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Fighting Illicit Trafficking of Cultural Goods—The ENIGMA Project

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Abstract: Cultural heritage is a testimony of past human activity, and, as such, cultural objects exhibit great variety in their nature, size, and complexity, from small artefacts and museum items to cultural landscapes, and from historic buildings and ancient monuments to city centers and archaeological sites. Cultural heritage around the globe suffers from wars, natural disasters, and human negligence. More specifically, cultural goods and artefacts are put at risk through several anthropogenic actions: Anthropogenic threats take various dimensions, ranging from theft from museums, private collections, and religious buildings, smuggling of and illicit trade in cultural goods, the irremediable looting and demolition of archaeological sites by clandestine excavators, or simply neglect of heritage sites. Illicit trading has expanded dramatically recently, especially in areas affected by armed conflicts and natural disasters, either aiming at destroying collective memory and dismembering people's identity or mostly motivated by the pursuit of profit. Moreover, the illicit trafficking of cultural goods contributes to the funding of terrorism, organized crime, and money laundering. The mission of ENIGMA, a EUR 4 million EU funded project, is to achieve excellence in the protection of cultural goods and artefacts from man-made threats by contributing to their identification, traceability, and provenance research, as well as by safeguarding and monitoring endangered heritage sites. ENIGMA objectives are designed to help the involved stakeholders better respond to this complex and multi-dimensional problem and leverage active collaboration by fostering and enabling interlinking of databases, and evidence-based deployment of preventative measures.

Keywords: cultural heritage; illicit trafficking; remote sensing; close-range photogrammetry; 3D modelling; decision support systems

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1. Introduction

It has been estimated [1] that 140,000–700,000 antiquities are transacted in Europe annually, with a total value of EUR 64–318 million [2]. It is impossible to distinguish licit from illicit transactions, as there is no way of establishing their authenticity or trading histories.

Generally, the bulk of the trade is made up of goods that are small in size and easy to smuggle, such as jewelry and coins. Coins in particular account for a disproportionate share of items seized. The World Customs Organization (WCO) reports [3] that the cultural goods most often seized are antiquities (such as inscriptions, coins, small seals, and the like), followed by archives of sound, film, and photographs, household items, and archaeological items.

Customs officers identified and recovered 9399 artefacts (~30% were coins) in 2019 and 22,462 artefacts (~50% were coins) in 2018. In 2016, 69% of seized items were smaller objects, such as antiquities (inscriptions, coins, seals and the like) and historical items (armor, arms). In 2015, 44,235 items were seized, and of those, 98% were coins.

In fighting illicit trafficking of cultural goods, the European Commission cooperates closely with a number of organizations to strengthen the regulatory environment [4]. These organizations include UNESCO, the International Criminal Police Organization (INTERPOL), the International Council of Museums (ICOM), the World Customs Organization (WCO), the International Institute for the Unification of Private Law (UNIDROIT), the United Nations Office for Drugs and Crime (UNODC) and the Council of Europe.

From this cooperation, initiatives to combat trafficking of antiquities have successfully been established and developed, e.g.,: ICOM Red List [5], Archeo [6], INTERPOL database of Stolen Works of Art [7], Art Loss Register [8], Psyche [9], ICOM Code of Ethics [10], EU CULTNET [11].

In addition, armed conflicts impose different types of damage to cultural heritage, such as [12]: (1) Deterioration and weathering due to lack of the needed sources and/or accessibility to maintain cultural properties; (2) Lack of military awareness or collateral damage. An example of this is the destruction of the minaret of the Umayyad Mosque in Aleppo after it became a base for the regime's snipers; (3) Intentional targeting by groups intending to damage the racial, national, or religious symbols of others or to impose specific ideologies. This is the case of the destruction of shrines by the Islamic fundamentalist group ISIS in both of Iraq and Syria; (4) Illicit excavations and trade of antiquities by organized networks, which often causes irreversible damage to the material culture, as in the case of the archaeological sites of southern Iraq and Syria; (5) Deliberate use by people to survive the harsh conditions of war. For example, the Roman tombs of the dead cities of northern Syria are used as shelters by families who lost their houses in the conflict.

ENIGMA (DOI: 10.3030/101094237) brings together 12 partners from six different European Union (EU) member states and one European Free Trade Association (EFTA) country (Switzerland). It represents a wide range of disciplines, experience and expertise, which are all necessary to reach the key objectives of this project, as detailed below:

- Two universities, bringing academic and research experience in the field of cultural heritage (CH) innovation and research;
- One center of excellence for Earth observation (EO), bringing capacity and research experience in the field of Earth observation;
- One research institute, bringing capacity and research experience in the field of trafficking of cultural heritage, from a technical, societal, legal, and psychological perspective;
- Five small and medium-sized enterprises (SMEs), bringing research experience in the field of information and communications technology (ICT);
- Two national agencies for museums, conservation practice and cultural heritage, bringing experience in user requirements, co-creation and co-development of procedures, demonstrating the benefits of ENIGMA and contributing to the development of shared digital facilities. They also provide the CH data to be used in the pilots;
- One law enforcement authority (LEA), bringing research experience in the field of law enforcement and, as an end-user, will be involved in the training and piloting activities. It also provides the knowledge and data on current databases and procedures used by LEAs.

