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Applying Simulation to Advance Resilience of Historic Areas to Climate Change and Natural Hazards

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Abstract. The EU-H2020 project *ARCH* aims to develop and adapt tools and methods for assessing and improving the resilience of historic areas to climate-related and other natural hazards [1]. One of these tools is CIPCast, a scenario simulation and decision support system for the analysis and forecast of risks and vulnerabilities of critical infrastructure components and their interdependencies. In this paper, we describe the basic functionalities of CIPCast, as far as the application to seismic risk assessment is concerned and we provide an overview of the models behind it. Furthermore, a brief discussion on how we plan to extend CIPCast to model and simulate potential risks and impacts induced by climate change to historic areas, and how this is intended to support resilience assessment strategies, is provided in the conclusions.

Introduction

Historic towns, old urban quarters, villages and hamlets, as well as historic landscapes make up a significant part of Europe: Natural heritage sites cover roughly 18% of the European land territory [2] and on average 22% of the European housing stock was constructed before 1946 [3]. These historic areas are deeply embedded in larger urban and rural environments (in which 72% of the European population live [4]), serving a role in preserving local identity and personality as well as local knowledge, while relying on interdependent infrastructure services to keep functioning. Historic areas are a major component of quality of life and play an important role in society and community well-being [5], as well as providing important environmental and economic functions.

Although climate change has become one of the most significant and fastest growing threats to people and their cultural heritage [6] the impacts of climate-related and other natural hazards on historic areas have not been studied extensively enough [7], and disaster risk reduction seldomly registers as a priority area for management of World Heritage property [8].

Therefore, there is a need for specific methods and tools for climate change adaptation and disaster risk reduction that take the unique physical, environmental, economic, social, cultural, and governance aspects of historic areas, as well as the enabling conditions they provide for taking action into account.

The EU Horizon 2020 research project *ARCH (Advancing resilience of historic areas against climate-related and other hazards)* [1] aims to take a step in this direction by providing a suite of tools for assessing and improving the resilience of historic areas, combined within a unified disaster risk management framework.

One of the tools developed within the project is an extension of the scenario simulation and decision support system CIPCast [9] in order to enable the assessment of impacts and risks to historic areas induced by climate change and natural hazards. This is an essential input for assessing the resilience of historic areas and identifying suitable resilience building strategies.

This paper gives an overview on how CIPCast functions and describes the extensions necessary to maximize its utility in the project context. The first section (sec. 1) gives a brief introduction to the ARCH project, followed by a general overview of the basic functionalities of CIPCast (sec. 2) and how these can already be employed to assess damage and impacts induced by seismic hazards (sec. 3). Following these explanations, the planned extensions of CIPCast (sec. 4), and how its results supports re-

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silience assessments (sec. 5) are described, before the paper closes with conclusions and an outlook (sec. 6).

1 The ARCH project

Advancing resilience of historic areas against climate-related and other hazards (ARCH) is an EU Horizon 2020 research project that aims to better protect historic areas from climate-related and other natural hazards induced risks. The project started in June 2019 and will run until May 2022.

Within a co-creation process, the project team of eleven research partners and the cities of Bratislava, Camerino, Hamburg, and València will create tools and methods to provide cities with better information and decision support for improving the resilience of historic areas. The results will be applied in pilot sites within the cities covering a diverse spectrum of historic areas: the historic old towns of Bratislava and Camerino, the Devin Castle ruin in Bratislava, the Speicherstadt and Kontorhaus World Heritage sites in Hamburg, as well as the La Huerta peri-urban farmland and Albufera national park in València. These areas are affected by a multitude of different hazards, amongst them earthquakes, heatwaves, fluvial and pluvial flooding, storm surges, erosion, and landslides.

The technical work in ARCH includes the preparation of a hazard object information management system that captures data on hazards and object conditions using newly deployed sensors and readily available open data platforms; an impact risk assessment framework that provides methods and tools for risk and impact assessment, including hazard models and scenario simulation for what-if analyses; the design of implementation pathways that identify potential resilience measures enriched with effectiveness scores, supported via a tool for graphical implementation planning; and a multi-stakeholder resilience assessment framework integrating the methods and tools as well as a platform for collaboration and sharing.

