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AN ADVANCED KNOWLEDGE BASE PLATFORM AND A DECISION SUPPORT SYSTEM FOR SAFEGUARDING CULTURAL HERITAGE

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EXTENDED ABSTRACT

La piattaforma TRIQUETRA, *Knowledge Base Platform* (KBP) è un componente chiave del Sistema di Supporto Decisionale TRIQUETRA (DSS), progettata per facilitare il monitoraggio e la protezione dei siti del Patrimonio Culturale (CH).

La KBP è composta da due elementi distinti: un *database* completo contenente tutti i risultati derivanti dalla revisione della letteratura condotta nel contesto del progetto, e una piattaforma *WebGIS* che integra e visualizza dati geospaziali relativi ai siti pilota del CH del progetto (cambiamenti climatici, geologia, storia, caratteristiche specifiche del sito, rischi e misure di mitigazione). Questi siti includono Aegina (GR), Choirokoitia (CY), Epidaurus (GR), Kalapodi (GR), Les Argilliez (SUI), Roseninsel (DE), Smuszewo (PL) e Ventotene (IT).

Servendo come un archivio elettronico, la KBP offre agli utenti l'accesso a un ampio spettro di dati relativi al patrimonio culturale, fonti bibliografiche e strategie di mitigazione, insieme a strumenti avanzati di filtraggio delle ricerche per supportare un recupero efficiente delle informazioni rilevanti.

L'obiettivo principale della KBP è di fungere da *repository* completo e strumento di visualizzazione, integrando tutti i dati condivisi all'interno del progetto TRIQUETRA, in un ambiente unificato e interattivo. Seguendo standard riconosciuti a livello internazionale, tra cui quelli del *Open Geospatial Consortium* (OGC) e del *Framework Infrastructure for Spatial Information in the European Community* (INSPIRE), la KBP garantisce interoperabilità, coerenza e una rappresentazione di alta qualità dei dati tra i vari siti del patrimonio culturale.

Caratteristica fondamentale della KBP è la sua capacità di sintetizzare e analizzare diversi *set* di dati associati ai siti pilota del CH. Attraverso la combinazione di dati geospaziali, ambientali, storici e di valutazione del rischio, la piattaforma costruisce un cubo di dati multidimensionale, una struttura robusta che permette di rappresentare, esplorare e analizzare in modo efficiente informazioni complesse su più livelli, tra cui tempo, posizione geografica, fattori climatici, caratteristiche strutturali e dei materiali, rischi e impatti, ecc.

L'approccio del cubo di dati consente di correlare dinamicamente variabili diverse, permettendo agli utenti finali e agli *stakeholders* di estrarre intuizioni significative e sviluppare strategie di conservazione basate sui dati stessi.

TRIQUETRA mira a creare un Sistema di Supporto Decisionale (DSS**)** solido, basato su evidenze, con l'obiettivo di supportare la valutazione del rischio e le strategie di mitigazione degli impatti dei cambiamenti climatici sui monumenti del patrimonio culturale. La *toolbox* del DSS comprende due moduli principali: il modulo di Quantificazione della Severità del Rischio e il modulo di Selezione e Ottimizzazione delle Misure di Mitigazione. Il primo mira a valutare l'esposizione al rischio e la sua gravità, il secondo è progettato per proporre misure di mitigazione personalizzate in base alle condizioni e vulnerabilità specifiche identificate durante il progetto per ogni sito pilota del CH.

Il Modulo di Selezione e Ottimizzazione delle Misure di Mitigazione è una componente fondamentale del DSS, che integra la KBP offrendo un archivio curato di misure di mitigazione specifiche per ogni sito, sviluppate nel contesto del progetto**.**

Consolidando strumenti di valutazione del rischio, misure di mitigazione e letteratura in un'unica piattaforma interattiva, il Sistema di Supporto Decisionale (DSS) offre ai professionisti del patrimonio culturale, e agli *stakeholders* rilevanti, le informazioni più appropriate. In generale, questo modulo mira a supportare ricerche avanzate su ciascun sito pilota del patrimonio culturale, contribuendo a migliorare il monitoraggio, sviluppare strategie di conservazione su misura e attuare efficaci misure di mitigazione del rischio.

