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A Framework for a Hazard Taxonomy to Support Risk Assessment of Tangible Outdoor Heritage

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Abstract: The variety of hazards with a potential impact on cultural heritage requires a multidisciplinary approach and a preliminary overview of the existing methods for risk assessment in order to define a comprehensive hazard taxonomy. The starting point of the research thus aims to build a multidisciplinary framework to support the risk assessment process according to the classification of cultural heritage based on the harmonization of European vocabularies' definitions and protocols. To collect the necessary information, such as hazard classification, indicators, indices and thresholds, a series of methodologies was adopted: analysis of the main international protocols and the EU Research projects related to risk assessment in cultural heritage, expert-based knowledge and a systematic literature review. The research aims to fill a gap in the field of quantitative and indicator-based risk assessment that does not present a unique and all-encompassing framework capable of collecting the main natural and anthropic risks along with the related taxonomy in a single repository. The framework has been set up to be consulted by researchers, professionals and public administrations to support the evaluation process of potential risks on tangible outdoor heritage enabling users to incrementally add exposure and vulnerability data for each specific risk.

Keywords: cultural heritage; historic built environment; risk analysis; hazard taxonomy; open framework

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1. Introduction

Cultural heritage (CH) is a vector of social and economic improvement. The composite ecosystem of its tangible and intangible components, made up of rituals and practices along with hand-crafted products, buildings and natural elements, offers the opportunity to develop innovative forms of rural, creative and slow tourism experiences, pushing toward a positive job creation trend. However, the current climate change (CC) process puts at risk the fragile equilibrium that interlinks natural and human environments in CH. Long-term changes in weather patterns and temperatures, known as CC, are considered one of the most serious threats of the twenty-first century [1]. This natural process, which has been occurring for millions of years due to variations in the solar cycle, has been accelerated in the last two centuries as a result of excessive anthropization and greenhouse gas concentration, upsetting the natural balance and increasing global surface temperature [2]. According to the UNESCO Climate Action Policy Paper, CC has become one of the most significant threats to natural and cultural world heritage sites, with potential impact on their outstanding universal value (OUV), including their authenticity, integrity and capacity for economic and social development at the local level, as well as the quality of life of communities linked to world heritage sites [3].

As a result, ICOMOS, a UNESCO advisory body, emphasizes the importance of adequately responding to, and preparing for, CC's risks to CH, considering it as a source of resilience and climate mitigation [4]. Not only CC, but also the OUV of CH is put at risk by anthropic action, which manifests itself in a series of direct and indirect actions capable of altering the ecosystem in which the protected asset is located. Anthropic risks represent a further level of complexity in the evaluation of prevention and mitigation strategies, as the evaluation of specific risks is in most cases qualitative and not quantitative.

The traditional distinction between natural and anthropic hazards is challenged by the combination and interaction of different hazards and causes, as natural disasters also cause migration and social conflicts, and human behavior accelerates natural processes. Phenomena related to CC and natural/anthropic risks raise new research questions and open new challenges for modern societies, requiring a broad multidisciplinary approach towards problem solving. The analysis of hazards with potential impact on the CH is a complex operation that brings into play a vast amount of data and, for this reason, requires a holistic and multidisciplinary approach, as well as an awareness of the existing methods of evaluation.

1.1. The PNRR Research Project

In light of this, the overall objective of the PNRR Research Project[1] is to deliver innovative solutions to mitigate the effects of CC and of natural and anthropic risks on selected case studies of Italian CH, based on the following methodological steps:

- Identification of knowledge gaps and development of an appropriate shared paradigm (new concepts), as well as coordination of data acquisition and integration;
- Evaluation of resilience and adaptation models of the past and re-appropriation of historical memory;
- Comprehensive risk analysis on the multivariate effect of CC and the interaction of different risks;
- Development of a shared framework for modeling, simulation and computerized data-driven monitoring;
- Integration of knowledge fields to support the multi-criteria decision method (MCDM);
- Development of an interdisciplinary framework for a decision support system (DSS) aimed at the redevelopment and design of architectural heritage and the historical landscape.

Italy is one of the countries with the highest number of sites registered in the UNESCO World Heritage List, with 58 world heritage sites, which includes tangible and intangible resources. Enhancing the value and the resilience of Italy's cultural heritage is a national priority in order to promote development and competitiveness. The selected case studies were identified among different categories of cultural heritage, including "Territory and landscape," "Historic City," "Archaeology," "Architecture" and "Collections."

1.2. Research Aim and Scope

The starting point of the research conducted by the Sapienza PNRR working group focused on a multidisciplinary framework to support the risk assessment process relating to the multivariate effect of CC and the interaction of different risks on the following categories of tangible outdoor heritage:

- Territory and landscape;
- Historic city;
- Architecture.

Specifically, the case studies selected in the framework of the PNRR research project are represented by Tortona and its "Valli del Tortonese" valleys; Piedmont; and the island of Mozia, Sicily. The framework was developed in accordance with the cultural heritage classification based on the harmonization of European vocabularies' definitions and protocols. This process provides a core resource for building a multidisciplinary and comprehensive framework structured around the classification of hazards; their categorization; and the identification of related metrics such as indicators, indices and thresholds. The integration of various data into a synthetic evaluation model is always underpinned by the multi-objective nature of the preservation of CH, which necessitates a quantitative or semi-quantitative definition of risks to estimate the intensity of mitigation efforts. The construction of the framework began with the analysis of major national and international risk assessment protocols in order to define an initial classification based on the two main risk classes, natural and anthropogenic. The synthesis and standardization of the classes were preparatory to the identification of a hazard taxonomy for the quantitative or semi-quantitative risk assessment. The taxonomy was completed through the analysis and systematization of the results of EU research projects, the use of AI chatbots and expert knowledge within a co-creation process leveraging the open-source nature of the framework, and a systematic review of the literature.

2. Materials and Methods

2.1. Risk Assessment Process

In the process of risk assessment, it is crucial to explore the interconnected dimensions of risk, focusing on the interplay between hazard, vulnerability and exposure [5]. Hazards, as defined by the Intergovernmental Panel of Climate Change (IPCC), are potential sources of harm, encompassing both natural phenomena and anthropogenic events "that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, and environmental resources" [6]. The dynamic interaction among hazards, vulnerability and exposure underscores the complexity of risk, necessitating a holistic approach to mitigate its impacts. Hazards are inherently diverse and dynamic, spanning geological, meteorological and anthropogenic domains. Understanding the frequency, intensity and spatial distribution of hazards is crucial for effective risk assessment [7]. Vulnerability, as defined by Adger [8], is the susceptibility of a system to harm, influenced by physical, social, economic and environmental factors. Social vulnerability often arises from disparities in wealth, education and healthcare access, as stated by IPCC, while physical vulnerability may result from inadequate infrastructure or inappropriate land use planning. A comprehensive vulnerability assessment is pivotal for identifying risk-prone areas and populations. Exposure refers to the degree to which elements at risk, such as populations, assets or ecosystems, are subject to a hazard [9], and spatial and temporal dimensions of exposure play a crucial role in determining risk levels. Mapping exposure helps to identify high-risk areas, enabling targeted interventions and resource allocation. Thus, risk assessment integrates hazard analysis, vulnerability assessment and exposure mapping to quantify the likelihood and consequences of adverse events [10].

