damaged items, under the guide of the team leader, which records all the interventions in the platform thanks to the voice-text app. The platform also suggests the moving and storing strategies to be used. The fragments of the marble lid are gathered, stored in boxes and protected with foam rubber, all of them bought and stored in the preparedness phase. After securing them, the fragments are at last transported in the first-aid storage room.

The performing of the drill with the support of the STORM tools and processes allowed to carry out the first–aid phase in a quicker and safer way for the CH items. The organisation of the rescue team was sped–up through the Platform, and the presence of first aid material in the Storerooms was particularly useful to rescue the CH in a quicker and safer way.

The complete video of the drill is available on the Storm Youtube channel:
https://www.youtube.com/watch?v=JUniNyao2WY&feature=youtu.be.

A second drill related to the recovery processess in case of sudden hazard, organized together with the CNVVF, will thake place on May 13th 2019.

Figure 2. Sudden Hazard drill at the Baths of Diocletian.

The **Slow Hazard Recovery Process** addressed in the Baths of Diocletian is the experimentation of biocompatible biocide products on stone artworks exposed in the south-west wing of the garden of Michelangelo's Cloister. The experimentation, started in October 2018 and still ongoing (a third phase is scheduled for the spring), is carried out in cooperation with the University of Tuscia and the collaboration of ENEA (National Agency for New Technologies, Energy and Sustainable Economic Development). It was decided to operate on a marble cippus with a large surface affected by a rather widespread and homogeneous attack of biodeteriogens. Instead of using the "traditional" chemical biocides, most of whose will be banned in a few months according to European law because supposedly carcinogens, different biocides of natural origin were used, in order to test their effectiveness. They were:

- Bio-Z: a product derived from an environmental bacterial strain Pedobacter sp MCC-ZE, non-pathogenic and non-sporogenic, isolated in ENEA laboratories. The application procedure requires that Bio-Z is incorporated into a support suitable for the specific situation, which facilitates the drafting and removal, leaving no residue on the work at the end of treatment.
- Liq: an extract of licorice leaves. The product, used at the 3% concentration, has given positive results on biofilm colonizers of stone artworks of the Vatican Gardens. It is an experimental product under development for registration by the German company TRIFOLIO-M.
- Nopal Cap (Opuntia mucilage and chili extract): a product derived from the vegetal mucilage of the prickly pear. The mucilage was known and used as an additive to mortars and plasters in the Mexican tradition since the pre-Hispanic era. Starting from the freeze-drying of the mucilage, a product with known characteristics (Nopalgel) is reconstituted in ENEA. Nopalgel, in association with other antimicrobial substances of natural origin (chilli pepper), was effective for the treatment of stone material colonized by persistent microbial biofilms.
- SME 1.11: a bacterial strain isolated by ENEA in the mining site of Ingurtosu. Presents biocidal activity towards black fungi; siderophores production; weak proteolytic activity; it does not exhibit lipase activity; does not solubilize the carbonates.
- MIX 10 bis (based on essential oils Cynnamomum zeylanicum, Eugenia caryophyllata, Coridothymus capitatus,) applied at the concentration of 1.3%.

- Benzalkonium chloride in a mixture of quaternary ammonium salts with a broad action spectrum and is effective against both bacteria and some fungi (applied at concentration 1%).

The surface to be treated was divided in equal parts with adhesive paper tape and the products were applied. After the application the surface was protected with polyethylene film to slow down evaporation and avoid the washout in case of rain, and with aluminum foil in order to avoid the interaction of solar radiation. Two weeks after the application, the protection layers of aluminum and polyethylene were removed, and the surfaces were rinsed with tap water and soft brushes in nylon bristles.

The best result seems to have been obtained with the SME1.11 applied through a Vanzan NF-C gel compress; the alcoholic extract of liquorice leaves applied by means of a Vanzan gel compress has also proved to be effective. In general, the compresses applied with the gel have been more effective than those applied with cellulose pulp. In consideration of the appreciable results obtained, it was decided to repeat the tests of the most effective products on other artifacts, in order to validate both the effectiveness and the application times. Therefore, one more marble item was chosen, with a surface affected by an attack of microorganisms as much as possible consistent, homogeneous and of significant extension, where to apply more compresses, grouped according to the times of contact to maintain (1, 3 and 7 days). As in the previous application, the surface has been divided with paper tape in equal parts for the application -with different contact time- of the following products:

- Liq (Alcoholic extract of liquorice leaves) (3%) applied by Vanzan NF-C gel compress;
- SME1.11 (Arthrobacter oxydans) applied by Vanzan NF-C gel compress;
- Mix 10bis 1.3% in deionized water, applied by cellulose pulp compress.

As in the previous experimentation, the removal of the compress was carried out with the help of spatulas, washing the surface with tap water and brushes in soft nylon bristles. The tests from one to seven day of contact, did not show, at a macroscopic observation, significant results. The minor result of the second treatment could be due to the different environmental conditions. In fact, a verification of environmental parameters (temperature and precipitation) demonstrates that during the second phase of the experimentation, temperatures were lower on average about 10 °C than during the first, and rainfall were much more abundant. Considering the good results obtained in the first phase of the experimentation, it has been decided to continue the tests in spring with more favorable weather conditions.

Achieved results - Results of the STORM project at the BoD site include both technical solutions for the monitoring and the early detection as well as the improving of processes related both to the maintenance/preparedness and to the first aid phases. The technical solutions installed thanks to the project's funds include firstly a weather station, that provides real time information to the STORM platform, sending alerts in case of extreme events. The areas selected for STORM experiments were also wi-fi covered, allowing a better communication for the sensors' data and an easier on-field use of the STORM platform and devices. Among the technical solutions, the FBG sensors installed offer an optimal solution for the data collection as they're almost invisible to the eye and can thus be used in any area of the site without spoiling the view of the ancient structures. The laser scanner also was useful for the structural monitoring of the Halls, and some experiments showed that it can be performed both in the preparedness and maintenace phase to check the movements of the building, and in the first aid phase. The collection of enough data will allow to better understand the decay rates and causes of the monument's buildings. Consequently, it will also be possible to plan better maintenance works according to the real needs of the monument, both in terms of scheduling and of the materials to be used. The low cost of the sensors installed and their potential benefits for the conservation of heritage assets amply justify the implemented system.