The remainder of this paper focuses on describing the simulation and decision support system adapted within the project and how this will be employed for the resilience assessment.

2 CIPCast Simulation and Decision Support System

CIPCast is a GIS-based Decision Support System (DSS) developed as part of the EU-funded FP7 project *CIPRNet (Critical Infrastructures Preparedness and Resilience ResearchNetwork)* [10]. CIPCast provides a database, an interoperable platform and a user-friendly WebGIS interface. These are conceived as a combination of free/open source software environments, for the real-time and operational (24/7) monitoring and risk analysis of built and natural environments, with special focus on interdependent critical infrastructures (such as electric power, water, telecommunication and road networks) and buildings [9][11][23].

CIPCast is based on a four-layer architecture:

- Within the **data preparation layer** basic data is collected, harmonized and organised for the following processing step.
- In the **data repository layer**, data and metadata are stored in a geospatial database implemented in PostgreSQL/PostGIS.
- Within the **analysis and elaboration layer** stored data and metadata are managed and published online to enable geo-processing and risk analysis.
- Within the **front-end layer,** data and functions from the previous layers are exposed to end-users via a WebGIS application.

Within this architecture, CIPCast provides five distinct functional blocks that feed each other:

- **B1 – Monitoring of Natural Phenomena** acquires data from different data sources.
- **B2 – Prediction of Natural Events** houses different hazard models to estimate the expected intensities for predictable events.
- **B3 – Prediction of Damage Scenarios** correlates the (estimated) hazard intensity with the vulnerability of elements located in an affected area to estimate potential direct damages (e.g. breakage of a transformer in an electric substation).
- **B4 – Prediction of Impacts and Consequences** correlates the potential direct damages to exposed elements with their (inter-)dependencies with other elements and the general system characteristics to estimate larger consequences (e.g. loss of service in an electrical network).
- **B5 – Support of efficient strategies** enables what-if analysis of different strategies to counter the effects of examined hazards.

The CIPCast **GeoDatabase** stores data related to exposed elements and hazards. For seismic hazards the database includes information on epicenter location, hypocenter depth and magnitude; for exposed elements it includes both static data, like structural characteristics of buildings, and dynamic data, like population dynamics. The data model used in the GeoDatabase differentiates between different classes of exposed elements, e.g. networks, like telecommunication, electricity, transport networks, and groups of buildings. Detailed information for exposed elements is stored to estimate vulnerabilities, e.g. build material, construction age, and number of inhabitants.

Currently, CIPCast includes hazard data collected from seismic sensors, weather stations (for precipitation, temperature, humidity, wind, etc.), and hydrometers (for inundation levels of river basins).

3 CIPCast-ES for Seismic Risk Assessment in Italy

CIPCast-ES is an extension of CIPCast specifically aimed at simulation of seismic hazards and at the assessment of related physical damage and impact scenarios [17]. This section provides an overview of the models embedded within CIPCast-ES that enable these functions and some explanatory case studies.

3.1 CIPCast-ES Seismic Hazard assessment

To allow the assessment and representation of *ground motion* and *earthquake-induced geotechnical* hazards, available data, layers and information were collated in the **GeoDatabase**.

This data was sourced from previous studies as well as from external web services. They include services provided by the Italian National Earthquake Center (http://cnt.rm.ingv.it/en) managed by the Italian national Institute of Geophysics and Volcanology INGV; hydrogeological risk maps provided by “Idrogeo” (https://idrogeo.isprambiente.it/), and a web platform on landslide and flood risk provided by the Italian Institute for Environmental Protection and Research ISPRA.

For assessing *ground motion* hazards CIPCast-ES includes the following data: known faults locations (see Figure 1); catalogues of historical earthquakes; and seismic microzonation maps. The latter provide, at the local scale, spatial information about the effect of the local geological conditions on ground-shaking.