2.2. Methodology Employed for Risk Assessment

Various methodologies and strategies are employed in risk assessment processes [11]:

- Quantitative risk assessment: This method takes a numerical approach, utilizing hazard scenarios and the valuation of at-risk elements;
- Event tree analysis: Employing a quantitative perspective, this method involves defining trees to establish relationships between diverse hazards and events;
- Risk matrix approach: This approach tackles risk qualitatively, allowing for the categorization of risks based on expert knowledge, particularly in situations where quantitative data are either lacking or limited;
- Indicator-based approach: This semi-quantitative method involves the use of indicators associated with each risk determinant or component (such as hazard, exposure and vulnerability). These indicators are then normalized, weighted and aggregated to derive a comprehensive risk score.

Most of the methodologies introduced above take a quantitative approach that requires a clear overview of hazard taxonomy, such as indicators, indices and thresholds.

2.3. Methodological Framework for Identifying a Hazards Taxonomy Identification

Thus, the starting point of the research consists of a systematic literature review of risk assessment approaches, methods and indicators. This process represents the basis of a multidisciplinary framework consisting of the definition of risk, its categorization, its metrics represented by a measurable index and its main target, according to the classification of CH based on the harmonization of European vocabularies, definitions and protocols. The framework is also developed as a result of a co-creation process based on a collaboration between professionals and academics. This process, integrating different indicators in a synthetic evaluation model, emphasizes the multidisciplinary and multi-objective nature of the preservation of CH. Overcoming this diversity, and therefore the barriers between disciplines, has been a research priority, thus requiring the sharing of expertise and data. The methodological framework is defined as follows:

- Analysis of the main international and national risk assessment protocols;
- Definition of the first risk classification based on two main classes: natural and anthropic risks;
- Identification of the main hazard components for quantitative or semi-quantitative risks assessment.

The second stage of the research is devoted to developing risk taxonomy through a series of strategies:

- Analysis of European Research Projects completed or nearing completion;
- Use of AI chatbots;
- Systematic literature review and co-creation process.

As a final outcome, a multidisciplinary framework will be developed. The database will allow for the quantitative or semi-quantitative assessment of natural and anthropic hazards, which will be described taking into account indicators, indices and thresholds.

2.4. Hazard Analysis and Taxonomy

To establish a comprehensive understanding of research on hazards, in our research, we gathered data from European and national agencies, identified the most pertinent and comprehensive reports related to the analyzed topic and assessed relevant online platforms for task development. Nevertheless, the in-depth overview of risk analysis at both national and European levels also relied on the findings from ongoing and completed EU projects, as well as scientific publications. Presented below are the primary selections that contribute to the task's perspective.

References with specific focus on CH and risk assessment (Tables 1–3):

Table 1. Three international references with specific focus on CH and risk assessment.

UNESCO World Heritage Convention	https://whc.unesco.org/en/factors/ (accessed on 2 November 2023)
International Center for the Study of the Preservation and Restoration of Cultural Property ICCROM	https://www.iccrom.org/publication/guide-risk-management (accessed on 2 November 2023)
ICOMOS—ICORP International Scientific Committee on Risk Preparedness	https://icorp.icomos.org/ (accessed on 2 November 2023)

Table 2. Two international references on risk assessment.

DRMKC—Disaster Risk Management Knowledge Center	https://drmkc.jrc.ec.europa.eu/risk-data-hub/#/ (accessed on 2 November 2023)
UN Office for Disaster Risk Reduction	https://www.undrr.org/implementing-sendai-framework (accessed on 2 November 2023)

Table 3. Three national references on risk assessment.

Department of Civil Protection Presidency of the Council of Ministers	https://www.protezionecivile.gov.it/it/ (accessed on 6 November 2023)
ISPRA—Istituto Superiore per la Protezione e la Ricerca Ambientale	https://www.isprambiente.gov.it/it (accessed on 6 November 2023)
INGV—Istituto Nazionale Geo-Vulcanologia	https://www.ingv.it/ (accessed on 6 November 2023)

The analysis of the main national and international protocols on risk identification was carried out on both general and specific levels regarding cultural heritage in order to identify risk clusters that may be considered invariant. During the first phase, the investigation was aimed at defining the risk class—natural, anthropic or anthropic/natural—of the corresponding type and the specific risk in relation to the different identified classes.

2.5. UNESCO World Heritage Convention

The first protocol analyzed, the UNESCO World Heritage Convention, proposes a comprehensive classification of primary and secondary risk factors that can have a negative influence on the conservation of the OUV in terms of the historical, artistic, scientific, aesthetic, ethnological or anthropological aspects of world cultural heritage. The primary risk factors were defined by establishing a broad spectrum of application in a variety of natural, anthropic and historical/cultural settings. The latter were summarized in thirteen distinct classes within the framework, with the possibility of including others if the supplied risk was not comprehensive or if further risk elements yet to be identified should arise.

The primary factors identified at the present time are the following: buildings and development, transportation and infrastructure, utilities and service infrastructure, pollution, biological resource use/modification, physical resource extraction, local conditions affecting physical fabric, social/cultural uses of heritage, other human activities, CC and severe weather events, sudden ecological or geological events, invasive/alien species or hyper-abundant species and management and institutional factors. Although the primary factors are not classified as natural, anthropic or anthropic/natural risks, the description of the secondary factors allows the classification within the framework to be easily refined.

Based on the identified primary and secondary factors, UNESCO proposes a list of 56 protected assets that are potentially at risk, along with the consequent loss of OUV, providing a purely qualitative description of the phenomenon.

2.6. International Center for the Study of the Preservation and Restoration of Cultural Property, ICCROM

As relates to cultural heritage, an additional classification of potential risk factors is provided by the International Center for the Study of the Preservation and Restoration of Cultural Property, ICCROM. The protocol defines a hierarchy of elements that work together to identify the specific risks. The analysis starts from the context within which the cultural heritage, be it a building, a monument, a project or a scenic site, is placed, identifying a series of factors that can contribute towards determining the risks, identifying them and managing them. These include environmental, political, sociocultural, administrative, financial and legal aspects, as well as potential stakeholders. The context analysis phase is preparatory for identifying the risks, which calls for defining:

- Ten agents of decay;
- Six layers of "enclosure";
- Three risk categories in relation to their likelihood of occurrence.

Agents of decay are factors that can cause damage and therefore result in loss of value of the asset being analyzed in a specific place and in a given setting. The ten identified agents are: physical forces, dissociation, incorrect RH, incorrect temperature, light and UV, pollutants, pests, water, fire, and criminals. For each of these, the protocol provides specific, multi-scale examples of possible risk sources and the potential damage they can cause to cultural heritage. In this regard, physical forces include as risk sources extreme events like earthquakes, wind and erosion, as well as the improper handling of artistic assets, while the possible effects include collapse and damage to the structures, as well as abrasion of their surfaces. The illustration of the agents of decay is accompanied by concrete examples that help to clearly identify their cause and the effects on cultural heritage. To contribute towards identifying the potential hazards, the concept of "Layers of Enclosure" is introduced, through which the architectural heritage being studied is placed in relation to the corresponding ecosystem that may be considered as a potential source of damage and as an element of protection from it. If the object for which a risk analysis is performed is an archaeological find, its "Layer of Enclosure" is the museum display case or the container in which it is conserved, while the ecosystem with which it relates is the room in which it is placed. Following bottom-up logic, the layers are defined as follows: support, fitting, room, building, site and region.

The final component of the analysis is the assessment of the likelihood that the risk will occur. The protocol proposes three categories:

- Rare events that take place once every 100 years (e.g., floods, earthquakes and destructive fires);
- Common events that take place several times over the course of 100 years (e.g., earthquakes and fires of low/medium intensity);
- Cumulative processes that can take place continuously or intermittently (e.g., corrosion of metals, erosion of stone).