2.3. Historical Centre of Rethymno

Challenges - The city of Rethymno is located in the middle of the northern road axis of the island of Crete (Figure 3). It is one of the most important Cretan urban centers with a constant occupation spanning from the Hellenistic period (323-67 BC) up to present. Today, the city has 35.000 inhabitants and the historical centre has 3000 inhabitants. In 1212 the city was conquered by the Venetians and in 1646 by the Ottomans, who remained in Crete until the beginning of the 20th century. The historical centre is surrounded by the sea from North, West and East, and was declared a monument in 1967 because of its historical, architectural and cultural value. The Fortezza fortress was founded on the rocky hill of Paleochora, in the northwest part of the city. Its total length is approximately 1370 m and the height of its walls varies from 6m to 13m. The fortress was designed by the Italian engineer Sforza Pallavicini. Its construction begun on September 13th 1573 and it was completed during the 1580s. It consists of four bastions on the south and east sides (St. Nicholas and St. Paul on the east, the

Prophet Elijah and St. Luke on the south) and three main salients on the west and north side. The space between the bastions and the salients is connected by simple straight walls. From the bastion of St. Nicholas to the bastion of St. Luke, the Fortezza fortification wall site is divided into three sections: scarpa, cordone and parapetto. Recent archaeological research in the southwest part of the fortress also revealed buildings of the Hellenistic period.

This short description of the site already reflects its complexity and diversity in terms of chronological, architectural and historic value. The Historical Center should be considered as a living heritage site where mitigation strategies between protection of the above values and its function as an occupied space should be defined.

The **natural hazards** mostly occurring at the Historical Center of Rethymno and the Fortezza fortress are:

- Flooding: The modern commercial port and its nearby Venetian port are the areas mostly affected by sea flooding. The mechanical action of water and marine salts (abrasion on surfaces) as well as its chemical action causes the destruction of the port's infrastructures and damages the coastal residences. Floods have increased in the last years due to the increase of wind intensity and duration which can reach up to 9 Beauford. During winter, flooding may reach the core of the historic centre posing an immediate risk for the monuments.
- Wind: the mechanical action of strong wind and the precipitation of marine salt cause erosion of the soft calcareous stones. Such stones have been used in the masonry of the Fortezza's fortification walls, on buildings of the Historical centre and the Lighthouse of the Venetian port. Wind also causes acceleration of moisture's evaporation from within the stone pores, increasing the mechanical damage of stone. Similar problems are observed on the mortar within the fortress wall masonry and the plastered surfaces of buildings.
- Vegetation: Plant roots, bushes and trees generate mechanical damage during their growth, which in turn leads to the disturbance of stone blocks and mechanical damage of drains, water pipes, telephone cables, etc.
- Earthquakes: Seismic activity poses an important risk for the city. According to the Greek Anti-seismic Regulation of 2000 and its subsequent update in 2004, Rethymno falls in category B, which follows the hazardous category C. Large cracks are also observed on the fortification walls of the Fortezza Fortress and on structures within it, such as the Episcopal mansion. These cracks may expand in the incident of an earthquake with catastrophic outcomes to the physical integrity of the

monument. Additionally, the cracks on the buildings may worsen because of the earth fillings that the buildings are constructed on.

- Dry-wet cycles: The dry-wet cycles, condensation and salt crystallization cycles cause mechanical damages in stones and metallic parts and favor chemical reactions within the stone and metal chemical compositions. Rain water erodes the stone surface and assists plant growth and bio-decay on the surface of the masonry. Wind and rain further intensify the damaging effect.
- Solar radiation: The intense and increased UV radiation that is observed especially during the summer period causes severe discoloration and fading of the pigments on the decorated surfaces of the buildings of the historic centre and the decomposition of coatings and varnishes on wooden surfaces. Extreme high temperature acts as a catalyst on corrosion, stone decay and biological growth.
- Main goal of the Ephorate is to prevent damage to its assets by planning and implementing conservation projects. Maintenance and regular inspections from the permanent staff of the Ephorate are regularly undertaken to ensure stability in the condition of the assets and minimize the risk in general and in particular in the case of emergency. Aim of the Ephorate is to improve its current practices through the technologies and processes proposed and tested through STORM.

The conservation and restoration practices, both implementing and preventing, are applied on both public and private buildings, including monuments of religious practice (Christian and Ottoman) located in the historic center. Conservation methods and materials approved by the Hellenic Ministry of Culture and Sports through specialists technical councils that examine each conservation project, are in accordance with the international guidelines: they are reversible, highly compatible with the materials to be conserved, environmentally sustainable and able to ensure the management of change without obscuring the historical, physical and aesthetic integrity of the monuments.

Risk assessment before STORM project was carried out macroscopically and by targeted surveys on areas of interest. The holistic approach that the project employs, that is the correlation of different technologies, services and processes for the assessment of natural hazards, has not been used before in the extend of assessing an entire region. STORM technologies and practices improve prevention works by taking into consideration the individual needs of a heritage site. This enables the design and prioritization of prevention and implementation practices tailored to the specific needs of each site. Thus, general guidelines are narrowed down and produce realistic frameworks.