ABSTRACT

The TRIQUETRA KBP, a core component of the TRIQUETRA DSS, comprises two key elements: a comprehensive database housing all outputs from the project's literature review and a WebGIS platform integrating data from pilot CH sites such as Aegina, Choirokoitia, Epidaurus, Kalapodi, Les Argilliez, Roseninsel, Smuszewo, and Ventotene. As a dynamic electronic repository, the KBP offers extensive data and advanced search tools for efficient information retrieval.

The TRIQUETRA project aims to develop a robust, evidence-based DSS to mitigate the impacts of climate change on CH monuments. The DSS toolbox includes the Risk Severity Quantification module and the Mitigation Measure Selection and Optimisation module. The latter provides tailored mitigation measures for each pilot site, offering tangible recommendations for risk mitigation through a multicriteria search feature that allows filtering based on cost, timeframe, and topological effects (Ioannidis *et alii*, 2024).

Designed for adaptability and scalability, the module leverages the KBP database to propose solutions by assessing site compatibility with others facing similar hazards. Supporting advanced research, it facilitates informed decision-making, enhanced monitoring, and tailored preservation strategies, contributing to the long-term protection of CH sites.

Keywords: *cultural heritage, decision support system, preservation, mitigation measures, climate change, knowledge base platform, topological effect, database, protection measures, tailored risk mitigation strategies, geospatial map, WebGIS*

INTRODUCTION

In this ever-changing technological landscape, efficient data management as well as accessibility to organisational knowledge are fundamental to fostering innovation, optimising operations and enhancing strategic decision-making. This kind of capabilities is particularly crucial in the field of CH management, protection and preservation, where dealing with complex datasets is key to developing evidence-based strategies for safeguarding CH sites against various hazards, ranging from climate change (CC) and natural disasters to human activities.

As a result, KBPs emerge as pivotal tools for data integration and visualisation in a series of industries and fields such as cultural heritage, health, transportation, agriculture etc., feeding DSS solutions that serve as key strategies for enabling data-driven decision-making leading to the holistic approach of the topic at hand.

In the case of KBPs, PopHR is a distinctive example of a KBP for population health data, providing users with valuable insights into public health trends (Shaban-Nejad *et alii*, 2016), while PDSIDES supports the development and optimisation of engineering systems providing knowledge regarding the design of such systems (Ming *et alii*, 2018). Furthermore, various emerging commercial KBPs provide stakeholders with powerful tools for data fusion, management and sharing, underlining the importance of digital repositories in a series of sectors.

Concurrently, WebGIS technology has evolved consistently, becoming an integral tool for a diverse variety of stakeholders, providing capabilities which include interactive accessibility to geospatial data, real-time data integration and advanced GIS-based analysis tools. The application of WebGIS across various domains has been the objective of several studies in recent years, including the development of a WebGIS for the holistic monitoring of critical infrastructures combining earth observation and in-situ data for the area of West Peloponnese, Greece in the context of PROION project (Magkoufis *et alii*, 2022), as well as the People&Fire WebGIS for the representation of the assessment of wildfire risk (Mileu *et alii*, 2024).

KBPs and WebGIS play a crucial role in the development of robust DSS solutions, providing them with all relevant data in order to enable informed decision-making and strategic planning, with notable applications such as in clinical diagnostics for assisting medical professionals in evaluating patient symptoms and monitoring disease progression (Kawamoto *et alii*, 2005), or in disaster management, enabling real-time disaster response coordination delivering an integrating framework for emergency preparedness (Chen *et alii*, 20008).