2. The Challenges

The past decades have seen the illicit trade in antiquities increasingly move online for all items but the most exclusive. The internet has lowered barriers to entry for would-be sellers. It has also made smuggled antiquities accessible to an exponentially larger group, resulting in a larger demand for especially small, inexpensive objects that can be easily shipped. This shift to online trade seems to have led to an increase in the number of small items traded.

Currently, there are technological tools in use by relevant European agencies and organizations, such as: X-ray scanners, databases, web crawling and scraping applications, image recognition tools using machine learning (ML) or other artificial intelligence (AI) techniques, communication platforms, smartphone applications (that allow the general public to record and share specific information about crimes related to cultural goods), social network analysis applications, crowdsourcing, metadata analysis, and messaging services.

However, the most illicitly traded antiquities are unknown and undocumented items, which significantly limits the usefulness of existing technological solutions. While some existing technologies can help with identification of cultural goods (CGs) that are known to be stolen, they do not substantially assist in the tagging and tracking of looted and undocumented items. Thus, human expertise and investigative skills remain the mainstream criminal justice responses, which obviously are far behind what the current technologies may offer.

3. Opportunities and Technology Limitations

There are potentially innovative technologies that have not yet been used or not widely exploited until now, such as:

- Satellite imagery analysis and remote sensing and monitoring: These technologies allow change in heritage sites, such as looters' holes or site destruction, to be detected by image recognition applications. Although these technologies do not directly address the trafficking aspects of the illicit trade in cultural goods, they may allow for interventions at certain sites towards protection and could alert authorities that cultural goods from certain sites and cultures may be about to appear on the market. They are also useful in detecting large-scale site destruction during times of extreme armed conflicts.
- Three-dimensional (3D) digital scanning technology: Because 3D scanning is a type of recording that is non-invasive, it has been widely adopted by the heritage preservation community for recording heritage objects and sites, particularly those that face various forms of threats. While there is an ongoing debate in this sector about issues related to intellectual property rights (IPR), appropriation, and access related to such 3D scans of CH items, digital scanning is widely seen as a positive development toward preservation. The existence of a 3D scan that proves that a CG is illicit, or illegal is likely to deter buyers and, potentially, thieves. Another potential use for 3D scanning technology lies in attempts to match undocumented looted antiquities to their source. In some situations, accurate digital scans of statue pedestals, tomb floors, remaining objects, and other damaged architectural and archaeological remains that are left behind by looters could be matched to digitally join cut surfaces or other features of cultural goods on the market. Finally, digital scanning technology, together with high-quality 3D-printed models of antiquities, has been put forward as a potential method to satisfy market demand for cultural goods. This reasoning posits that collectors might be convinced to purchase copies of particular pieces of ancient art instead of authentic antiquities.
- Tagging and tracking technologies: Various forms of marking and tagging have been proposed, including radio-frequency identification (RFID) tags that could be scanned and, to a lesser extent, tracked; tagging in the form of clear liquid painted on the object that is invisible to traffickers but visible under certain circumstances to law enforcement or contains identifiable chemical signatures; and tags attached to objects that would, theoretically, monitor their movements in real time. For the most part, these tagging technologies have been proposed by private companies, rather than by law enforcement or other professional stakeholders, and their utility and efficacy are questionable most of the time. They cannot be used for cultural goods that are previously undocumented, and in most cases, there is no obvious added value in using such new tagging technologies.
- Blockchain technology: This can be applied only to known and inventoried cultural goods.
- E-sniffers and "electronic noses": Practice has shown that such technologies are very expensive and cannot be used on a large scale.

4. ENIGMA Objectives

ENIGMA has three types of objectives: Scientific and innovation objectives (SO), technical objectives (TO), and demonstration, dissemination and exploitation objectives (DO).

The SO objectives include SO1, the co-design of a novel concept of a unique authenticity identifier (UAI); SO2, mitigating anthropogenic threats to heritage sites by integrating EO techniques and Geographic Information System (GIS) to produce remote sensing tools; and SO3, developing an advanced decision-support and communication platform that will deal with the research and development aspects of ENIGMA. During the implementation of SO1, the development of a novel concept of the unique authenticity identifier (UAI), which will be based on a holistic documentation of the CH tangible objects, will be realized. The development of advanced tools for processing satellite imagery and their integration into the ENIGMA platform to raise alerts regarding endangered heritage sites will be realized through SO2. Finally, during the implementation of SO3, the concept and modules of a decision-support and data/communication platform will be developed.

The TO objectives include TO1, the co-creation, development, and testing/validation of UAI tools; TO2, advanced machine-learning for CH object clustering and stratification; and TO3, advanced metadata analysis for interlinking existing disparate data sources focused on the technical implementation of research and development results. TO1 will implement and validate the UAI suite of tools through a series of pilot scenarios. TO2 will extend the UAI concept to include AI techniques to uncover possible connections of an unknown-sized CG to known inventoried objects or heritage sites. Finally, TO3 will provide a technical solution for data sharing and interlinking of existing disparate databases and inventories.