The Risk Assessment activities that were performed on the pilot site of Rethymno produced a clear view of the quality and quantity of hazards. The visualization through WEB-GIS maps provides direct assessment of the degree of hazard and threat on a cultural heritage asset under investigation relevant to its location. So, information is spatial specific and allows the design of conservation and restoration projects for the monuments under investigation.

The analysis of climate data and the production of the climate change model of Rethymno is of paramount importance since the preservation of a monument is a continuous task and treatments should be tailored to last as long as possible. Furthermore, the outcomes initiate a discussion on local, national and international level in sustainability measures.

The necessity to assess the degree of damage of a monument and link it to specific natural hazards leads to the employment of a range of analytical technologies and methodologies. The contribution of FORTH as technical partners and the involvement of private civil engineers as well as the contribution of National Observatory of Athens (NOA), Institute of Geodynamics as stakeholders provided a holistic assessment of the conditions of the monuments and the agents of decay affecting them.

The implementation of the STORM platform where all the analysis outcomes are readily available provides ease of access anywhere. That enables direct comparative assessments of the monument in question and the decay factors affecting it in situ. Furthermore, the STORM processes available through the platform enable the management of important information, such as site / area / item description and preparedness actions.

Lastly, the employment of services such as the crowdsensing applications developed through STORM creates a link between the heritage management and the public. The participation of visitors to the assessment or even alerting the Ephorate of Antiquities of Rethymno for detectable threats provides a twofold outcome: a) it serves the Ephorate to have access on possible changes on the monument in time intervals that an expert assessment is not scheduled; b) it grows public awareness and engagement towards cultural heritage preservation.

Trial experiments - Five experiments focus in STORM technologies and the evaluation of the analytical outcomes of the on-line and off-line sensors as well as the methodologies employed for the Risk Assessment. The aim is to assess these outcomes in terms of effectiveness to provide information on the state of preservation of the monuments. Doing so, informed decisions will be available to the actors involved in the preservation of the monument. Furthermore, the outcomes are made available through the Sensory Map and Visual Analytics services in the STORM platform in order for the EFARETH team to have direct access and use them for studying data and files from different time periods and areas and provide suggested actions for conservation, restoration or preparedness through the Quick Assessment services. The crowdsensing experimentation is scheduled for April 2019 and it will take place at the wall that is part of the façade of the double gun hole in St. Lucas bastion in Fortezza Fortress and at the Lighthouse in the Venetian Port (Historical Centre). Furthermore, there will be two more experiments – exercises to test the processes of dealing with hazardous events: HCR_EXP7 and HCR_EXP8. These experiments are designed as to improve the preparedness and response actions of all the involved actors depending on the type of hazard (slow or sudden onset hazard). The aim of the Ephorate of Antiquities of Rethymno is that these exercises should be repeated at regular intervals, after the completion of the STORM project, in order to check the response of its competent teams.

HCR_EXP7: Process experimentation for Sudden Hazard– Earthquake: The experimental scope focuses on testing the preparedness and response actions of first aid actors. The earthquake drill will take place at the area of St. Paul's bastion, at Katehaki Street, on the east side of the fortification wall of the Fortezza Fortress.

HCR_EXP8: Process experimentation – Salinization (slow hazard). The experiment focuses on the effective response through implementing conservation on stone weathering at the stone surface of the Lighthouse of the Venetian Port due to excessive salt accumulation after prolonged heat period (salt crystallization).

Figure 3. Rethymno pilot site.

Achieved results – From the pilot activities results can be concluded that Ground Penetrating Radar (GPR) can be employed as a complimentary risk assessment method especially for monitoring historical buildings' wall thickness. The 2D and 4D Electrical Resistivity Tomography (ERT) results were quite promising and fulfilled the initial expectations showing the efficiency of the method in assessing the integrity of standing cultural monuments. The merged point-cloud obtained by laser scanning was then employed for the creation of a digital surface model in computer graphics, which will be extremely helpful in planning or simulating restoring intervention to the exteriors or the interiors of the lighthouse. In the fortification walls of the Fortezza fortress as well as the interior of the St. Luca's bastion and the Soap factory at the Historical centre of Rethymno, the applications produced a model of comparison that allows the visualization of changes through colour-scale images with distances in centimeters. The advantage of such an approach stays in the possibility to get numerical values for the discrepancy and also to consistently monitor any modification of such values at defined events.

Regarding the weather stations, the environmental data produced can be visualized in easy to use graphs through the STORM services and stored in the STORM platform for direct access. This will enable direct comparative study of the conditions of assets and their exposure to environmental agents of decay in order to tailor preventive and interventive conservation actions. Furthermore, conservation treatments tested through different environmental conditions will enable the evaluation of actions and their improvement. The raw data of the weather stations are being collected locally and simultaneously used in the crack meters monitoring methodology in order to see the impact of the relative humidity and the environmental temperature on the wall cracks. Relevant to the crack meters data collection and modeling crack displacement, the experiment is still ongoing. The experiment for the construction of the seismic model of the Lighthouse by NOA is still in progress, that is the construction of the seismic model of the Lighthouse of the Venetian port.

2.4. Roman Ruins of Tróia

Roman Tróia was a large urban industrial agglomerate built on a sand embankment between the Sado River estuary and the Atlantic Ocean. It specialised in the production of salted fish and fish sauces and was active between the 1st and 5th centuries AD (Pinto, Magalhães and Brum 2014); all structures were covered by sand dunes after being abandoned. Discovered in the 16th century due to coastal erosion, the archaeological remains include a number of fish-salting factories, with 27 workshops (compartments with vats along a courtyard or corridor) spread along 2 km; today, the site is a National Monument in the Portuguese World Heritage Tentative List.