For assessing *earthquake-induced geotechnical* hazards CIPCast-ES includes the following data: surface faulting; seismic-induced landslide potential (see Figure 1); seismic-induced rock-fall potential; liquefaction potential; and potential for permanent soil deformation.

Based on this data a *seismic hazard simulation* allows to model and represent the location, extension and intensity of expected ground shaking generated by real or user-defined (artificial) events.

The simulation of real events is undertaken to support emergency management. In this case, a quasi-real time estimation of the extent and severity of the seismic ground shaking after an earthquake event is fundamental to provide a rapid, efficient and effective response. The simulation of end-user defined events is instrumental to support risk mitigation planning as explained in Section 3.3.

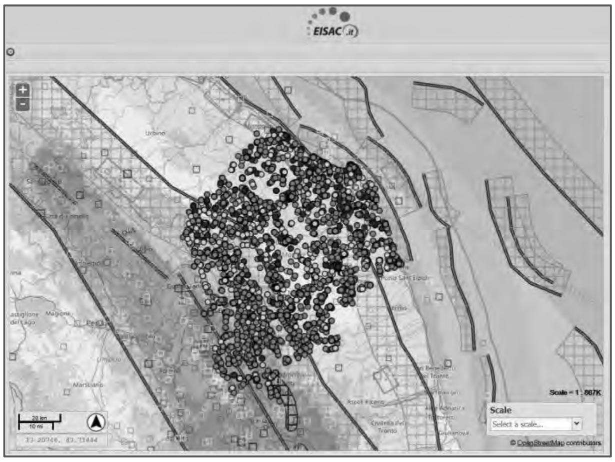

Figure 1: CIPCast-ES screenshot showing: seismic probabilistic hazard map and known-fault location maps from INGV, overlaid with cultural heritage assets (point locations).

In both cases the required inputs are:

- the location of the epicentre, i.e. latitude and longitude, X_E, Y_E;
- the depth of the hypocentre in kilometre D_H [km]; and
- the magnitude, M, expressed according to the Richter scale.

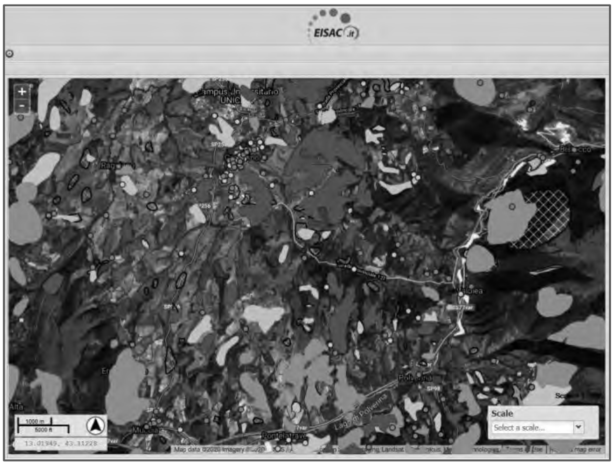

Figure 2: CIPCast-ES screenshot showing: Landslide risk maps from Italian P.A.I. “Piano Assetto Idrogeologico” overlaid with cultural heritage assets (area locations).

For real events, location and magnitude of any seismic event with a magnitude larger than M=3 are acquired automatically and represented in real time within CIPCast-ES.

For end-user defined events, the user provides the relevant parameters, usually based on a catalogue of historic events and known fault locations (Figure 4), both accessible in CIPCast-ES.

Once the parameters are defined CIPCast-ES calculates where, to what extent and with which intensity ground shaking will propagate using *Ground Motion Prediction Equations (GMPEs),* or *“attenuation”* relationships. GMPEs provide a means of predicting the level of ground shaking and its associated uncertainty at any given site or location, based on magnitude, source-to-site distance (i.e. distance between the epicentre and the location of an exposed element), local soil conditions, typology of the fault mechanism, etc. GMPEs are empirical-based equations derived after post-processing of recorded accelerations or observed damages generated by historical earthquake events[1].