2.7. DRMKC—Disaster Risk Management Knowledge Center

An additional general and trans-scalar reading of the risks is provided by two international agencies: DRMKC—Disaster Risk Management Knowledge Center and UN—Office for Disaster Risk Reduction. The former offers a classification of the risks based on eight classes, each of which presents risk types and specific risks. The identified classes are as follows: geophysical, hydrological, meteorological and climatological as natural risks; technological and transportation as anthropic ones; and biological, denoting events born from the interaction between natural and anthropic phenomena. To support the analysis, the protocol offers a "digital vocabulary" based on ShowVoc datasets, aimed at outlining the taxonomy of the risk while identifying its main components.

The database is structured as follows:

- Risk class;
- Risk type;
- Specific risk;
- Description of the risk;
- Metrics (in the event of quantitative assessment);
- Bibliographical references and sources.

The instrument came into being with the intent to organize the existing knowledge in a complete taxonomy. This taxonomy aims to cover not only the components of the risk (potential damage, exposure, and vulnerability/resilience), but also the management processes and phases (for example, risk assessment and inventory of data on losses due to catastrophes). An additional tool offered to support the analysis of the risk in all its components—damage, exposure and vulnerability—is the RISK DATA HUB, through which a WEB GIS application allows the potential damage of a particular asset (building, population, economy) for a geographical area to be displayed, taking a specific risk into consideration from time to time.

2.8. UN—Office for Disaster Risk Reduction

Lastly, on the international level, consideration was also given to the UN—Office for Disaster Risk Reduction classification, which is articulated in clusters based on seven risk classes: meteorological and hydrological, geohazard, environmental, chemical, biological, technological and societal. Each class has different risk types corresponding to the specific risks. Supporting the classification is a webpage with a "Knowledge Base" section where the taxonomy of the risks, hazard, exposure and vulnerability may be examined in greater depth, with content updated daily.

2.9. Department of Civil Protection, Presidency of the Council of Ministers

On the national level, as an initial instrument, that of the Department of Civil Protection, Presidency of the Council of Ministers was analyzed, which provides a holistic vision of the issue of risks, identifying nine types of risk: seismic, meteo/hydrological, volcanic, seaquake, forest fires, health, environmental, nuclear and industrial. For these, a purely qualitative description of the phenomenon is provided with reference to the national risk prevention plan and the risk prevention strategies. No indications are provided as to the risk classes or the specific risks. A broader discussion is referred to such national agencies as ISPRA—Istituto Superiore per la Protezione e la Ricerca Ambientale and INGV—Istituto Nazionale GEO-VULCANOLOGIA concerning discussion of the specific risks set in relation to hydrogeological and seismic events. In this case, the description of the specific risk is broadened with indices, indicators (where present) and metrics.

2.10. Initial Clusterization of the Risks Based on 4CH Project

First, an initial partial clusterization of the risks was performed by analyzing the results of the progress of the European 4CH Project (2021–2024)[2]. The 4CH provides a general classification of the risks based on the two main macro areas of natural and anthropic risks. As concerns natural phenomena, an additional classification was made for risks derived from cumulative processes, which is to say all the forms of deterioration that gradually accumulate over time or any process or intermittent and fluctuating event that takes place more than once a year, as well as risks due to catastrophic events that are often beyond human control. The risks belonging to the first sub-category (cumulative processes) are classified as natural and biological. The former comprise the following types of risk: sea level rise, glaciation, erosion, silting, desertification, ground-water, deposition and vibration. The biological risks comprise animal migration, vegetation, pests, decay and degradation. For the second sub-category, the classification proposed in the context of the 4CH Project is as follows: invasive species and extreme climate and geological events. The risk types underlying the invasive species category include fauna and flora, while the extreme climate events are fire, downpours, squalls, floods and hail. To conclude, extreme geological events are tsunamis, earthquakes, landslides and volcanoes. For the anthropic class, a subdivision is proposed based on intentionality: intentional and indirect risks of causing damage to the cultural heritage. The intentional risks are in turn classified between management and crimes against cultural heritage. As concerns the former, we find the following risk types: modern re-use, corruption, quarrying and political; and for the latter, vandalism, arson, theft, illegal excavations, illicit trafficking and collectors. The family of indirect anthropic risks comprises building/infrastructure/industry, land conversion, heritage management, socio-cultural risks and other. The building/infrastructure/industry category comprises industrial activity, constructions, transportation, pollution and mining. In land conversion, agriculture and forestation are included; in heritage management, negligence, neglect, restoration, tourism industry, visitors and handling are included; and in the socio-cultural category are changes in values, veneration, loss of traditional knowledge and performance.

2.11. Hazard Classification in the Light of PNRR Research Project

Through the analysis of the deliverables dedicated to the mapping of risks and the development of case studies, the types of risks belonging to the natural and anthropic risk categories could be identified, and we thus completed the taxonomy by providing the missing information relating to indices, indicators and metrics of use for the purpose of the quantitative assessment of the risks. The classification proposed by the 4CH project was implemented with respect to the one proposed by the main international protocols that are the object of our study, as well as in relation to the specific research purposes. In particular, the final classification was configured as the result of the following operations:

- Homologation to the taxonomy used in the 4CH project with reference to the main international classes;
- Implementation of the natural risk types closely related to CC (e.g., heat waves and cold waves);
- Introduction of risk types resulting from interaction between natural and anthropic phenomena that can impact the conservation protection of CH;
- Specific classification of certain risk types that make reference to generic phenomena (e.g., pollution, floods);
- Selection of anthropic risks in relation to the specific purposes of the research.

The following is the classification that was developed (Table 4).

Table 4. Natural and anthropic risks with which to define the taxonomy.

NATURAL RISKS	ANTHROPIC RISKS
Extreme weather events	**Pollution**
Heat waves	Air pollution
Cold waves	Water pollution
Downpour/heavy rainfall events	Soil pollution
Squall/windstorms	**Building/Infrastructure/Industry**
Hail	Carbonation and CO2 uptake of concrete
Desertification	Salt crystallization
Metereological drought	Corrosion
Environmental	Mining
Fire	Overtourism
Sea level rise	**Land Conversion**
Storm surges	Agriculture/forestation
Silting	**Heritage crime**
Frost ground	Vandalism
Erosion	Illicit trafficking
Coastal erosion	**Management**
Soil erosion	Corruption
Flood	Modern re-use
Floods	Political
Coastal floods	**Socio-cultural**
Flash floods	Loss of traditional knowledge
Fluvial–riverine floods	**Other**
Geological events	War
Earthquakes	

Volcanoes
Landslides
Avalanches (indirect)
Tsunamis (indirect)
Biological
Decay
Vegetation
Plant pests
Animal migration
Invasive species
Flora/fauna
Biodiversity loss

Having completed the classification and identified the risk types, the second phase of the research was related to the definition, if possible, of the associated specific risks, the probability classes, the indicators, the indices and the metrics of use for the purpose of quantitative or semi-quantitative assessment of the risk in relation to cultural heritage. The database's structure was articulated as follows:

- Risk class;
- Risk type;
- Specific risk;
- Probability classes (in the event of qualitative assessment);
- Indicators;
- Indices;
- Metrics (in the event of quantitative assessment);
- Bibliographical references and sources;
- Glossary.