Challenges - The STORM risk assessment of the site of Tróia clearly showed that its most threatening hazard, critically affecting all shoreline structures, is coastal erosion, resulting from hydrodynamic factors such as tides and waves of local generation. Tides are semi-diurnal and have great amplitudes, varying between 3m (average of highest tides) and 1.4m (average of lowest tides) in the nearby harbour of Setúbal (Andrade et al. 2013). Along the site, the tide current field is very strong due to the proximity of the south canal of the estuary, where currents may reach 1m/s in an ebb tide. Moreover, the coastal area is exposed to the predominant north quadrant winds that, together with the large area of generation, c. 2km of the estuary, generate waves of low amplitude but high frequency (Silveira *et al.* 2014: 262).

Tide currents are low but frequent undulation cause daily wetting-drying cycles on highly vulnerable construction elements (e.g. mortars and soft stones), promoting the softening and erosion of building materials and archaeological objects. Furthermore, their constant removal of sand from under those already fragile structures is causing structural imbalances leading to fractures and collapse. Some of the walls exposed to the tides additionally bear the weight of the large sand dune behind them, aggravated with each heavy rain and storm. Rain and humidity, and the consequent proliferation of vegetation and biological colonisation are a constant threat in an open-air site such as Tróia, especially concerning for the conservation of the late Roman wall paintings in the early Christian Basilica.

The monitoring and the conservation of such a large site, with many different areas, difficult to protect from environmental hazards but also from vandalism, is the greatest challenge for a site manager.

Trial experiments - To face the different challenges, a number of experiments were implemented and will be shortly described. First of all, no power grid existed in the site before the STORM project, so solar panels were installed to allow experiments, the installation of sensors and Wi-Fi data transmission.

Supporting risk preparedness and emergency response via resilient communication was one of the goals of the STORM project. This implies having alternatives to a potential loss of communication infrastructures during a disaster. Hence, an AC750 Wireless Dual Band 4G LTE Router was placed in the ruins, plus a (main) link was established to a connection about 2km from the site. In case of main link failure, the 4G connection is established. Also, the sensors can store data internally and forward it after the communications are back online; in case of full failure the data can be retrieved from the sensors through a data card.

An Oregon Scientific WMR-300 weather station was set in the visiting circuit, providing data on temperature, dew point, humidity, precipitation, wind (speed, direction and gust) and air pressure through a Raspberry Pi 3 and WeeWx adaptation to the STORM platform, where alert thresholds can be set, triggering an alarm if the limits are crossed. The Raspberry also gets tide data from a sensor in the bay of Setubal deployed by the EU Joint Research Centre.

Photogrammetry was experimented in two use cases in the shoreline (in Workshops 21 and 23), subject to intense coastal erosion and to potential landslides from the dunes behind them, aiming at the detailed monitoring of the decay rates of the constructions, their digital conservation and 3D reconstitution. The photogrammetric survey used a Nikon D5600 with a 50mm lens (Nikkor AF-S 50mm f/1.8G) to collect photos. Processing was carried out with Agisoft Photoscan (today Metashape) Professional running in an i7 3 GHz processor / 32 GB RAM. Dense point clouds and digital elevation plans were produced in each survey of the selected case studies. The comparisons between georeferenced point clouds allow greater accuracy in the surveys. To complete the task of comparison, point clouds were used through the open source software Cloud Compare. Part of the experiment was to train the site team in photogrammetry for regular use; some external teams (OPPIDA SL, University of Marburg and Theia) supported in these surveys.

The induced fluorescence (IF) sensors described in Chapter 3 were experimented in the early detection and monitoring of biofilms (moss, algae, lichen, fungi, and/or bacteria) in the Basilica on a monthly basis, primarily focusing on the north-east painted wall and providing a surveying and diagnosis service (Figure 4). For both LIF and SFS (see Chapter 3), the evolution of the intensity of the peaks caused by infestation signatures enables a specialist in the area of biological fluorescence to derive two parameters, M and G, characterising correspondingly the infestation magnitude and the infestation gravity. The measurement points related to biofilms freely growing in the painting free area of another wall provide a surveillance and monitoring service that uses the concept bio-community as a sensing agent. The service involves measurements: (a) at some fixed locations on the wall and (b) on the surface of four samples tested using both LIF and SFS techniques, located in places where the influence of weather conditions is more pronounced. For these measurements the infestation gravity always attains its minimum value, indicating that no measures should be taken to clear the sampling surface from the bio-community. Here the principle parameter is the infestation magnitude M, characterised on the basis of the fluorescence spectrum intensity in the points of maximums of the corresponding signatures (chlorophyll and proteins – two typical signatures of this type detected at point 7 are illustrated in Chapter 3, Figure 25).

Figure 4. Induced fluorescence experiments at the Troia pilot site.

In order to more accurately establish the impact of environmental conditions on the decay rates of the Basilica frescoes, it was decided to monitor the evolution of three different wall paintings resorting to environmental sensors coupled with image recording and crack-meters. Three sensor nodes, featuring low-cost sensors connected to a Raspberry Pi, with Wi-Fi data transmission to the STORM platform, were thus built and installed.

One node was placed in the above-mentioned northeast wall, monitoring the evolution of a crack, via crack-meter and high-resolution (HR) photo-graphic recording, plus environmental data, resorting to light, temperature and humidity sensors placed in direct contact with the wall.

A second node monitors the external face of the northwest wall of the building next to the Basilica, which is exposed to the dominant winds from the North and Northwest, and whose paintings exhibit clear signs of active decay. To clarify the causes and rate of wall painting damages in this area, it was decided to monitor (i) microclimatic conditions in the close vicinity of the frescoes, including light, temperature and relative humidity; (ii) wind speed and wind-driven rain affecting the wall, using an anemometer and a rain gauge, respectively; and (iii) material loss progression, registered by a time-lapse HR camera.

The third node sits in the external face of the southeast wall of the building next to the Basilica, directly exposed to weather hazards and in a very serious condition. Given its deterioration patterns, esp. missing elements, disaggregating mortars and cracks, the sensors – light, temperature, relative humidity, crack-meter and an HR camera – were placed on the southeast face of the wall.