In CIPCast-ES different GMPEs can be selected by the end-users allowing for the calculation and representation of seismic hazard maps with different metrics, i.e.:

- *Macroseismic Intensity, I*, [24];
- *Peak Ground Acceleration PGA* and *Spectral Acceleration, Sa* (T), [25];
- *Peak Ground Velocity, PGV*, [27]
- *Spectral Displacements Sd* (T), [27].

The selection of the most appropriate metric to represent the seismic hazard depends on the focus of the analysis; for example, *PGA* and *Sa* (T) have been observed to be more appropriate when the focus of the analysis is the structural performance of above-ground structures such as buildings while *PGV* and *Sd* (T) are suitable when the focus is on buried infrastructures. *Macroseismic intensity* on the other hand, is a qualitative descriptor of the effects of an earthquake at a particular location, as evidenced by observed damage on the natural and built environment and by the human and animal reactions at that location. Although a qualitatively metric, it is still used when adopting empirical-based models for assessing seismic vulnerability, such as the one described in section 3.2 for residential and monumental buildings.

Figure 3 provides an example of the official ground motion map after the L’Aquila earthquake on April 6, 2009 at 03:32 CEST, represented in *PGA* [%g].

While official ground shaking maps are released by INGV around 45 minutes after an earthquake event occurs, the basic parameters necessary for simulation are usually published only a few minutes after an event. This allows to easily check and validate simulation results with actual event data.

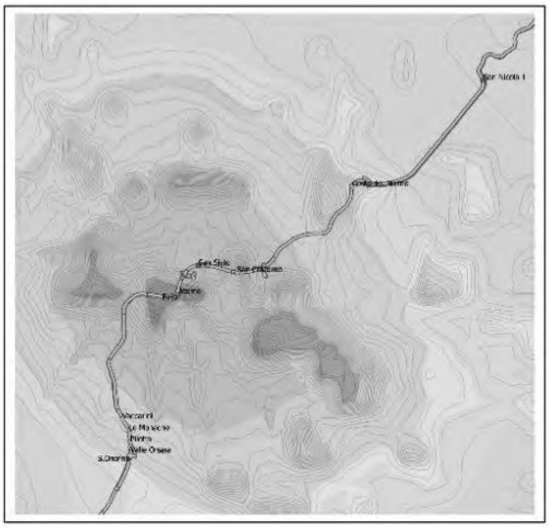

Figure 3: Official INGV ground motion map after April 6, 2009 L’Aquila earthquake overlaid with A24 Highway route.

For example, to simulate a ground-shaking map for the L’Aquila earthquake a user would choose the following parameters:

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[1] An exhaustive compilation of GMPEs defined in the period range 1964-2019 can be found here: http://www.gmpe.org.uk.

- epicentre location 42.3476° N, 13.3800 °E,
- magnitude $M = 6.3$,
- hypocentre D_H [km] = 9.46 km.

Because CIPCast-ES allows to calculate ground shaking maps in quasi real time it is able to support emergency management operations with first estimates of the location, extent and level of ground shaking in the affected territories. Simulated maps are substituted in CIPCast-ES with official maps, as soon as they become available.

3.2 CIPCast-ES Vulnerability and Physical Damage assessment for buildings

To allow the assessment and representation of built-environment elements and of potentially exposed population the **GeoDatabase** includes: Administrative boarders (regions, municipalities and census tracks) and associated data on population (including gender, age, occupation, etc.) sourced from the Italian National Institute of Statistics; location and basic information on critical infrastructures like electrical transmission systems, gas transmission systems, main sources of electricity production, transport systems (road network, railways, airports), as well as the locations of strategic buildings like hospitals, barracks and schools.

Data about residential buildings is stored at single building level, when possible, or as aggregated data linked to geographical units otherwise. This includes data on construction age, construction material (masonry, reinforced concrete, timber, prefabricated,), type of structural system (e.g. frame versus shear walls for reinforces concrete buildings, bricks versus stones for masonry buildings), and adoption of seismic codes for design or retrofitting.