The DO objectives comprise DO1, an innovative and effective communication/dissemination tool for stakeholders' liaison; DO2, the implementation of the ENIGMA tools/applications in realistic operational environments; DO3, the validation of tools through pilot cases—policy briefs; and DO4, disseminating and communicating the technological, conceptual, and practical outcomes for raising awareness across the wider community of CH professionals and the public and exploiting synergies with other EU projects, enhancing societal impact for the demonstration, dissemination, communication and exploitation of ENIGMA's results. During the implementation of DO1, the development of a collaborative stakeholder engagement platform will be realized. DO2 will focus on the implementation of ENIGMA tools, including performance analysis of tools in advanced usage scenarios, iterative (technological) refinement/validation processes, etc. Through DO3, the real-world validation of the developed tool suites, platform, and application programming interface (API) will be implemented. In addition, DO3 will also produce policy recommendations based on the lessons learned. Finally, DO4 will focus on dissemination, communication, exploitation and awareness-raising activities at large, including linking and clustering activities with related, ongoing EU-funded projects and the creation of training modules and webinars among its activities.

5. Ambition—Advances beyond the State-of-the-Art

5.1. Authenticity and Traceability

Current State-of-the-Art: The identification of an object [13] usually contains the minimum amount of information required for investigative purposes, which can also be used as a first step for the further development of a professional inventory, or the simple listing of cultural property for individual owners.

Authentication faces various challenges [14], and we need to avoid confusion between two distinctive operations:

- The fake object purports to be what it is not and creates confusion over authenticity or authorship.
- The forgery, which is a term technically restricted to fake written documents that can support a cultural object's alleged provenance.

Thus, the research for provenance is a vital part in the establishment of authenticity and traceability. However, provenance research is an arduous endeavor. As a matter of fact, fake objects often come with fake provenance. Like stolen artefacts, they are often accompanied with forged documents, the quality of which is increasingly impressive. The faking of provenance documentation has become cutting-edge expertise that can be the central element of organized fraud. Thus, provenance research always must be completed with other methods.

Currently, smartphone APIs exist that allow LEAs and the public to check antiquities against objects registered as stolen in particular databases. This technology is designed to match antiquities' pictures with Interpol's stolen art database [15]. Some examples are the ID-Art [16] (Interpol) and iTPC [17] (Comando Carabinieri Tutela Patrimonio Culturale-TPC). ID-Art uses the object-ID [18,19] norm, which determines the minimum amount of information required to document collections of archaeological, cultural, and artistic objects, to facilitate their identification in case of theft. It includes measurements, the medium or materials used, the theme, the maker/artist and any distinguishing features, as well as guidelines on photographing the item. However, the use of mere visual and textual checks is not adequate to fully check authenticity and trace CGs. In addition, such image recognition techniques only work for known stolen cultural goods, while also producing high false positive rates in favor of low rates of false negatives.

Finally, since blockchain is a data ledger that is constantly being verified, blockchain technology represents a way to document provenance [20,21]. Currently a number of companies have sprung up, offering a blockchain-based registry for existing works of art, e.g., ARTORY https://www.artory.com (accessed on 10 May 2023), VERISART https://verisart.com/ (accessed on 10 May 2023), CODEX PROTOCOL https://codexprotocol.com/ (accessed on 10 May 2023) and EVERLEDGER https://everledger.io/ (accessed on 10 May 2023).

Beyond State-of-the-Art: The major challenge for authenticity and traceability is to tackle looted, stolen, or fake objects as well as fake provenance documents.

ENIGMA will go beyond the state-of-the-art by developing a UAI, based on a holistic documentation of tangible cultural heritage objects. This will extend the evidence base by making use of a broad band of information not currently included in the used databases. Prominent examples of such technology include 3D scans, geometry/radiometry, material science, surface complexity, and textual/historical contexts.

In addition, ENIGMA will extent the UAI concept to include spatial/location associations as well as ML techniques based on federated learning (FL) and graph theory to uncover possible connections of an unknown-sized CG to known inventoried objects or heritage sites. The rich set of additional, scientifically documented and proven CG objects and artifacts will support not only its quicker and unique identification, but also provide 3D geometrically complete and semantically rich documentation of broken or damaged objects, thus supporting in a major way the possibility of reconstruction and reunification of pieces residing in remote museums or private collections.

Finally, ENIGMA will contribute to raising awareness, as well as the development of joint research and collaboration on a global model FL server architecture, using a large array of distributed devices that could benefit from rich local datasets for each round of FL training by utilizing the advantages of blockchain technology to adequately tackle the problem of fake provenance, as well as that of malicious attacks during the model uploading process.

Way to go: An excellent working example of the envisioned concept will be based on the model that some partners developed during the VIGIE 2020/654 study [22]. This model will be adapted and enhanced to include all of the necessary extra parameters, which will be further combined and quantified into a digital composite indicator that we have coined the "unique authenticity identifier (UAI)". Figure 1 presents an overview of the authenticity and traceability tool workflow.