This manuscript aims to provide an overview of the TRIQUETRA KBP which serves as an electronic repository providing all relevant data to the TRIQUETRA DSS, which is also presented in the context of this paper. In particular, the Mitigation Measure Selection and Optimisation module and its relation to the KBP is presented, detailing its design, function and current contents.

GENERAL DESCRIPTION OF THE TRIQUETRA KBP

The TRIQUETRA KBP is a comprehensive electronic repository incorporating a variety of advanced search functionalities enabling discoverability, organising and categorisation of the project data.

The architecture of the KBP is built around two distinct components: the Bibliography component and the WebGIS component. These two key applications of the platform serve as hub containing all the data and information related to the pilot CH sites of the project (Fig. 1).

Specifically, a wide range of scientific reports, research papers and relevant literature are listed in the Bibliography component, as a result of the thorough literature review conducted through the first year of the project. In the context of this review, a classification system was developed based on specific criteria including title, country, type of risk, monitoring methods, mitigation measures and relevant time periods for each CH site that is listed.

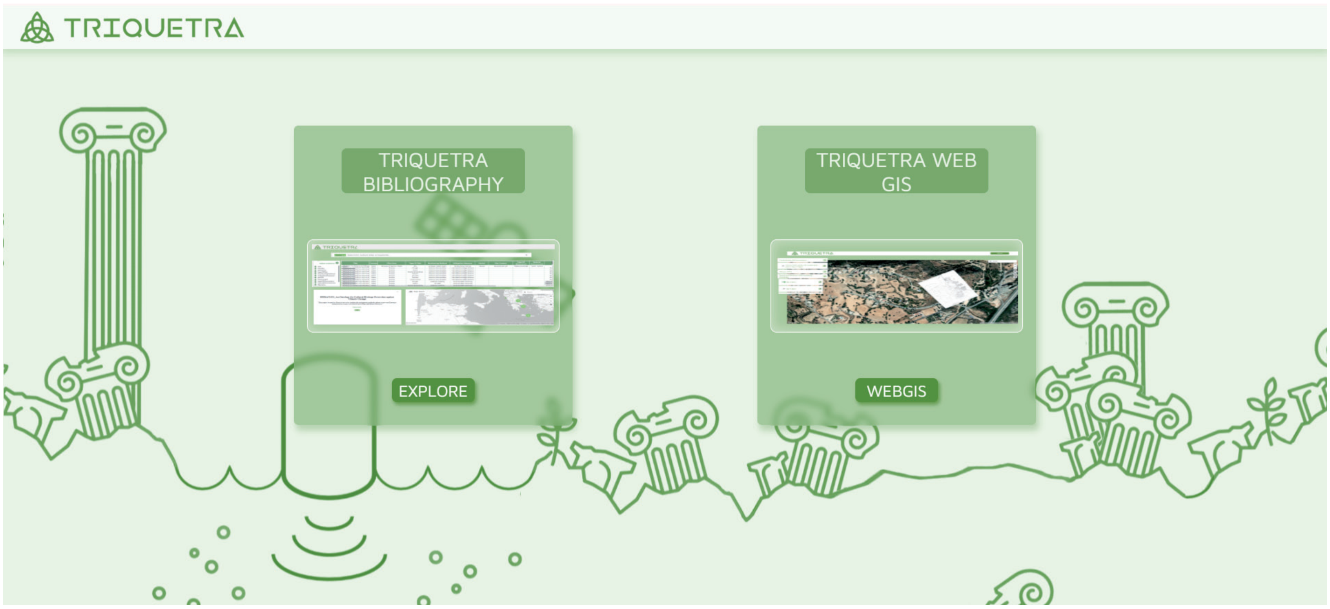

Fig. 1 - The homepage of the TRIQUETRA KBP depicting the two components

Concurrently, the WebGIS component hosts all geospatial datasets that are related to the pilot CH sites of TRIQUETRA, compiling the outcomes of the tasks of the project. The WebGIS component also seamlessly integrates EU web services, such as Copernicus Services and on-site observation open services.