For the **Prediction of Damage Scenarios** (i.e. B3 Module) for buildings, the *Macroseismic-Mechanical cross-calibrated Method* [28][29] is implemented. This method allows to assess the seismic vulnerability of building groups, statistically aggregated in a geographical unit, and of single buildings as a function of their *seismic vulnerability* and of the *ground-motion* at their location (see Section 3.1).

The *seismic vulnerability* of buildings is measured by the *vulnerability index V* and the *ductility index Q*, calculated based on building typology and constructive, geometrical or additional features able to affect and modify building behaviour when subjected to earthquake shaking. One way to calculate the *vulnerability index V* is to combine a *basic vulnerability index V** and a *vulnerability index modifier ΔV*, where V^* reflects the building typology and ΔV the sum of influencing features:

$$V = V^* + \Sigma\Delta V \qquad (1)$$

Table 1 lists basic vulnerability indexes for different building categories (I to VII), construction materials (masonry or reinforced concrete) and construction periods. Figure 3 shows an example visualisation of vulnerability indexes on census tract level.

	Masonry	V*		RC	V*
I	< 1919	0.79		-	-
II	1919 - 1945	0.73		-	-
III	1945-1971	0.69	**V**	< 1971	0.59
IV	> 1971	0.65	**VI**	1971-1981	0.55
	-	-	**VII**	> 1981	0.42

Table 1: Basic vulnerability indexes V* for different building categories, construction periods and construction material. RC: Reinforced Concrete

Once the seismic vulnerability is assessed, the expected damage can be estimated as follows:

$$\mu_D = 2.5\left[1 + tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \qquad (2)$$

where:

- μ_D is the *average expected damage for a group of buildings or an individual building*;

- V is the value of the *vulnerability index*;

- Q is the *ductility index* assumed to be 2.3 for ordinary building categories like the ones from Table 1;

- I is the *Macroseismic Intensity* as described in the previous section.

$D_0 = \mu_D < 0.5$;	$D_3 = 2 \leq \mu_D < 3$;
$D_1 = 0.5 \leq \mu_D < 1$;	$D_4 = 3 \leq \mu_D < 4$;
$D_2 = 1 \leq \mu_D < 2$;	$D_5 = 4 \leq \mu_D \leq 5$.

Table 2: Categorization of expected damages based on [30]

In order to categorize the expected damage μ_D the EMS-98 damage grade scale [30] is applied. This scale differentiates between six different levels D_k: D_0 no damage, D_1 slight, D_2 moderate, D_3 heavy, D_4 very heavy, D_5 collapse/destruction. Table 2 lists how expected damages are categorized and Figure 4 shows an example visualization on census tracks level.

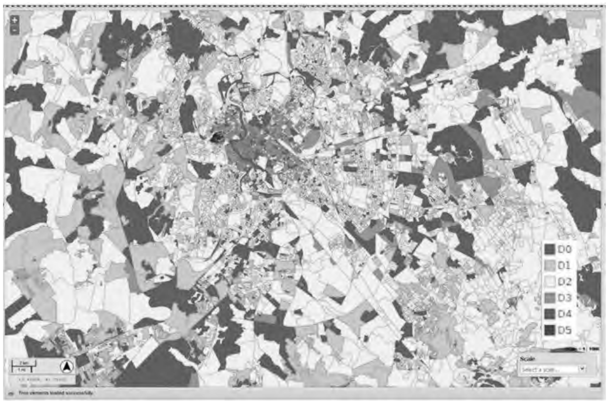

Figure 4: Example of the earthquake-induced damage assessment at census track levels [29]

4 CIPCast Extensions for ARCH

In order to employ CIPCast in ARCH, the **GeoDatabase** will be extended to include maps and data representing historic areas and heritage buildings, classified into moveable heritage, archaeological resources, buildings and structures, cultural landscapes, associated and traditional communities and intangible heritage as described in [31].