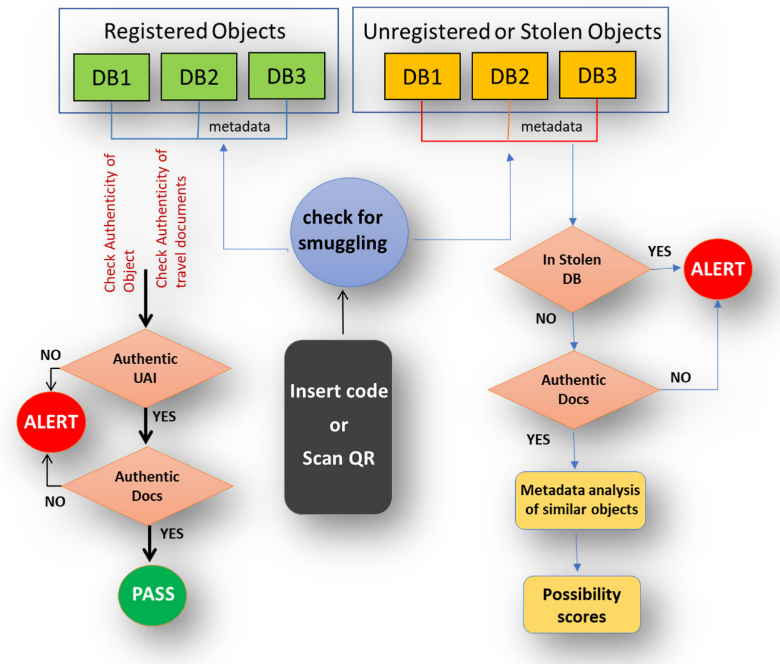

Figure 1. Authenticity and traceability tool workflow for registered and unregistered or stolen objects.

We cannot assume that all known antiquities will be fully documented this way at once. However, it is valid to assume that a good number of antiquities include in their documentation a good percentage of the above information. In addition, the envisioned structure is expandable in the sense that when further information is available, it can be readily inserted into the database. A major barrier in enabling database interlinking is the (justified to a degree) reluctance of the end-users to share the full documentation files. To overcome this, we plan to share only metadata information, according to the validated and certified Europeana model, while original data will remain in the owners' custody.

It is valid to assume that, occasionally, unregistered and unknown CGs will appear on the market. When legal, it is expected that these items will be registered in the respected databases and properly certified through the appropriate metadata and provenance documents. Therefore, if an unregistered CG appears, most likely it will be either a case of a fake object, or a case of a looted object.

ENIGMA tackles this problem by extending the UAI to include additional associations as well as the use of ML/AI tools for cluster analysis and graph theory to uncover possible connections of an unknown-sized CG to known inventoried objects or heritage sites. Specifically, the envisioned data structures will attach properties (e.g., material, dimensions, surface, ambient conditions, age, content semantics, spatial/location associations) to the "digital twins" of the registered CGs to reduce the "disconnection" or "misconnection" and thus facilitate and simplify the connectivity, correlations, and interpretations of CH items. This information will be used to match undocumented looted antiquities to their source, through similarity scores that will indicate probabilities of correct matching.

5.2. Remote Sensing, Monitoring and Safeguarding System

Current State-of-the-Art: Cultural heritage sites worldwide are threatened significantly by illegal activities, such as looting and other anthropogenic threats causing intentional damage, usually in cases of nations under distress or war-conflict regions [23]. These activities can cause irreversible damage to CH landscapes, monuments, and artefacts being trafficked and occasionally sold illegally [24,25]. In fact, the damage caused and the unavailability of reliable and timely information are some of the stakeholders' main concerns. Thus, stakeholders and the scientific community have sought ways to minimize looting activities and other intentional damage through the employment of novel technologies.

Recently, EO and remote sensing technologies, through the exploitation of satellite and aerial images as well as ground-based sensors, have assisted in this direction. EO data can provide valuable information for damage monitoring and assessment irrespective of weather conditions, time of day and site accessibility conditions, whereas at the same time, they can cover very large areas with a single satellite image. Several image processing techniques, such as vegetation indices, principal component analysis (PCA), and automatic extraction after object-oriented classification, can be used to monitor CH sites of interest. The integration of space-based with ground-based data to verify/validate the EO-based results has led to reliable results for sites of cultural heritage interest [26–29]. Although these technologies cannot prevent looters, the EO-based results can warn local stakeholders of illegal excavations taking place, assisting them in adopting relevant measures and applying restrictions [30].

Beyond State-of-the-Art: A major challenge for the detection of looting and other illegal activities in areas of CH interest is the provision of reliable and timely information—exploiting the big EO data now available—to stakeholders.

ENIGMA will go beyond the state-of-the-art by developing advanced ML-based satellite image processing and change detection techniques utilizing all available data (optical, SAR), to monitor endangered heritage sites systematically.