A Wireless Acoustic Sensor Network (WASN) was developed and installed in Tróia in a hidden shelter in Workshop 21, in January 2019, with the purpose of recognising the audio signals of events of interest and, at the same time, monitoring additional physical quantities from the network of deployed sensors, and relay the data representing these quantities to the STORM Cloud. The data is being regularly stored, processed and monitored, warning on potentially harmful conditions for the structures under surveillance. As most of the site is off the power and network grids, a solar panel/battery/regulator was installed nearby to ensure data transmission by the WASN 3G interface.

Achieved results - The different experiments are ongoing, some at an early stage after a long period of designing or preparation, so the results are more solid in the case of resilient communications or induced fluorescence detection and preliminary in the case of the sensor nodes in the Basilica or the acoustic sensor (WASN). The communications Gateway is resilient through redundancy of connections. To enhance this resilience, and in case of a short communication outage (sensor to Gateway or Gateway to STORM platform), the sensors can store the data collected. A secondary but important result was the Wi-Fi coverage of the main site area, allowing the future deployment of new sensors. The weather station, deployed in December 2017, provides real-time information through RF connection to the STORM platform, enabling permanent monitoring of the weather conditions, as well as dispatching alarms in the case of extreme events, when the atmospheric values cross preset warning thresholds, which are initially based on long-term observations (see Chapter 2 for details). The weather station data allow for the refinement of these pre-defined alarm triggering thresholds, which can be defined in combination with other sensors deployed at the site. Additionally, their assessment against deterioration assessment methods (e.g. IF sensor) assists the establishing of cause/effect relationships, and allows the constitution of a local meteorological database for medium- and long-term analyses, including climate change analysis.

The photogrammetry of the two use cases provides an architectural record archive with comparable images, which objectively documents all alterations occurring in the archaeological structures and their progress. Five surveys have been performed (June 2016, September 2017, March and September 2018, March 2019). The geo-referenced point clouds models processed in Agisoft Photoscan are being overlapped at Cloud Compare, two at each time. So far, the differences among models are very slight, and it is not possible to be sure if they derive from real alterations or from comparing models not obtained in the same exact conditions, since different teams contributed to these models in each survey. So, the first lesson is that surveys must be done in the same exact conditions. Nevertheless, it is entirely possible that in the elapsed period no significant alteration was caused in the objects chosen for experimentation.

The IF analyses started in August 2017, making it one of the longest STORM experimental campaigns. In that period, an impressive amount of IF spectra have been accumulated, enabling individuation of the chlorophyll and protein emissions from the background fluorescence of the underlying substrate. Insignificant amounts of residual biological material were detected at most of the measurement points of the northeast wall, in no way large enough to reach the infestation gravity level triggering an alarm situation. Pronounced annual oscillations of the fluorescence intensity (min/max ratio about 20%) were observed using the well-developed lichen and algal bio-communities located outside of the northeast Basilica wall as a sensing agent. Although no straightforward correlation between the fluorescence dynamics and the ambient conditions was observed, the analysis carried out up to date indicates that future LIF and SFS measurements would be beneficial for the timely indication of ambient conditions favouring the proliferation of biological contamination.

The sensor nodes in the Basilica, deployed in December 2018, were devised so as to enable confronting degradation agents (environmental factors) with deterioration patterns (cracks, mass loss, fading), which, after enough data is collected, will allow for a solid understanding not only of specific decay rates but also of their most pressing underlying causes. Thus, conservation and maintenance plans can be specifically tailored for the frescoes, both in terms of scheduling and when deciding which actions and materials will be the most compatible with the long-term preservation of the paintings (Pérez *et al.* 2013).

Threshold values were set for concerning factors, combining measurements from these sensors and the weather station, to trigger alerts and corresponding emergency preparedness plans, for instance if an area is flooded, if the cracks suddenly vary, or if strong winds hit the protective structure. The low cost of current sensor technologies and their potential benefits for the conservation of heritage assets amply justify the implemented system.

The Tróia WASN was designed to detect events such as extreme weather phenomena, e.g. thunderstorms, intense wind, and/or raining or hail; strong sea wave splashing or irregular (human) activity detection, e.g. vandalism, machinery, etc. Preliminary data show that the system is operating as expected, transmitting audio and environmental data to the WASN back-end (see Chapter 4). The accurate recognition of these events, through efficient sound classification, may aid in the assessment of human-generated actions or environmental events with a potentially hazardous effect on the site.

2.5. Ancient City of Ephesus

Ephesus is located 70 km southwest of Izmir on the Western Aegean coast of Turkey. The history of the settlement goes back to the Neolithic Age (beginning from the 7th millennium BC) at Cukurici Mound up to the Medieval and post-Medieval period at Ayasuluk, until present day at Selçuk. The great theater is the most impressive and the largest structure of the city. Leaning on the western slope of Pion Mountain it has a capacity of 30.000 spectators. Built around the 3rd century BC as one of the greatest Hellenistic period structures in Ephesus, the Great Theater was extended by restorations in Roman period and became the largest among the theaters in Anatolia on antiquity. The structure has a diameter of about 150m, the cavea has sixty-six rows of seats, divided by two diazoma (walkway between seats) into three horizontal sections. The stage building was three-storied and 18 meters high. The façade facing the audience was ornamented with columns, niches, windows and statues. There are five doors opening to the orchestra area, the middle one of which is wider than the rest. The structure was constructed with stone blocks, marbles and backfill materials, which are composed of rubble and mortar.