In order to complete the taxonomy and provide a framework that was as comprehensive as possible, the work proceeded as follows:

- Assessment of the projects financed by the EU framework programs that are concluded or in the completion phase, considering the timeframe of the past ten years, 2013–2023;
- Use of artificial intelligence (AI) chatbots;
- Literature review and co-creation of the database with the support of specialists in the sector;
- Analysis of reports of national and international agencies specialized in managing and assessing specific risks (e.g., The World Meteorological Organization);
- Consultation of specific databases on the taxonomy of risks.

2.12. Selection of European Project on CH Multi-Risk Assessment

Our analysis of some of the main European projects on the topic was conducted using CORDIS, Community Research and Development Information Service, a database that collects the results of the projects financed by the EU framework programs for research and innovation (from FP1 to H 2020). A set of keywords was used to scan the database in relation to the specific purpose of the research, considering the timeframe of the past ten years (2013 to 2023). The analysis was immediately restricted to the projects with multi-risk analysis and assessment processes. An additional investigation was conducted on the INTERREG CENTRAL EUROPE platform, which has a database of projects financed by the specific EU 2014–2020 fund, subdivided into four categories: INNOVATION, LOW-CARBON, ENVIRONMENT/CULTURE and TRANSPORT. The screening focused on the ENVIRONMENT/CULTURE category. Within this category, the choice was made to more deeply analyze two projects, which made it possible to obtain elements of use for further refining the risk taxonomy.

The first of these projects was ProteCHt2save (2016–2019) (Supplementary Materials S1). In particular, the main focus of the research pertaining to the mitigation of the natural risks derived from CC, and in particular the floods and fires derived from periods of serious drought, was analyzed with the intent to preserve CH through a multi-scale approach, from the artefact to the landscape, using tailor-made solutions marked by the relative simplicity of their application. Analysis of the deliverables made it possible to track a partial classification of the natural risks derived from CC, with some indices and indicators of use for the purpose of a quantitative assessment of the associated risks.

Other data for the completion of the framework were extrapolated from the Strench (2020–2022) project using the associated digital platform. The portal provides a list of natural risks derived from CC, such as heavy rain, flood, drought and extreme heat. Moreover, some climate variables are defined, like minimum temperature, maximum temperature and precipitation, which may be considered as determinant factors in the definition of the risks. For the specific risks cited above, various indices and indicators of use for the quantitative and semi-quantitative assessment were reported, in addition to a description to facilitate understanding of the associated phenomenon (Supplementary Materials S2).

In the context of the projects financed by the EU framework programs, Prothego—PROTection of European Cultural HEritage from GeO-hazards (H2020, 2015–2018) (Supplementary Materials S3) deals with the issue of protection from CH with respect to the risks derived from such geomorphological events as landslides, earthquakes and phenomena associated with volcanic activity. Analysis of the project's deliverables allowed partial data on the taxonomy of geomorphological risks, like threshold values and indicators for a qualitative or semi-quantitative assessment, to be collected. No indices were present.

Additional research on the potential natural and anthropogenic risks derived from CC that may affect CH was performed in the setting of the Heracles Project (H2020, 2016–2019). Analysis of the deliverables and publications [12] made it possible to identify the specific risks selected for the qualitative assessment that were related to structural damage based on macroscopic observation of the surface of the built CH asset. The checklist was comprehensive in terms of indicators that allowed for condition assessment through a scale of values, from very low (1) to very high (5). This process allowed us to estimate the effects of specific hazards on the architectural heritage assets. Moreover, a series of external factors that can influence the CH was defined to analyze potential hazard, and features that can help to estimate the vulnerability and exposure were listed. From the materials available, it was not possible to clearly define indicators or indices applicable for the quantitative assessment of the risks. Units of measurement were declared for some of the potential hazards listed (Supplementary Materials S4). In conclusion, the Heracles project defines a risk categorization based on four classes: environmental, geomorphological, costal environment and anthropogenic and socioeconomic; it also provides information about potential hazards (units of measurement) and exposure and vulnerability factors that can help with the condition assessment of CH.

The work undertaken in the STORM project (H2020, 2016–2019) underlies the development of decision-making tools aimed at facilitating the preservation of CH in the face of the challenges raised by CC. Analysis of the deliverables made it possible to create a taxonomy of the main natural risks associated with CC, with clear indication of indices and indicators (Supplementary Materials S5).

The RESIN project (H2020, 2015–2018) studies standardized procedures to assess the vulnerability of CH, evaluating the effectiveness of adaptation and mitigation measures. These procedures serve as a guide for decisions and the creation of mitigation strategies. For the purpose of the assessment, 31 natural risks were selected, and for 18 of them, the indices and indicators for a quantitative assessment were reported (Supplementary Materials S6).

A holistic vision based on a data-driven process regarding the impact of the natural risks associated with CC on cultural heritage is provided by the European SHELTER Project (H2020, 2019–2023). Analysis of the deliverables and milestones yields a clear classification of the natural risks, developed through dedicated analysis summary sheets where essential information can be retrieved to outline the damage components associated with the following risk types: geophysical, meteorological, climatological and hydrological. For the following types, the main biophysical and climatic factors that may be considered as "determinant," as well as the specific, derived risks, were identified. To complete the analysis, summary sheets were used for each risk that cast light on the following: risk type and class, possible receivers or exposed assets, analysis scale, timeframe (forecast) and threshold value with respect to which the potential risk is to be determined (Supplementary Materials S7).

2.13. Artificial Intelligence as Research Assistant: Using Chatbot

To complete the framework's taxonomy, use was made of artificial intelligence (AI) tools, particularly the CHATGPT 3.5 OPENAI chatbot, an automatic learning model that uses deep learning techniques to generate text [13]. These machines are trained by human beings and by other machines using an enormous dataset updated to 2022. In order to determine indicators, indices and metrics of the specific risks belonging to the two risk classes (natural and anthropic), the following queries were submitted to the chatbot:

- "(SPECIFIC RISK) indices and metrics";
- "Can you specify the unity of measure of indices?"
- "(SPECIFIC RISK) indices and metrics scientific references" (Supplementary Materials S8).

Although the operation was handy for methods and timing, three actions were needed to verify the scientific reliability of the results:

- Analysis of indicators, indices and metrics provided by the chatbot through a comparison with specific scientific publications and with data contained in European Projects that have concluded or are in their performance phase;
- Verification of the references provided by the chatbot on specific databases (e.g., Scopus);
- Selection of risk indicators and indices, excluding those that refer to exposure to vulnerability.

The verification of the references provided by the chatbot that was utilized in the experiment confirmed their reliability with respect to the topic discussed, but also highlighted many possibilities for use and many problems yet to be resolved. In particular, it is emphasized that this latter phase made the methodology unsuitable for searching the parameters being studied, given the vastness of the specific risks identified. Therefore, the use of this tool is still to be confined to the preliminary research phase in order to restrict the field of investigation, especially as relates to the anthropic risk class. An additional innovation and possibility is outlined by ChatGPT 4's version 4 Turbo, in which a specific chatbot can be created which is able to develop and analyze a set of scientific publications in order to provide specific data required by the user. This operation might facilitate the research by considerably reducing the time dedicated to the literature review.

2.14. Report Analysis and Co-Creation through Expert-Based Knowledge

An additional tool used to compile the database sought the parameters that describe the specific risks in reports of national and international agencies and through the consultation of industry experts able to provide expert-based knowledge on given specific risks. Consulting the reports of International Agencies made it possible to complete or implement the taxonomy of the following specific risks:

- Anthropic risk, air pollution [14];

- Anthropic risk, soil pollution in agriculture [15];
- Anthropic risk, overtourism [16];
- Natural risk, extreme weather and climate events [17,18];
- Natural risk, fire [19];
- Natural risk, avalanche [20];
- Natural risk, flash flood [21];
- Natural risk, soil erosion [22];
- Natural risk, drought [23].