Moreover, ENIGMA, through the integration of EO and ground-based results, will provide alerts for illegal activities (i.e., illicit excavations) in CH sites and monuments that can lead to the prevention of such activities in the future. In this direction, the use of AI in satellite image classification and object detection, as well as in the fusion of datasets from different sensors, will increase detection accuracies, minimizing false alarms and mobilizing local authorities to intervene only when needed.

Way to go: UNESCO contributes to risk reduction and especially to "Science, Technology and Innovation for Resilience" and "Disaster Risk Reduction for Culture & Sites" among others [31]. A call for interest in GEO community activity, "Earth Observations for Climate Change Impacts on World Heritage Cities", is currently underway. European Space Agency (ESA) Thematic Exploitation Platforms (TEPs) [32] areas collaborative exploitation platforms, a virtual work environment providing access to EO data and the tools required to work with them through a coherent interface. EU member-state ministries, intelligence centers, and intergovernmental organizations such as the United Nations (UN) monitor illegal looting and damage detection in specific areas through two products: conflict damage assessments to identify the extent and type of damage, and activity analysis to assess whether an illegal activity has taken place.

ENIGMA will exploit current tools/datasets and research and develop an emergency management platform for CH preservation that will leverage Copernicus data and ML/AI tools (Figure 2) to:

- early detect any threat or damage to CHs by comparing incoming Copernicus data on CH sites and monuments of interest under monitoring with previous archive data stored in the data space. Any deviation or change will trigger an automated alert, sent to relevant local authorities. Alert thresholds will be set through ML-based image processing so that false alarms are prevented.
- support research on CH by enabling the comparison stages of sites, monuments and artefacts coming from diverse sites and collections. Advanced AI reasoning techniques will be implemented to identify and analyze the multiple factors that affect the conservation of CH sites, facilitating the identification, monitoring, and quantification of direct and indirect impacts.

ENIGMA will follow the recommendations of relevant European initiatives (e.g., the International Data Spaces Association—IDSA) for the design of European common data spaces, which suggests training ML models on top of highly distributed digital platforms based on a federated learning paradigm to preserve privacy and exploit the benefits of edge computing. Following this trend, it will be possible to produce superior AI models without centralizing massive amounts of data in a single cloud location.

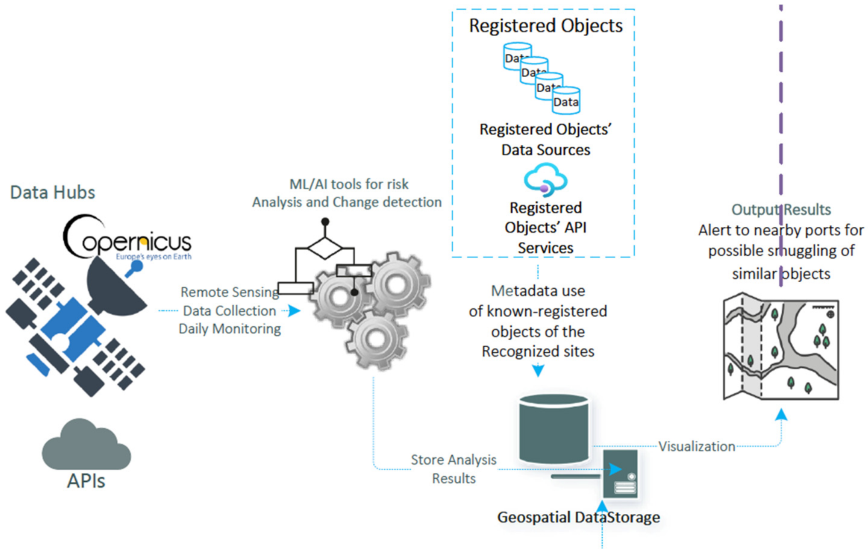

Figure 2. Architecture of the emergency management platform for CH preservation including data sources, data processing and output results.

5.3. Enabling Database and Inventory Sharing and Interlinking

State-of-the-Art: ID-Art is a mobile application that follows Interpol's "Stolen Works of Art" Database structure, which is based on the Object-ID norm, an internationally recognized documentation standard conceived to identify and record cultural goods. Carabinieri's "Database of illegally removed cultural artefacts", iTPC, seems to differentiate from this, while other databases and inventories (such as Art Loss Register [33], the FBI's National Stolen Art File (NSAF) [34]), follow other norms.

The Object-ID Record Sheet contains major information (i.e., type of object; materials and techniques; measurements; inscriptions and markings; distinctive features; title; subject; date or period; maker; short description), while supplementary information is also recommended (i.e., inventory information; related written material; place of origin/discovery; cross reference to related objects; present condition of the object; permanent location of the object; institution; location within the institution; date of acquisition or accession; acquisition or accession method; loan history).

Since different norms are used, the full integration of these disparate databases is rather impossible, not to mention that LEAs are not aware of all of these databases, queries require specific keywords, and some databases require formal requests to be accessed.