In order to ensure data integration and interoperability, the KBP leverages open OGC (Open Geospatial Consortium) web services, adhering to standardised frameworks for data exchange, such as Web Map Service (WMS) for delivering map layers as raster images and Web Feature Service (WFS) for the provision of vector-based geospatial datasets.

The Web Server acts as a gateway that processes client requests, e.g. inquiries for specific geospatial datasets that are stored in the KBP. These requests are redirected to an open-source server, responsible for handling and generating the appropriate response, which is then conveyed back to the Web Server. In turn, the Web Servers returns the results to the client. This type of streamlined communication enables optimal system performance, ensuring the simultaneous and efficient management of multiple client requests.

For each pilot CH site, a classification process resembling the one conducted during the literature review process was carried out, based on the type and characteristics of available data. These include diverse datasets, such as historical and archaeological records, topographic data (such as aerial photographs, orthophotos, DEMs and point clouds), geophysical data, climatology data etc. (Tab. 1).

GENERAL DESCRIPTION OF THE TRIQUETRA DSS

Complementing the TRIQUETRA KBP, the TRIQUETRA DSS is designed to provide a holistic approach to managing and safeguarding the pilot CH sites. At the core of the DSS is a user-centred approach, where potential users, stakeholders and policymakers created user stories which defined the expected functionalities of the DSS. These scenarios cover the potential needs and interactions of all relevant stakeholders with the platform, enabling the system to leverage knowledge and data from the adjacent KBP.

The concept of the DSS is to integrate project outputs such as risk identification, assessment and quantification, in order to

Level 1	Level 2	Level 3
Aerial Imagery	(.jpg)	
	(.png)	
	(.tiff)	
AOI	(.shp)	
Elevation	DEM	(.jpg)
		(.png)
	Ortho	(.tiff)
Geo-environmental Data	Administration	(.shp)
	Basin	
	Chemicals	
	Climatology	
	Geology	
	Hydrology	
	Topography	
Geophysics Figures	(.jpg)	
	(.tiff)	
Site Plans	Excavation Plans	(.jpg)
		(.png)
	Overview Plans	(.shp)
		(.tiff)

Tab. 1 - Structure of layer folders and data types of the WebGIS component

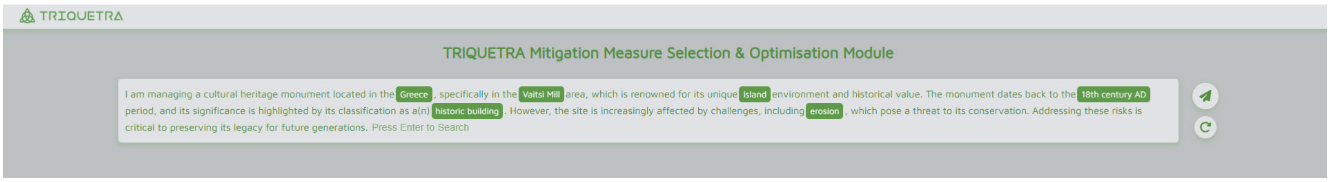

Fig. 2 - Example of the scenario-based user interface

determine the level to which the pilot CH sites are threatened, and provide a list of tailored mitigation measures for their protection.

A user story is a brief, structured description of a software feature or requirement, as defined from the perspective of the potential user and typically follows the format:

"As a type of user, I want to some goal so that some reason." (LUCASSEN *et alii*, 2016).

As soon as the user stories are gathered, they are classified based on different criteria depending on the needs of relevant stakeholders. Afterwards, the TRIQUETRA DSS is designed to search and analyse the literature contained in the Bibliography component of the KBP, based on user-defined keywords regarding a specific CH site.