With a multidisciplinary and open-source framework having been prepared, certain risks were defined thanks to a process of co-creation exploiting the expert-based knowledge of the Sapienza University of Rome research unit, which is composed of researchers from various disciplinary sectors. Through the co-creation process, the taxonomy of the following risks was defined:

- Anthropic risk, carbonation and CO2 uptake of concrete [24];
- Anthropic risk, salt crystallization [25];
- Anthropic risk, corrosion [26,27];
- Natural risk, invasive species and biodiversity loss [28];
- Natural risk, plant pests [29];
- Natural risk, desertification [30].

2.15. Systematic Literature Review (SLR)

The SLR process was adopted, within the setting of this research, above all to identify the missing components within the framework relating to the natural and anthropic risks (Table 5) of use for a semi-quantitative and quantitative assessment, as well as, in the absence of these, to identify the methodologies and criteria employed in the assessment processes. In particular, work was conducted with respect to two research queries (RQs):

- (RQ1) Are there indices and metrics to be applied to anthropic or natural risks for quantitative assessment?
- (RQ2) What criteria (indicators) do these research articles employ for anthropic risk assessment?

Table 5. Risks to be evaluated with the SLR process.

RISKS: NATURAL	RISKS: ANTHROPIC
Severe Weather	**Pollution**
Hail	Water pollution
Environmental	**Building/Infrastructure/Industry**
Sea level rise	Mining
Silting	**Land Conversion**
Frost ground	Agriculture/forestation
Erosion	**Heritage crimes**
Coastal erosion	Vandalism
	Illicit trafficking
	Management
	Corruption
	Modern re-use
	Political
	Socio-cultural
	Loss of traditional knowledge
	Other
	War

In relation to the research queries, the SLR process followed these steps:

- Determining the keywords for building an effective research string in which the first term related to “Risk assessment” and the second term related to the specific risk, e.g., “Air Pollution.” Conversely, a possible third term, as well as synonyms, might be employed to reduce the research field by identifying the specific setting, e.g., “Cultural Heritage,” “Indicators and indices” or “Hazard modelling”;
- Defining a list of inclusion and exclusion criteria (Table 6);
- Selecting and analyzing the relevant research.

Table 6. The inclusion and exclusion criteria for the SLR.

Factor	Inclusion Criteria	Exclusion Criteria
Document Type	Peer-reviewed journal articles Peer-reviewed conference articles Primary research	Grey literature (e.g., M.Sc. and Ph.D. theses) Books and book chapters Secondary research
Year Range	Between 2013 and 2023	Before 2013 and after 2023
Ultimate context and intimate context	All kinds of cultural heritage (e.g., urban context, historical sites, historical buildings, landscape) Quantitative risk assessment for a specific hazard in generic contexts, including cultural heritage ones	Qualitative risk assessment
Relevance to the objectives	The articles address “Risk Assessment” for a specific hazard and answer one or more research query(ies)	The article discusses a specific topic not relevant to the research queries
Language	English	Limited to (English)
Research topic		Qualitative anthropic risk assessment

In order to select the database most efficient for the purposes of the research, three of the leading web search engines were compared (Figure 1):

- Rome Digital Library System of Sapienza University- SBS (Discovery Sapienza) powered by EBSCO host (https://web.uniroma1.it/sbs/discoverysapienza, accessed on 15 December 2023);
- SCOPUS peer review database (https://www.scopus.com, accessed on 15 December 2023);
- GOOGLE SCHOOLAR free web search engine that specifically searches scholarly literature and academic resources (https://scholar.google.com/, accessed on 15 December 2023).

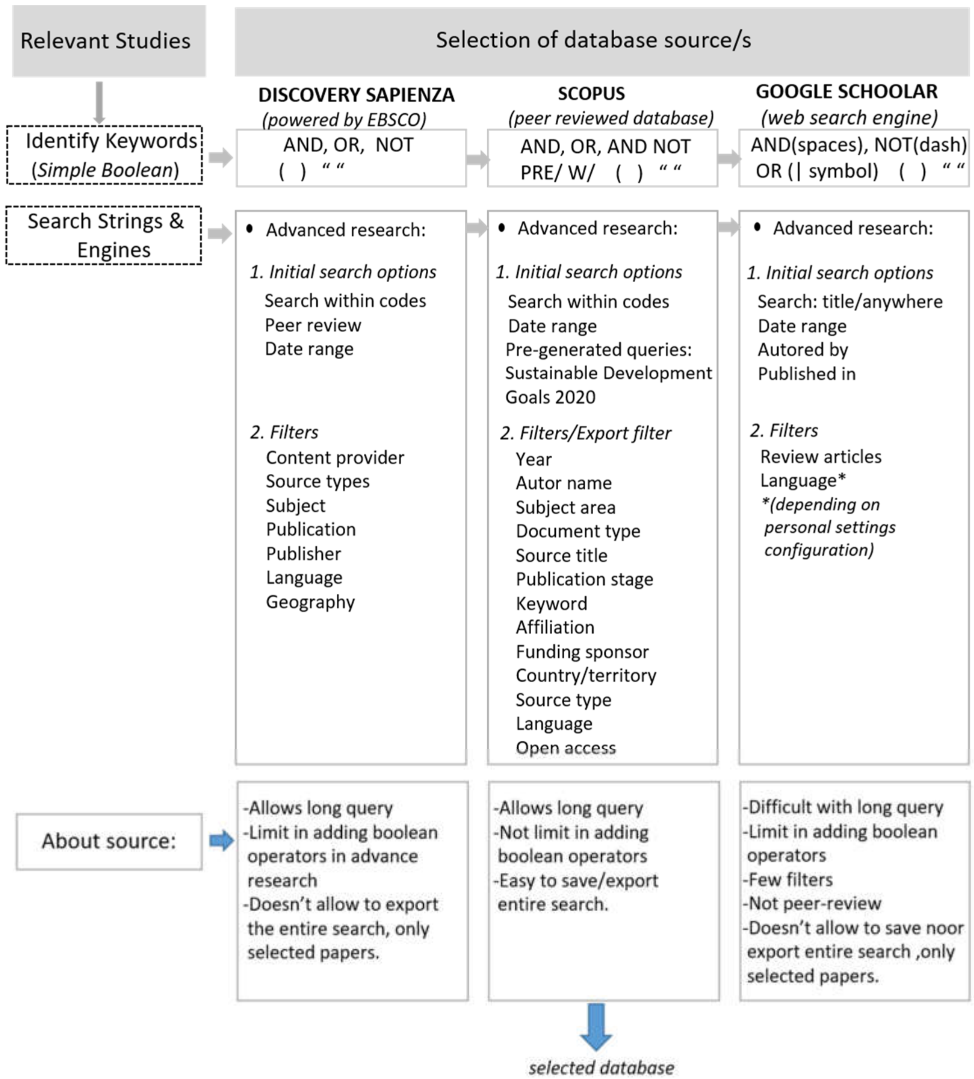

Figure 1. Database selection.