Beyond State-of-the-Art: ENIGMA will overcome this barrier by introducing beyond state-of-the-art metadata extraction of existing databases using a web crawler/scraper. Metadata of existing databases contain information on the configuration of fusion middleware components, based on application development frameworks and information about the applications in use. Advanced types of fusion middleware will be able to support multiple repository types and schemas, allowing for potential interfacing and automatic validation of Entity Data Model (EDM) Extensible Markup Language (XML) schema metadata.

Way to go: ENIGMA will develop a smart data retrieval system designed to extract metadata/data, images, and videos from databases for stolen artefacts in real-time. To bypass the technical limitations of the available APIs regarding databases, a web crawler/scraper will be developed to extract data from the web interfaces of the relevant databases. This system will crawl data on entities identified as potential suspects for illicit trafficking of cultural goods and extract their web content as well as produce clean text, image, and video objects, creating interlinking between the databases. To ensure technical interoperability, data security, and scalability of the proposed system, metadata will be converted to the EDM XML norm using ML techniques.

5.4. 3D CG Reconstruction from Incomplete Information

Current State-of-the-Art: We have to distinguish two situations: (1) The object exists and is accessible, but it is fractured or damaged; (2) The object no longer exists, or it is not accessible.

In the first case, the process to repair and preserve these objects is tedious and delicate; objects are often fragile and the time for manipulation must be short. Using geometry processing and shape analysis, the repair problem can be solved using a computational approach. The object is 3D-scanned, and then an algorithm analyzes the 3D shape to aid the reconstruction. For instance, Papaioannou [35] proposes an unsupervised shape analysis to repair damaged objects with good approximations. However, the prediction of missing geometry of damaged objects is still the main problem. Traditional methods assume that man-made objects exhibit some kind of structure and regularity [36]. The most common type of method used is based on symmetry, where the symmetries in the object are detected and what is missing is obtained by affine transformation. Unfortunately, this often does not work for heavily damaged objects. A more promising approach based on deep learning has proved to be highly successful in processing 3D voxelized inputs [37,38] and has also been recently used with generative adversarial networks (GANs) [39–41].

For the second situation, all existing accessible objects can be digitized but not those that are inaccessible due to war, spoiling or devastation. It is of utmost importance to use techniques to reconstruct these objects we cannot digitize. The goal of image-based 3D reconstruction is to infer the 3D geometry and structure of objects and scenes from one or multiple 2D images. This longstanding ill-posed problem is fundamental to many applications such as object recognition, 3D modelling, and animation. An excellent survey concerning image-based 3D object reconstruction has been published by Han et al. [42].

Beyond State-of-the-Art: Recovering the lost dimension from just 2D images has been the goal of classic multi-view stereo and shape-from-X methods, which have been extensively investigated for many decades. ENIGMA will use deep learning techniques [42–44] to reconstruct 3D objects from partial information, existing photos, films descriptions, storytelling, or parts of images.

Way to go: Many of the deep learning-based 3D reconstruction algorithms directly predict the 3D geometry of an object from RGB images. Some techniques, however, decompose the problem into sequential steps that estimate 2.5D information such as depth maps, normal maps, and/or segmentation masks. The last step, which can be implemented using traditional techniques such as space carving or 3D back-projection followed by filtering and registration, recovers the full 3D geometry. ENIGMA plans to explore these methods and also the approach introduced by Choy et al. [45], who proposed an architecture called 3D Recurrent Reconstruction Network (3D-R2N2), which allows the network to adaptively and consistently learn a suitable 3D representation of an object as information from different viewpoints becomes available.

5.5. Immersive CH Training Metaverse and Related Augmented Reality (AR)/Virtual Reality (VR)/Mixed Reality (MR) Applications

Current State-of-the-Art: Learning and training have been lately performed using various audience-engaging tools and applications. Some of these tools and applications have started to use AR and VR technologies, while a few large corporations have started using MR technologies. The cost of their development and use, especially that of MR, is still quite high and prohibitive for SMEs and smaller research and training organizations (RTOs). However, the high level of audience engagement and the immersive user experience through the use of these tools for different purposes has been widely recognized.

Beyond State-of-the-Art: ENIGMA aims to implement, test, validate and demonstrate such immersive learning applications for stakeholders' and end-users' training, education and demonstration using AR, VR and MR technologies via a CH metaverse platform.

Way to go: The metaverse platform will be used to host and launch AR/VR/MR apps suited to different stakeholders' training, education and learning needs. The platform will be utilized also as a means of multi-actor training and collaboration between different national and European CH authorities, local governments, and law enforcement agencies. Furthermore, simulations and trials using different scenarios will be possible with the support of both the platform and the AR/VR/MR applications.

6. ENIGMA Action Plan

ENIGMA is organized into three phases (Figure 3) and seven work packages (Figure 4), each led by a partner experienced in the corresponding area.