In the context of the Mitigation Measure Selection and Optimisation module, the DSS follows a specific pipeline structured in the form of storytelling, where the user provides detailed information about the monument at hand, including the potential hazards it faces, and in real-time, the module retrieves and suggests mitigation measures that have been successfully applied in similar cases encountered in the Bibliography component of the KBP.

The scenario-based interface guides the user through structured input fields, which are either manually typed or selected from dropdown menus regarding the following parameters: (a) country, (b) pilot area, (c) natural environment, (d) historical period, (e) type of monument and (f) type of risk as shown in Figure 2.

Each of the aforementioned categories holds a different level of significance in the mitigation measure selection process, meaning they contribute with a different weight to the final recommendation suggested by the module. Taking into account the requirements of the project and the user stories provided by relevant stakeholders, the type of monument and the type of risk were given the highest priority. Next, the natural environment in which the monument is located is considered, as it plays a key role in the determination of potential hazards and vulnerabilities. Finally, the historical period, country and specific location of the monument are taken into consideration, with the latter limiting the results to the literature that explicitly mentions the monument of interest, considering the fact that the recommended mitigation measures heavily rely on the degree of similarity between the CH site of interest and documented examples in the KBP.

The user can then refine and optimise the results even further, setting a series of parameters such as the cost, implementation timeframe, area of application, topological effect and risk score range, as outlined in Table 2.

Optimisation parameters	Values Range
Cost	0-10 (low to high)
Implementation Timeframe	0-10 (short-term to long-term)
Area of Application	0-10 (limited to broad)
Topological Effect	0-10 (minimal to high)
Risk Score	0-100%

Tab. 2 - User-defined optimisation parameters

These values represent a qualitative assessment of each proposed mitigation measure, based on relevant literature where these measures have been implemented and evaluated.

To illustrate the functionality of the module, an example user story is presented. In this user story, the CH site of interest is located in Portugal, namely the Grilos Church, a baroque church which is part of an urban landscape in Porto and is threatened by the risk of flooding. For this user story, some of the proposed mitigation measures include (*i*) adaptation plans, (*ii*) disaster resilience planning and (*iii*) coastal dunes. The score of compliance of each of the proposed measure is highly influenced by the cataloguing of paper keywords, which derive from the literature review conducted during the development phase of the KBP. Thus, if the specific CH site of interest is directly referenced in a paper, the system typically assigns a 100% compliance score to the mitigation measures referenced in the paper, since they have already been applied to that CH site.

DESIGN AND IMPLEMENTATION

The TRIQUETRA KBP adopts a dual-front-end architectural approach, separating the User Interface (UI) into two distinct components: the Bibliography and the WebGIS, as mentioned before. This design choice is driven by the need to accommodate diverse user requirements in data interpretation and visualisation, ensuring an optimal user experience, while also considering that each component manages different types of datasets, which correspond to different types of activities.

Similarly, the UI of the Mitigation Measure Selection and Optimisation module of the DSS aims to provide optimal performance and scalability, leveraging the advanced capabilities of the React.js framework, which enables the interconnecting components approach of the platform for efficient rendering and scalability.

The primary goal of the front-end design is to ensure seamless integration of the module with the pre-existing TRIQUETRA components, namely the KBP, while maintaining alignment with the overall design vision. Moreover, performance optimisation techniques are implemented to improve interaction fluidity and system efficiency, focusing on intuitive navigation, accessibility and user engagement, fully embracing the user-centred design approach.

Bibliography component

In the Bibliography component, data is displayed in a tabular format, similar to traditional databases, ensuring a structured and intuitive presentation. The user is able to interact with the data through table management features, including filtering options and sorting functionalities, as well as through an integrated map tool. The map tool serves as an alternative, more visual search option, dynamically updating both the map display and the tabular data based on the current map extent defined by the user.

A data table is an effective method for analysing and presenting large datasets with a variety of different fields and entries, providing a clear representation of information, while also conveying the scale and diversity of the dataset.