During the course of time, Ephesus Great Theater has suffered some damage and been subject to the risk of collapse due to the natural disasters, mainly earthquakes or human interventions. The *skenè*, especially, has been substantially deformed in terms of structural integrity and stability. The structure has been renovated several times by using different materials. During the structure's life, construction materials have been deteriorated and have lost their qualities. Currently the northern and southern part of the theater are considered to be risky areas and closed to reach of visitors. In previous years, steel supports have been inserted on the purpose of solving the static problems and supporting the block stones especially in the south analemna. In 2019, the realization of a restoration project has just started.

Challenges - For Ephesus Ancient City there is no comprehensive study identifying the primary natural hazards other than earthquakes (A document prepared by UNESCO in 2015 for Cultural Heritage Nomination has information to a degree). Through STORM, identification of natural hazards, threats, exposure and vulnerability assessment were performed. Hazard analysis one more time reveals that earthquake is the most damaging sudden onset disaster, hence early assessment of the structural behavior under earthquake excitation is one of the most important challenges in the project. Monitoring of the seismic activity at the site, which was not available before the project, and providing useful information (e.g. for use in producing warning message) into the STORM platform in timely manner are other challenges. Through the platform rapid information on disaster and damage on the structures can be achieved. This information is critical to speed up communication with response authorities.

An earthquake drill by a voluntary rescue team has not been realized at the site before the project. A successful drill both in terms of saving human life and also cultural assets is another added value of the project to the site.

Hazard analysis also reveal that the pronged dry period/heat wave is the major slow onset disaster at the region. Hence continuous monitoring of meteorological conditions (e.g. precipitation, humidity, temperature and wind) is necessary. The nearest meteorological center is 8 km away from the site in Selçuk village. Online monitoring of the station is not possible for individuals, but daily weather information since 1971 can be obtained on request. Evaluation of the data from initial weather station data and climate projection by Zentralanstalt für Meteorologie und Geodynamik (ZAMG) is another challenge of the STORM project.

Trial experiments - The experimental campaign in Ephesus addresses two main hazards: "earthquake" as a sudden hazard and "prolonged dry period/heat wave" as slow hazard. The earthquake scenario is approached through two complementary experimental scenarios. The first one (ACE_EXP1) tests and validates the technological solutions deployed at the pilot site. The second one (ACE_EXP2) involves multiple external actors in order to assess the performance of the emergency response process. Finally, a third scenario (ACE_EXP3) will test the process response to slow hazards as prolonged dry periods / heat waves, one of the main risks at the pilot site.

ACE-EXP1- Sudden Onset Disaster –Earthquake: Specific objective of the experiment is to produce alarm signal from data obtained from sensors in the field. Before the experiment the most vulnerable parts of the theatre are identified through a numerical modelling of the structure. Model was excited under hypothetical earthquake ground motions that meet four different earthquake levels given in Turkish Building Earthquake Code (2018). Details of this issue are explained in previous Chapters. Same numeric model is used to determine the limit state for the rocking and sliding damages. Sliding and rocking damages are considered the most dangerous for the structure because the item in question (which weighs tons) could completely topple and cause extreme damage to both the visitors and the structure itself. Earthquake may cause partial collapse, fracturing of structures and casualty of visitors.

During the experiment threshold levels were set to lower values to detect and trigger with lower acceleration events. A synthetic pulse was generated near the sensor. In addition to that we were lucky enough to have a real earthquake to trigger the system. An earthquake of Mw=4.2 occurred on 25.01.2019 70 km North of Ephesus and triggered the system (Figure 5).

Exercise followed the below stages:

1. Earthquake alarm signal: threshold level is exceeded. Earthquake information is sent.
2. Real time earthquake signal is captured.
3. Near real time damage assessment procedure: depending on the earthquake level, platform will provide predefined image of the potential damage in the entrance wall. Integration of images with platform is still in progress. When the integration is completed exercises will be repeated.
4. Warning message about damage level received by authorities.

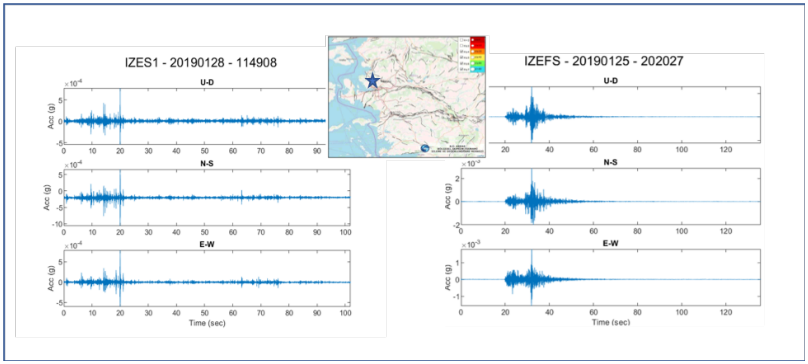

Figure 5. Recordings of the sensor located at base level (left). Source of recording: artificial pulse produced by the team near the sensor (right). Source of recording: a real earthquake on 25.01.2019 20:20.27 Mw=4.2 at Menemen-Izmir.

ACE-EXP2- Sudden Onset Disaster: earthquake Exercise. On 16th of February 2019, an earthquake drill was performed at the Great Theater of the Ephesus Antique city. 88 people including Bogazici University STORM Team, staff of Ephesus Museum Directorate, GEA Search and Rescue Team and ICOMOS-ICORP Turkey specialists actively participated in the drill.

Scenario: a damaging scenario earthquake occurs; the main entrance of the cavea collapses and blocks the exit. Six people are trapped under/near fallen stones. An artifact falls down on an injured person.