For the research in question, the decision was made to exclude the use of Google Scholar, as it has no peer review filters in the initial phases of the search, and Discovery Sapienza for problems relating to the host and the accesses, privileging the use of SCOPUS (SC). The initial results of the test were obtained by applying the TITLE-ABS-KEY codes to all the "query string" fields. The SC database did not automatically detect the duplicated elements. Starting from the initial query, the research was conducted for each specific risk indicated in the table 5. Due to the specific nature of each of the risks and in order to achieve the best results, the initial query was modified (again within the search field) by changing the order of its terms or eliminating some of them until we obtained the query suitable to yield the results (Figure 2).

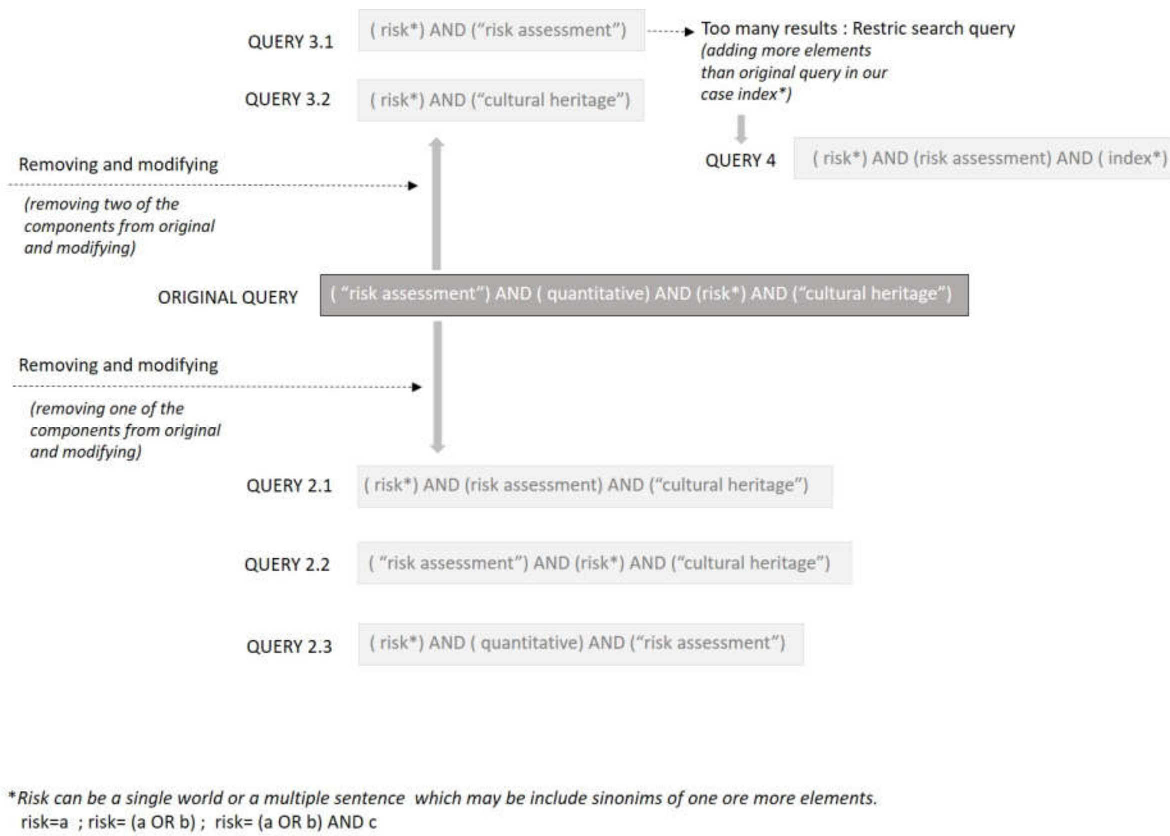

Figure 2. Adding and modifying Boolean expressions.

The selection was further restricted by applying the "Study Area" filter on SC in order to refine the research by excluding disciplinary areas that fell outside the research setting. The selected studies, divided into folders for each specific risk, were exported into the (RIS) format using the Rayyan online platform (htps://www.rayyan.ai, accessed on 5 January 2024) for screening. The software in question allows users to analyze each article by displaying the title, abstract, keywords, publisher and authors to determine the product's inclusion, exclusion or uncertainty in order to respond to the research queries.

2.15.1. Water Pollution

The SLR process for the anthropic risk relating to *Water Pollution* employed the following research query (RQ): "Risk assessment" AND "Water pollution" AND "Water Quality Index." The RQ yielded 88 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S9).

An initial analysis of the articles was carried out using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this second phase, 28 papers were selected, with respect to which six scientific articles were analyzed in relation to the description and assessment of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Water Pollution* [31–36] in order to implement it in the prepared framework.

2.15.2. Hail

The SLR process for the natural risk *Severe Weather*, relating to *Hail*, employed the following RQ: "Risk assessment" AND "Hail". This research yielded 22 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S10).

An initial analysis of the articles was carried out using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this second phase, two papers were selected for which an analytic study was performed relating to the definition and assessment of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Hail* [37,38] in order to implement it in the prepared framework.

2.15.3. Coastal Erosion

The SLR process for the natural risk *Severe Weather*, relating to *Coastal Erosion*, employed the following RQ: "Risk assessment" AND "Coastal erosion". The RQ yielded 120 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S11).

An initial analysis of the articles was carried out using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. Given the vastness of the results, the keyword "coastal erosion" was employed to focus on the specific risk. As a result of this additional screening, seven papers were selected, for which an analytic study was performed relating to the definition of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Coastal erosion* [39–45] in order to implement it in the prepared framework.

2.15.4. Siltation

The SLR process for the natural risk relating to *Siltation* employed the following RQ: "Risk assessment" AND "Siltation". The RQ yielded 12 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S12).

An initial analysis of the articles was carried out using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this additional screening, four papers were selected, for which an analytic study was performed relating to the definition of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Siltation* [46–49] in order to implement it in the prepared framework.

2.15.5. Frost Ground

The SLR process for the natural risk relating to the *Frost* phenomenon employed the following RQ: "Risk assessment" AND "Frost," which yielded 74 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S13).

An initial analysis of the articles was carried out using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this additional screening, 14 papers were selected, for which an analytic study was performed relating to the definition of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Frost* [50–62] in order to implement it in the prepared framework.

2.15.6. Sea Level Rise

The SLR process for the natural risk relating to the phenomenon *Sea level rise* employed the following RQ: "Risk assessment" AND "Sea level rise". This research yielded 449 results as research products within the previously defined inclusion and exclusion criteria. To perform an additional screening of the results, an additional keyword, "Index", was used, for which 48 scientific products were obtained (Supplementary Materials S14).

An initial analysis was performed using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this additional screening, seven papers were selected, for which an analytic study was performed relating to the definition of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Sea level rise* [63–70] in order to implement it in the prepared framework.

2.15.7. Mining

The SLR process for the natural risk relating to the phenomenon *Mining* employed the following RQ: "Risk assessment" AND "Mining hazard". The RQ yielded 11 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S15).

An initial analysis was performed using the pertinent abstracts in order to identify the presence of indicators and indices of use for a quantitative or semi-quantitative assessment of the specific risk. As a result of this additional screening, two papers were selected, for which an analytic study was performed relating to the definition of the risk. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Mining* [71,72] in order to implement it in the prepared framework.

2.15.8. Deforestation/Land Conversion

The SLR process for the natural risk relating to the phenomenon *Deforestation/land conversion* employed the following RQ: "land OR agricultural" AND "expansion" OR "land" AND "cover" OR "use" AND "changes" OR "deforestation" AND "quantitative" AND "risk assessment." The RQ yielded 56 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S16).