To allow the assessment of climate change induced scenarios the **GeoDatabase** will need to be extended to include related hazard maps (e.g. for floods or extreme temperatures) under different climate scenarios. These maps will be derived from numerical simulations, climate hazard indicators, optical/thermal earth observation maps, high-resolution aerial and satellite maps, and from existing data services, e.g. Copernicus Climate Change Service [21].

4.1 CIPCast extensions for assessing damage to historic buildings

In order to estimate seismic damages to historical buildings the same function as for residential building (see equation 2) will be employed, using adapted *V* and *Q* index values. These values will be calibrated using earthquake-induced damage sustained by cultural heritage areas and buildings during the last twenty years.

It is important to note that a vulnerability index assigned to a monument simply by a typological classification represents an average value that does not account for the distinctiveness of the single building and does not allow singling out the most vulnerable structures among buildings of the same type. Therefore, the vulnerability assessment will be refined to reflect peculiar characteristics and features of historic buildings that might increase or decrease their vulnerability, e.g. via a survey that collects relevant parameters like maintenance conditions, quality of materials, structural regularity (in plan and in elevation), size and slenderness of relevant structural elements, possible interaction with adjacent structures, presence of retrofitting interventions, etc.

4.2 CIPCast extensions for assessing climate change induced scenarios

To allow for the simulation of damage and impact scenarios induced by climate-related hazards CIPCast needs to be extended with the capability to manage additional input data and additional simulation modules. The basic framework for CIPCast-CC (*CIPCast Climate Change module*, also referred to as *ARCH DSS*), will be similar to CIPCast-ES, i.e. physical damage induced by climate change on the built environment in historic areas will be assessed as a function of hazard, exposure and vulnerability. Specifically, ARCH DSS will include

- models for index-based vulnerability assessment at area and single building level (e.g. compare to [32][33]);
- models for physical damage assessment that combine a) hazards parameters; b) position and typology of heritage; and c) heritage vulnerability; and
- models for the estimation of functional, economic and societal impacts.

For the latter, cause-effect models are necessary, which can for example be derived by developing impact chains in multi-stakeholder workshops [34].

5 Integration of CIPCast in the ARCH resilience assessment

The ARCH project adapts the Urban Adaptation Cycle [35] to describe the resilience management process of historic areas. One step in this process is the assessment of hazards, vulnerabilities, risks, and resilience. The resilience assessment is based on the UNDRR Disaster Resilience Scorecards for cities [22] and buildings [35]. As part of the resilience assessment, users need to identify the most relevant hazard and risk scenarios for the historic area that is being assessed and should formulate resilience enhancing measures to eliminate resilience weak spots. Here, CIPCast will be employed to enable users to identify and simulate hazard scenarios, assess potential impacts and identify the most suitable measures to raise the resilience.

The resilience assessment will be implemented as a web-based, semi-quantitative, multi-stakeholder self-assessment questionnaire that covers topics like governance processes to increase resilience, financing resilience, restoration and recovery for resilience, social justice in resilience management, and environmental issues in resilience. The resilience assessment is intended to guide users through this process, link to relevant tools at appropriate steps and support better coordination among relevant actors. The result of the resilience assessment will be given as a weighted resilience score for the historic area with linked resilience enhancing measures and additional information for decision-makers.

6 Conclusion

We described the planned use of modelling and simulation for assessing the resilience of historic areas against the impact of climate change and other extreme events. Aims and scope of the ARCH project were introduced, the CIPCast Simulation and Decision Support System, its planned extensions, as well as a brief application example were described.

As next research steps, CIPCast will be extended as described in section 4. The hazard models and simulation approaches will be integrated with a database of resilience building measures to support formulation and comparison of resilience building strategies. These functionalities will be integrated in a resilience assessment framework based on the UNDRR Disaster Resilience Scorecards for cities and buildings that include further – non-physical – resilience aspects (e.g. community resilience) to support the formulation of comprehensive resilience actions plans for historic areas.

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