In general, the earthquake exercise for Ephesus consists of 2 stages:

1. The generation of the automatic earthquake alarm signal: we demonstrate the importance of using STORM-SHM instrumentation and real time sensor data. Structural damage is estimated by comparing the measured data with the predetermined threshold values. An automated text message (short SMS or e-mail) is received by all participants. In order to avoid any possible false alarm, some advanced event triggering procedures before sending the warning message is used. During the experiment a warning message is sent from the sensors to site manager through e-mail. E-mail content includes a representative figure showing the probable degree of damage at the entrance wall due to the earthquake. Herein, we demonstrate the reduction in the post-earthquake response time for automated (STORM solution) and non-automated (standard procedures) cases. This section is the indication of the effectiveness of the STORM solutions (measurement, processing and services) for emergency management.

2. Activation of the emergency response team: staff at the site informs the manager about the injury/damage. Emergency response teams (SAR) are called. Manager and staff move to site. When they arrive to the site, they will see that the main entrance of the Cavea has been blocked by fallen stones.
   Rescue operation 1: evacuation of people from the theatre (main entrance-exit blocked), directing them to alternative emergency exits. Theater is evacuated by security staff using predefined safe routes and visitors assemble at the meeting place 'Agora'.
   Rescue operation 2: saving trapped people; 6 injured people in and around the theater are rescued by SAR team.
   Rescue operation 3: saving valuable items (artistic assets, historical sculptures saving, collection and saving of damaged-broken items). Fallen stones and a broken artifact at the theater are reported and first aid to artifact is done by ICOMOS-ICORP Turkey specialists. Further recommendations on how to stabilize the entrance wall are given. Artifacts are removed from the area to a safe place.

ACE EXP-3 (slow onset disaster) Prolonged Dry Period/Heat Waves. The scope of this experiment is to evaluate the material sensitivity to the temperature changes. So far available literature on stone durability due to excessive temperature change is collected. Effect of the temperature change to damage will be evaluated. Based on collected information threshold temperature values will be decided.

Before the experiment a discussion on the threshold level of the meteorological slow onset hazards was done with partners from ZAMG. Site specific threshold for the slow onset hazard of Ephesus was determined. They have found that a period of 156 consecutive dry days is an extreme case for the Ephesus area under current climatic conditions (taking the climate reference period 1971-2000). If the amount of consecutive dry days (days with less than 1 mm of rain or other precipitation) observed at Ephesus crosses this threshold, an alarm could be set to warn for a 'prolonged dry period'.

This threshold was determined using the following method:

Step 1: The daily precipitation data for the Selcuk station were used to determine the yearly maximum number of 'consecutive dry days' for the period 1971-2000.

Step 2: From the 30 yearly maximum values obtained in step 1, the 90th percentile was determined. This is taken as the threshold reported above.

It is also indicated that thresholds as defined for slow onset disaster can be taken as a baseline suggestion by the site managers, and then adjusted to take into account the knowledge and experience the site managers. (Roos Dewit, personal communication, 2018).

Achieved results - This section will present the achieved results in the experiments ***ACE-EXP1*** and ***ACE-EXP3.*** This will be the results so far in the project, but experiments are ongoing until May 2019.

4 accelererometers were deployed on the basement and top level of the theater in April 2017. Continuous data flow between Bogazici University Data Center and sensors are provided. Resilient communication between site- Bogazici University Data Center and STORM platform has been established. As a technological solution of the project, a meteorological station is deployed at the highest point of the theatre in February 2018. Online data flow can be followed through the platform. The weather stations have provided a regular stream of useful data, when compared to other local weather stations and official data.

STORM Platform helps to monitor both ambient and seismic activity, something that was not achieved prior to the project. It is worth noting that, ambient vibration and seismic data are used to reveal the dynamic behavior of the structure to portray the damage levels beforehand.

Earthquake thresholds (percent of acceleration of gravity) assigned to accelerometers enable us to produce not only near real time signal to warn/inform the site manager about the event but also the expected structural damage at the most vulnerable part of the structure: north entrance wall.

3. Conclusions

More than thirty experimental scenarios are testing and validating the STORM solutions at technological, services and process level in 5 pilot sites. Numerous experimental scenarios foresee the participation of external actors: their involvement enriches the testing campaign and impacts positively on the dissemination and potential exploitation of the project outcomes. The STORM pilot experiences show, once again, the added value of the multidisciplinary work, linking technical and pilot site-oriented objectives on the agreement of a common approach to the experimental campaign, working closely with the aim of Safeguarding Cultural Heritage through Technical and Organisational Resources Management.

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Epilogue

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Fabio Perossini

Summing up

The challenges in protecting cultural heritage have grown in the past years. Even though on one hand the technological advancements have given us the capabilities of addressing risks and threats, the nature and level of threat of the same risks has grown enormously. Both climate change and human actions are creating new risks, or add to the old ones, increasing the severity of damage caused.

In this book, reporting on the results of the STORM projects, a comprehensive coverage of risks, mitigation strategies and recommendations for the protection of cultural heritage have been presented, including

- 7 recommendations for the improvement of government policies on cultural heritage risk management;
- a frame of reference (FoR) providing the conceptual basis for the development of the STORM methodologies and platform;
- integrated methodologies of risk assessment;
- use of sensors and ICT technologies for timely artefact diagnosis and early detection of potential threats;
- data management and analysis of collected sensory and crowdsourced data;
- tools and services towards the sharing of knowledge facing critical events in Cultural Heritage sites;
- exploitation of the capabilities of computer clouds to efficiently manage the information;

- and presented a full System Architecture inspired by a layered architectural principle meeting the challenges and requirements arising from the presentations given in the book.

Future Technical challenges

Nevertheless, the fight towards the protection of our cultural heritage is never ending. The increasing potential of technology, introduced by the advent of the Internet of Everything, the remarkable results of the use of *Artificial Intelligence* and the capabilities of blending the digital and the physical worlds into realistic *mixed reality cyber-physical representations* are expected to give ground for even greater advancements towards the protection and preservation of cultural heritage.