An initial analysis was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage. As a result of this screening, 27 papers were discarded, while for the remaining 19, an analytic study of the portion relating to the definition of the risk was performed. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Deforestation/land conversion* [73–91] in order to implement it in the prepared framework. Although CC was indicated as the main cause, the scientific community is increasingly aware of the role played by anthropic pressures on the natural ecosystems. The indicators and indices identified to measure the deforestation risk are linked mainly to characteristics of the soil and vegetation.

2.15.9. Vandalism

The SLR process for the natural risk relating to the *Vandalism* phenomenon employed the following RQ: "vandalism" AND "cultural heritage," which yielded 21 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S17).

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage. As a result of this screening, 9 papers that could not be related to the research question were discarded, while for the remaining 12, an analytic study of the portion relating to the definition of the risk was performed. In this second evaluation process, five papers were excluded. The SLR made it possible to define indicators and indices of use for a quantitative assessment of the specific risk *Vandalism* [92–98] in order to implement it in the prepared framework. Evidence of the classification of various types of vandalism that can affect cultural heritage (e.g., graffiti, ideological vandalism) was found. The only code found in the SLR was related to the Security Rating Index (SRI), while many of the indicators could be used to comprehend the level of vulnerability of cultural heritage in the event of a hazard.

2.15.10. Illicit Trafficking

The SLR process for the natural risk relating to the *Illicit trafficking* phenomenon employed the following RQ: “illicit trafficking” AND “cultural heritage”. The RQ yielded 23 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S18).

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage. As a result of this screening, 9 papers that could not be related to the research question were excluded; for the remaining 15 articles, an analytic study was performed relating to the definition of the risk. In this second evaluation process, only one paper was excluded. The SLR [99–112] made it possible to define indicators to be implemented in the framework of use for measuring the probability that this risk might take place, most of which were linked to policies for managing the cultural heritage and to natural and anthropic events (e.g., wars) that influence the management of CH. Analysis of the articles showed a growing sensitivity to illegal traffic, as demonstrated by recent initiatives by UNESCO and ICOMOS to increase the level of protection against illegal trafficking, as well as by international cooperation policies to make the specific legislation uniform. No evidence was found of the use of indices for the purposes of quantitative assessment of the specific risk.

2.15.11. Corruption

The SLR process for the natural risk relating to the *Corruption* phenomenon employed the following RQs: “corruption” AND “quantitative” AND “risk assessment” (RQ1) (Supplementary Materials S19), “corruption” AND “risk assessment” (RQ2) (Supplementary Materials S20), “corruption” AND “quantitative” AND “risk assessment” (RQ3) (Supplementary Materials S21). The RQs yielded 5, 56 and 14 results, respectively, as research products within the previously defined inclusion and exclusion criteria.

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage. As a result of this screening, 2 articles from query RQ1, 33 from query RQ2 and 7 from RQ3 that could not be related to the research questions were excluded, while 32 were subject to analysis. For the 33 selected papers, an analytic study of the portion relating to the definition of the risk was performed. In this second evaluation process, 14 papers from RQ2 and 4 from RQ3 were excluded. The SLR made it possible to define indicators and indices to be implemented in the proposed framework [113–127]. The corruption risk was distinguished into various settings, all of which were directly correlated to political instability and to ideological differences that create religious and political tensions, generating a high degree of instability. The main consequence of corruption in CH is illegal trafficking.

2.15.12. Adaptive Reuse

The SLR process for the natural risk relating to the *Adaptive reuse* phenomenon employed the following RQ: “adaptive reuse” AND “cultural heritage”. The RQ yielded 112 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S22).

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage, and 90 articles were excluded. For the 22 selected papers, an analytic study relating to the definition of the risk was performed. In this second evaluation process, seven papers were excluded. The SLR made it possible to define indicators to be implemented in the framework of use for measuring the probability that this risk might take place, most of which were linked to policies for managing the cultural heritage [128–142]. During this period of growing urbanization, CH can play a key role in achieving the goals for sustainable development, as is widely recognized by such international institutions as the United Nations (UN); the United Nations Educational, Scientific and Cultural Organization (UNESCO); and the International Council on Monuments and Sites (ICOMOS). On the other hand, the impact of conservation projects and the reuse of CH can cause damage and loss of identity. The assessment of the risks related to the reuse projects are indispensable for assessing the projects' feasibility. No evidence was found on the use of indices for the purposes of the quantitative assessment of the specific risk.

2.15.13. Traditional Knowledge Losses

The SLR process for the natural risk relating to the *Traditional Knowledge losses* phenomenon employed the following RQ: "losses" OR "losing" AND "traditional knowledge" AND "cultural heritage." The research yielded 15 results as research products within the previously defined inclusion and exclusion criteria (Supplementary Materials S23).

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage, and nine articles were excluded. For the six selected papers, an analytic study relating to the definition of the risk was performed. The SLR made it possible to define indicators to be implemented in the framework of use for measuring the probability that this risk might take place [143–148]. Traditional culture is linked to the nature and customs of small communities that have maintained an intimate bond with CH over the years. One of the main risk factors is globalization, which comprises a series of transformations in the economy, in society and in the use of the territory. Today, along with the effects of CC, this has led to the loss of a large amount of knowledge connected to both tangible (including buildings and landscapes) and intangible cultural heritage. Indices have been identified to measure the risks of loss of ethnobotanical knowledge in areas of high naturalistic interest.

2.15.14. Political Instability

The SLR process for the natural risk relating to the *Political instability* phenomenon employed the following RQs: "political instability" AND "risk assessment" (RQ1) (Supplementary Materials S24) and "political instability" AND "cultural heritage" (RQ2) (Supplementary Materials S25). The RQs yielded 31 and 9 research products, respectively, within the previously defined inclusion and exclusion criteria.

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage, and 24 articles were excluded for the RQ1 and 6 for the RQ2. For the remaining seven articles from RQ1 and three articles from RQ2, an analytic study relating to the definition of the risk was performed. In this second evaluation process, two papers from RQ1 were excluded. The SLR made it possible to define indicators to be implemented in the framework of use for measuring the probability that this risk might take place [149–154]. Political instability is the origin of other possible risks, such as wars, corruption and vandalism, that that can directly strike CH in the form of illegal traffic of assets or destruction in the most extreme cases. Political instability is listed in many articles as one of the main risks for the conservation of CH. No specific indicators to quantitatively measure the specific risk were identified, except for the Energy Security Index (ESI), which is in direct correlation with political stability.

2.15.15. War

The SLR process for the natural risk relating to the *War* phenomenon employed the following RQs: "war" AND "risk assessment" AND "cultural heritage" (RQ1) (Supplementary Materials S26) and "war" AND "quantitative" AND "risk assessment" (RQ2)

(Supplementary Materials S27). The first RQ yielded 6 results within the previously defined inclusion and exclusion criteria, while the second one yielded 16.

An initial screening was performed using the following search filters: quantitative, risk, risk assessment, index, indicators and cultural heritage. The screening process excluded three articles from RQ1 and nine articles from RQ2 that could not be correlated with the queries being searched. For the selected papers, an analytic study relating to the definition of the risk was performed. In this second evaluation process, one paper was excluded from RQ1 and two papers were excluded from RQ2. The SLR made it possible to define indicators to be implemented in the framework of use for measuring the probability that this risk might take place, but there is no evidence of the use of quantitative indices [155–161]. The analysis shows that war has a devastating impact on CH, becoming a triggering factor for such other risks as soil and water pollution; on natural ecosystems; on the economy; and on a country's political stability.