The Bibliography component integrates a tabular view of the data combined with an interactive map, offering a detailed description of each paper and its variations, while also categorising them based on their geographical relevance as shown in Figure 3.

WebGIS component

The WebGIS module utilises MapBox GL to visualise geospatial data and layers collected and generated throughout the project, rendering them in a 3D environment with advanced visualisation capabilities. Compared to other alternatives, MapBox GL offers a significantly lower network bandwidth requirement, enhancing performance and accessibility (Zunino *et alii*, 2020).

To ensure intuitive navigation, the platform organises geospatial data into nested components, simplifying navigation among layers and point clouds, while preserving data integrity and consistency.

The WebGIS component incorporates the same navigation tools as the Bibliography component, including pan, zoom, tilt and search functions, while also providing additional functionalities such as the ability to keep multiple layers activated simultaneously and manage them collectively, customise map styles based on user-needs and visualise 3D representations of CH sites through point cloud data (Figure 4).

DSS calculation engine

The Mitigation Measure Selection and Optimisation module basically comprises of a two-step process, namely a weighted-matching scoring algorithm which generates a "similarity confidence score" fir each bibliographic entry-based n user-provided keywords. The second is a filtering algorithm that further refines and optimises the retrieved entries according to user-defined criteria, ensuring more relevant and precise results to user-needs.

The UI of the DSS module is designed around the concept of interactive digital storytelling, allowing users to create their own scenario with guided assistance from the module itself.

Users are encouraged to engage with the module from the moment they initiate the system, ensuring an interactive experience, constructing their own story choosing or typing the different types of keywords the module requires to activate the query process as presented in Figure 5.

The module then generates a ranked list of proposed mitigation measures, evaluated based on the criteria previously mentioned. The ranking follows a low-to-high classification