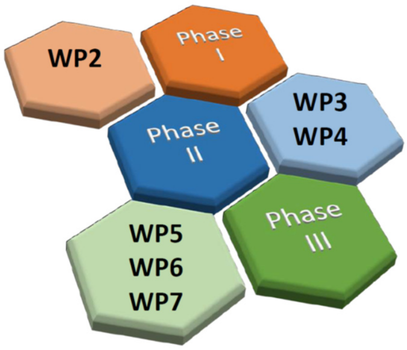

Figure 3. ENIGMA implementation phases and organization.

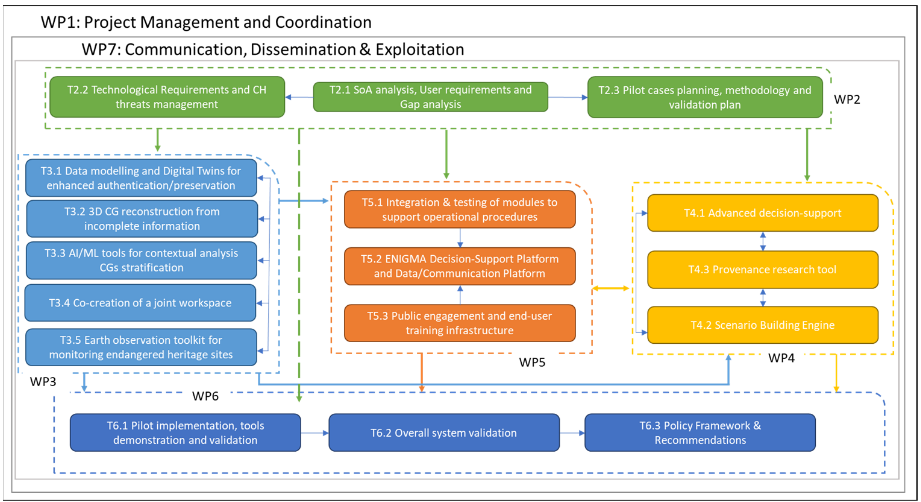

Figure 4. ENIGMA PERT diagram presenting the work packages, the respective tasks and their connections.

- Phase I "User requirements, architectural model and decision making" refers mainly to deployment of WP2.
- Phase II "Development of ENIGMA modules and tools" refers to deployment of WP3 and WP4.
- Phase III "ENIGMA Deployment, Validation, and Training" refers to deployment of WP5, WP6 and WP7.

WP2 will run during the first year and, after an analysis of the user requirements, will set the technological requirements as well as the planning of the pilot cases and the way the developed tools will be validated. This will guide the development of the required technologies mainly in WP3 and WP4. Specifically, WP3 will accommodate the development of digital suites for the digital identification and tracking of cultural goods, while WP4 will address the decision support and public engagement part. These outcomes will feed iteratively the work of WP5, which will be in charge of integrating and testing the various components. WP6 will follow with the demonstration and validation of the developments through the implementation of pilot cases, and subsequently translating the findings into policy recommendations. WP7 will deal with the communication, dissemination and exploitation of the project results and also take care of the training part. Like WP1, which will handle project management, WP7 will span the whole project life. The overall architecture of the ENIGMA platform is presented in Figure 5.