3. Results and Discussion

Open-Source Framework for Driven Reasoning in Risk Assessment

The research was developed in order to fill a gap present in the field of quantitative and semi-quantitative risk assessment. It was based on a numerical approach where the indicators must be normalized, weighted and aggregated to derive a comprehensive risk score. The state of the art on the topic does not present a unique and all-encompassing framework capable of collecting information on indicators, indices and metrics to be consulted in order to evaluate potential risks to cultural heritage through remote-sensing analysis and monitoring. To carry out a synthesis and a collection of the indices, indicators and metrics, a series of strategies was adopted, including an analysis of the main international protocols, a study of European projects for the multi-risk assessment relating to cultural heritage, consulting expert-based knowledge and conducting a systematic literature review.

Most of the analyzed protocols, except for the DRMKC, provide no classification of the risk based on the definition of the class, type, and specific risk. The DRMKC provides a "digital vocabulary" for which a clear taxonomy of the risks is outlined that facilitates understanding of these risks for users with no specialistic know-how. The tool also provides metrics for the quantitative assessment of the risks, even if, in many cases, the data are no longer available. In no case is information provided for indices and indicators of the specific risks. The analysis of the general classification proposed by the main national and international protocols was preparatory for the definition of the two main risk classes, natural and anthropic, and for the selection of the various types of risk to be associated with the respective classes within the comprehensive research framework.

An initial partial clusterization of the risks was performed by analyzing the results of the progress of the European 4CH Project, which provides a general classification of the risks based on two main macro areas: natural and anthropic risks. The classification proposed by the 4CH project was implemented with respect to the one proposed by the main international protocols that are the object of this study, as well as in relation to the specific research purposes.

In order to complete the taxonomy and provide a framework that is as comprehensive as possible, two main strategies were adopted: the assessment of the projects financed by the EU framework programs (2013–2023) and literature review and co-creation of the database with expert-based knowledge.

The analysis of the major funded European projects taken into consideration here (15 in total) shows how the setting of the risks associated with natural phenomena, for the most part those linked to CC, is the one most investigated, and there is a solid classification of the risks and a complete description of the associated phenomena in both qualitative and quantitative terms. For the latter, the taxonomy relating to indicators and indices described above was employed as a starting point for developing the framework. Lastly, in light of the investigation that was performed, there are no funded projects aimed at more deeply analyzing the anthropic or the natural risks associated with CH which would aim to assess possible interactions between the two components.

The framework was completed through expert-based knowledge due to the fact that the research group was composed of scientists from different disciplines, as well as using a systematic literature review (Supplementary Materials S28). The processes were focused on finding the missing information on specific risks that would be useful to complete the framework in a most comprehensive way.

Using the methodology described above made it possible to develop an open-source framework based on a reasoned classification of risks that presents data relating to indicators, indices and metrics whose consultation facilitates the quantitative or semi-quantitative assessment of the natural and anthropic risks that may have repercussions on CH, from architectural heritage to the natural landscape, in a multi-scale dimension.

Publicly available datasets were created in this study. These data can be found here: [https://docs.google.com/spreadsheets/d/1bg9UyY8tctCj3eFlao3GGA-zHk31tiLhTpfVFSl_3EFs/edit?usp=sharing] (accessed on 1 February 2024).

4. Conclusions

The framework collects the main natural and anthropic risks related to tangible outdoor heritage with the related taxonomy in a single repository. It is an open document which can be implemented over time through expert knowledge, and can be consulted by researchers, professionals and public administrations preparing for risk assessments in the CH sector. The proposed model will be implemented with the exposure and vulnerability risk components, which characterize the various risks in relation to the applicative context (site-based evaluation process) in order to provide a complete assessment framework. The framework's structure permits additional specializations in greater thematic depth should it be necessary to update the list of specific risks.

The current state of ongoing PNRR research, which has identified, quantified and evaluated some of the major risks relating to CH due to CC, extrapolated indices and measurement indicators, is allowing for the development of innovative methodological knowledge models aimed at defining exposure and vulnerability of the built environment and the definition of fundamental enabling technologies (KET). This represents, within the technological culture of the project, a priority research direction which will be needed in order to intervene in the processes of adaptation and control of phenomena due to CC. In particular, the framework is preparatory for the development of a multi-criteria matrix (MCMA) which, along with the use of modeling implemented through Geographic Information Systems (GIS), will make it possible to rapidly model and simulate intervention scenarios. It will also allow for their progressive validity to be predicted in the short, medium and long term in concrete case studies. The development of MCMA is still an area of applied research that is in progress; it is difficult and laborious, and one of the most delicate steps to reflect and work on in the coming years is the correct selection of input data and values to be considered. In this context, the data collected by remote sensing or satellite images, while on the one hand representing a strategic asset for providing a real image of the phenomena and for predicting their development over time, on the other hand can prove problematic due to excess information or lack of homogeneity of data. This is a complex process that requires the technologist to have an open dialogue with scholars from different disciplines who operate in CH and the territory. It represents a notable enrichment of the technological discipline itself and possibly opens up multiple fascinating fields of investigation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/heritage7060140/s1, Supplementary Materials S1: ProteCHt2save summary sheet, Supplementary Materials S2: STRENCH summary sheet, Supplementary Materials S3: Prothego summary sheet, Supplementary Materials S4: Heracles summary sheet, Supplementary Materials S5: Storm summary sheet, Supplementary Materials S6: Resin summary sheet, Supplementary Materials S7: Shelter summary sheet, Supplementary Materials S8: Hazard taxonomy through AI chatbot, Supplementary Materials S9: Results of SLR on water pollution risk, Supplementary Materials S10: Results of SLR on hail risk, Supplementary Materials S11: Results of SLR on coastal erosion risk, Supplementary Materials S12: Results of SLR on siltation risk, Supplementary Materials S13: Results of SLR on frost ground risk, Supplementary Materials S14: Results of SLR on sea-level rise risk, Supplementary Materials S15: Results of SLR on mining risk, Supplementary Materials S16: Results of SLR on deforestation/land conversion risk, Supplementary Materials S17: Results of SLR on vandalism risk RQ1, Supplementary Materials S18: Results of SLR on vandalism risk RQ2, Supplementary Materials S19: Results of SLR on Illicit trafficking risk, Supplementary Materials S20: Results of SLR on corruption risk RQ1, Supplementary Materials S21: Results of SLR on corruption risk RQ2, Supplementary Materials S22: Results of SLR on corruption risk RQ3, Supplementary Materials S23: Results of SLR on adaptive reuse risk, Supplementary Materials S24: Results of SLR on Traditional Knowledge losses risk, Supplementary Materials S25: Results of SLR on political instability risk RQ1, Supplementary Materials S26: Results of SLR on political instability risk RQ2, Supplementary Materials S27: Results of SLR on war risk, Supplementary Materials S28: PRISMA chart flow for SLR.

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Conflicts of Interest: The authors declare no conflicts of interest.

Note

1. Research Project PE05-CHANGES-SPOKE Protection and Conservation of Cultural Heritage against Climate Changes, Natural and Anthropic Risks, Thematic line: n. 3 "Multi-source digital data and metadata related to environment and historic landscape", P.I. Prof. Alessandra Battisti.
2. The 4CH project deals with the study of methods, procedures, and tools of use for creating a center of expertise capable of dialoguing with national cultural institutions, providing support and consulting as concerns the protection of the cultural heritage in relation to natural and anthropic risks.

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