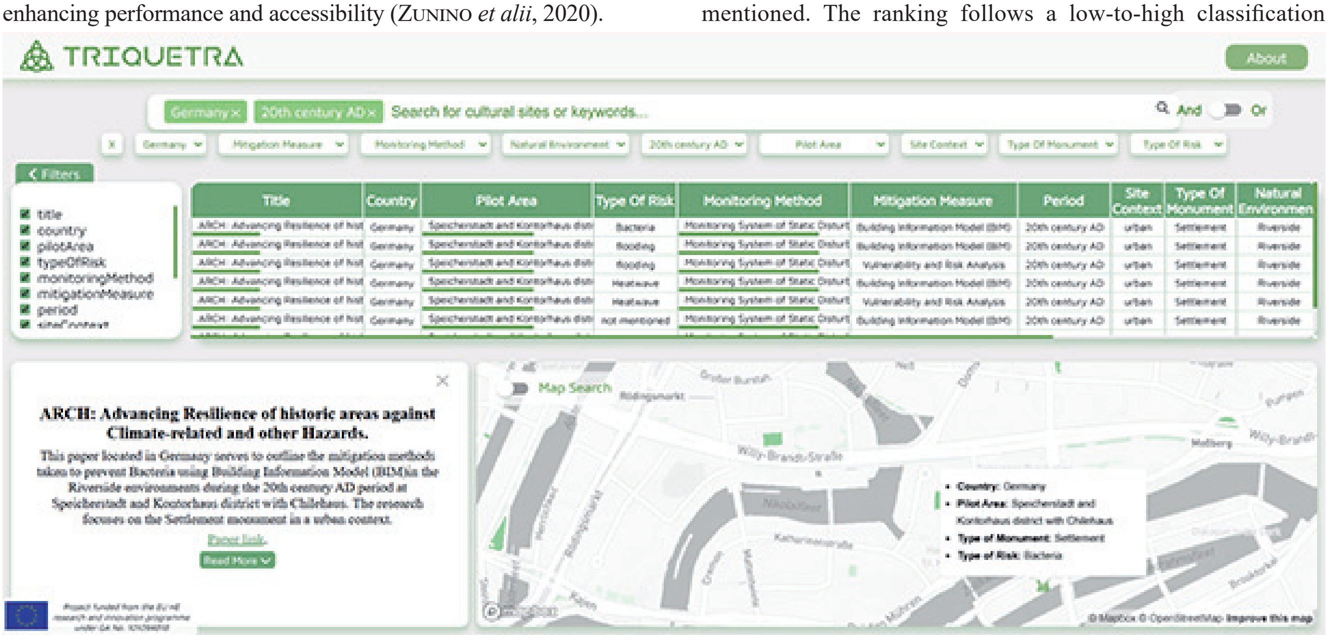

Fig. 3 - The UI of the Bibliography component of the KBP

Fig. 4 - The UI of the WebGIS component of the KBP

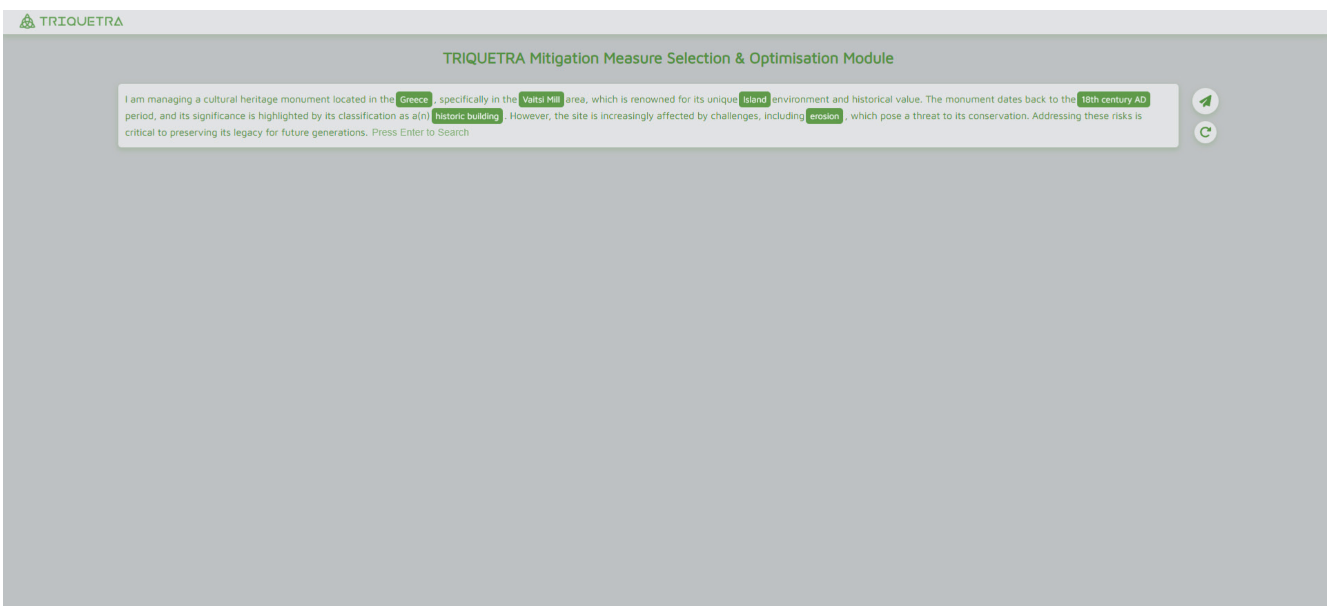

Fig. 5 - The process of creating a "story"

system, indicating the proximity of the characteristics of the CH site of interest to the CH site referenced in the literature. This proximity is visually represented in the upper right corner of each mitigation measure card using a colour scale (green-yellow-red) indicating the level of similarity.

Additionally, each mitigation measure card provides key details referring to the monitoring method applied in the referenced study and the identification number of the corresponding publication, based on the literature review conducted in the context of the KBP (Figure 6).