Therefore, in the epilogue of this book, a quick reference to the things to come, and the technologies and advances which will definitely be on the spotlight. The first one comes from the domain of industry and manufacturing, and is that of the ***Digital Twin***. Digital Twins are used in the past year in manufacturing, in order to study and identify potential problems of a product, mainly by simulation. The ability of Digital Twins to exhibit properties of the physical objects they are related, allow the study of potential problems, without interacting with the physical object. This can be very helpful also in the case of cultural heritage protection, since modeling of artifacts or structures towards the provision of their Digital Twins can help perform surveys and simulations without any intervention to the actual (physical) item.

The second reference to the future technologies, should be made to the ***Internet of Everything***, which already provides the foundations for an ecosystem of cyber-physical interconnected entities, both living and objects. The reference architecture model of IoT featuring layered architectures, open programmable APIs, and linked data, enable the efficient sharing of knowledge in a re-usable way, which can quickly transform the previously raw data collected by sensors, to meaningful information, and subsequently functionally extend it by allowing the link to external services and tools over the exchange of open data.

One would expect to read about AI and Computer cloud as the next future technologies to be referenced here. However, cloud computing has already been mentioned in this book, as the enabling technological framework over which all paradigms and the featured architecture for efficient monitoring, and prevention services have been based. Therefore, it is considered that the cloud (or even its youngest sibling: edge cloud (where devices at the edge of the network assume the role of the cloud nodes), are definitely going to be the dragging force in every technological framework for cultural heritage protection. AI on the other hand, though is starting to breathe intelligence in every "e-thing", can have a special role here. And this is in bringing everything together, in an intelligent ecosystem servicing cultural heritage protection, built on the foundations for the next generation of visitor's experience and experts' tools. In this ecosystem, visitors of a web site will no longer have a linear experience (simply visiting the different exhibits and artifacts), but will instead be able to engage in an interactive way with the exhibits, through direct (voice) conversation with them, enjoying a truly personalised experience. For experts, the digital representation of knowledge will not be static (as it is, even in the case of the digital twin), but will feature also the functionality and connectivity which will allow the seamless link to third party services, and direct feed to AI tools, producing new knowledge, and offering direct processing of information under the supervision and guidance of the experts.

Beyond technical issues

STORM project was the best opportunity to cope with the challenge of merging technologies with human and cultural oriented practices, such as conservation and restoration. Creating a never seen synergy between these two approaches (technology and CH needs) in view of mitigating effects on cultural heritage, it is expected to enormously increase the mitigation of the damages created by climate change disasters.

The main question, coming from the experience done and this book snapshots on that, is how we will capitalize that experience in our future. We can say that an optimistic attitude could be justified by the achieved results in all multidisciplinary areas covered in the last three years but as you read in this book there is a lack of regulation and the consequent poor financial support for these issues.

As in the better tradition of innovation, small organisations and startups could play a relevant role in bringing the innovation in real life. This will probably be done using strategies which could count on local financial support and the possibility to have advanced regulations provided by local authorities. With an estimated cost to run a STORM experiment ranging from 8 to 10 k€ (using the platform released at the end of the project), SMEs and start-up focused on this potential business should run several experiment in order from one side to assess technologies and prioritise them, on the other side to consolidate preparedness and first aid methods in order to better fit the site manager's needs.

Communication between different actors will play a major role in the future achievements: the project itself had serious issues in establishing good communication among different competences so to say that now, after three year project, it should be great to start a new challenge not having to deal with all the previous communication issues. But communication is also the key element of emergency management. The recent event which affected the Notre Dame Cathedral (Paris, 15/04/2019), was a matter of discussion between STORM partners and during those discussion we figured out that probably the proper preparedness was not in place. Preparedness could dramatically reduce the reaction time and the effectiveness of intervention after a disaster; in the project we concentrated our focus on natural disasters both slow and sudden ones but same principles could be applied to disasters in general with the proper risk assessment.

As a final though we are convinced that new professionalisms could grow from the project experience, starting from cultural heritage experts such as conservators, restorers, archaeologists, architects, art historian involving specific branches of engineering; that could create new job opportunities for all those people provided that they will receive the proper education and practice experience.

STORM has been a great experience and has increased the awareness on how digital innovation can bring a strong support to the safeguard of our cultural heritage and identity. But Storm is just a start of a wonderful adventure that will hopefully continue with the support of all the involved stakeholders: policy makers, cultural professionals, public authorities, technology and service providers and the entire society.

STORM

Toward a more effective Cultural Heritage Disaster Resilience facing Climate Change Hazards

STORM Project **Safeguarding Cultural Heritage through Technical and Organisational Resources Management** intends to develop an integrated approach for a better management of the risk that endanger cultural heritage, through the creation of tools and instruments designed to assist in decision making during crisis or natural catastrophes, along the distinct phases of prevention / mitigation, preparedness, response and recovery.

Objective 4:
Models and services for generating and managing a situational picture based on data collected by physical and human sensors.

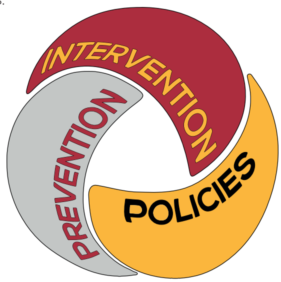
Objective 5:
Methodologies, practices and software tools for more reliable maintenance, quick restoration and long-term conservation.

Objective 3:
Survey and diagnosis based on the study of materials properties, particular environmental conditions, and profile of cultural heritage sites.

Objective 6:
Collaboration and knowledge-sharing framework for the community of stakeholders.

Objective 2:
Mitigation of natural hazards and the assessment, management of threats.

Objective 1:
environmental assessment methodologies and services assessment.



Objective 7:
Proposal on adaptations and major changes in existing policies and validation of new knowledge of government processes.

Objective 8:
Cost analysis for the sites protection against natural hazards managed by the STORM data analytics tools.

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