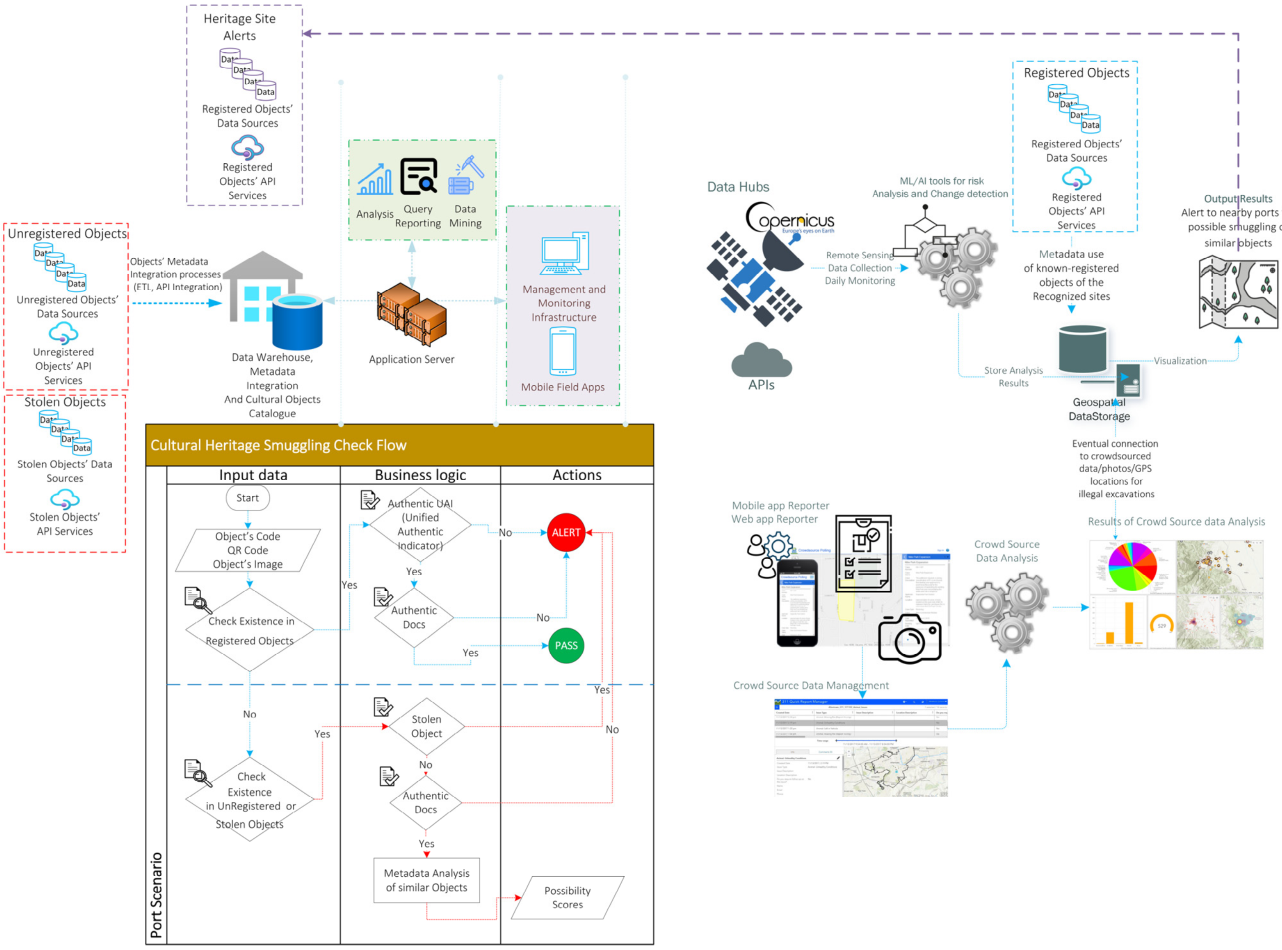

Figure 5. ENIGMA system architecture demonstrating the different tools and applications that will be developed and their interconnections.

7. Expected Key Elements

ENIGMA targets the following needs:

- The growing risk of anthropogenic threats to CH objects and sites demands technologies at all levels of the risk management cycle.
- The economic and social losses caused by a threat to CH can be significantly reduced through advanced provenance research, safeguarding and deployment of preventative measures. Thus, there is an urgent need for an integrated protection system.
- Development of policies demands the communication and cooperation of different stakeholders, for effective support of decision-making at all levels.
- Raising awareness of both experts and the public assumes, among others, an effective training process.

with the following expected results:

- A unified advanced decision-support platform that integrates all developed technologies, targeting all phases of the risk management cycle.
- A novel methodology for CG dentification and an innovative holistic documentation protocol, enhanced by advanced ML/AI tools and information sharing among existing disparate data sources, including use of Copernicus infrastructure.

- Deployment and validation of ENIGMA tools/applications in realistic operational conditions through pilot cases, with the effective participation of end-users.
- A collaborative stakeholder and public engagement platform for innovative and effective communication and dissemination as well as issuing policy recommendations.
- A mobile application for public engagement, awareness raising, training and scenarios simulation.

targeting the following groups:

- TG1: CH ministries, institutions, archaeological departments
- TG2: Museums, galleries, collections
- TG3: Art market
- TG4: CH professionals, archaeologists, art experts
- TG5: Inter-governmental organizations, NGOs
- TG6: European LEAs, border guards, customs
- TG7: Industrial stakeholders
- TG8: Creative industry
- TG9: Copernicus services
- TG10: Research community, academia, ESR
- TG11: General public, citizens, young generation
- TG12: Relevant European projects
- TG13: Governments and policy makers

and achieving the following impacts:

- Scientific and technological: improved technological tools and analysis to protect cultural artefacts from falling victim of destruction, theft, illicit trade.
- Scientific: improved interdisciplinary knowledge and capabilities of CH stakeholders to prevent, detect and disrupt illicit trafficking of CGs.
- Economic: less money laundering, trade in illicit CGs, sustainable communities that will coordinate and align R&D in the domain of combating illicit trafficking.
- Societal: more-engaged and sensitized creative industry, public administrations, experts and citizens in protecting CH, as well as in enriching and accessing this common CH data space.

ENIGMA will develop a plethora of technologies and methods as well as other services of high operational significance. The overall ENIGMA architecture and implementation approach is designated to provide, at the end of the project, a platform that will have been demonstrated in relevant conditions.

ENIGMA aspires to develop (1) a unified advanced decision-support platform that integrates all of the developed technologies targeting all phases of the risk management cycle, (2) a novel methodology for CG dentification and an innovative holistic documentation protocol, enhanced by advanced ML/AI tools and information sharing among existing, disparate data sources, including the use of Copernicus infrastructure, (3) a collaborative stakeholder and public engagement platform for innovative and effective communication, dissemination, and issuance of policy recommendations, and (4) a mobile application for public engagement, awareness-raising, training and scenario simulations. All ENIGMA tools/applications will be deployed and validated in realistic operational conditions through pilot cases, with the effective participation of end-users.

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