Finally, the user can filter the mitigation measures proposed by the module, in order to get an optimised suggestion based on their needs, using the corresponding filtering tools in the menu located above the list of the results.

CONCLUSIONS

The monitoring, preservation and risk assessment of CH sites present a multidimensional challenge, requiring a systematic, data-driven approach for informed decision-making, allowing stakeholders to manage complex datasets,

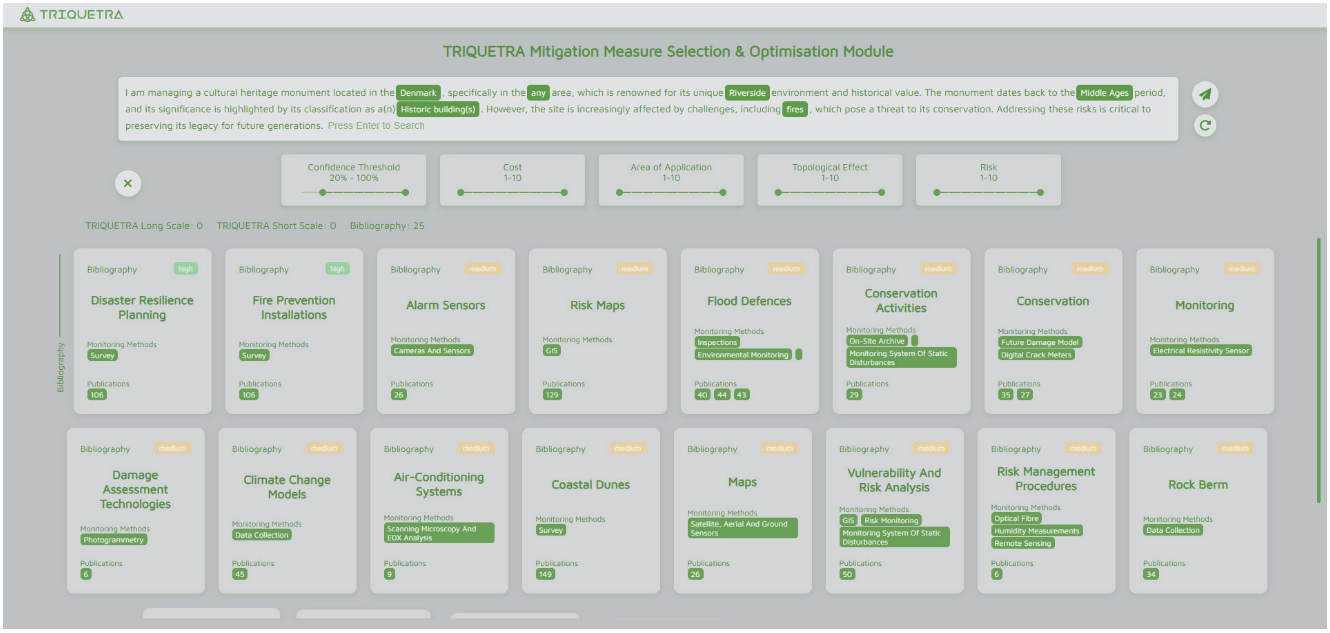

Fig. 6 - An example of the list of proposed mitigation measures

assess risks and develop holistic conservation strategies.

Developed within the TRIQUETRA project, the KBP and the DSS along with its modules, serve as comprehensive tools towards this direction. On one hand, the KBP represents a comprehensive digital repository, consolidating up-to-date knowledge on CH sites based on literature review, but also on the pilot CH sites of the project. On the other hand, the DSS and its modules actively facilitate evidence-based decision-making, integrating geospatial analysis tools, risk assessment methodologies and mitigation strategies.

Ultimately, both tools are set to play a pivotal role in the systematic and strategic management of CH sites, fostering a sustainable technology-driven approach to CH safeguarding, by supporting collaborative decision-making through the integration of a wide variety of datasets.

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