Future-Proofing Heritage Future-Proofing Heritage with ARGUS: A Multimodal Digital Twin Approach for Sustainable Preservation

George Pavlidis[1]*, Anestis Koutsoudis[2], Despoina Tsiafakis[3], Melpomeni Karta[4], Vasileios Sevetlidis[5], Vasileios Arampatzakis[6], Apostolos Sarris[7], Miltiadis Polidorou[8], Victor Klinkenberg[9], Zeyd Boukhers[10], Lingxiao Kong[11], Emeri Farinetti[12], Fernando Moreno Navarro[13], Ioannis Kakogiannos[14], Sofia Aparicio[15], Javier Ortega[16], Fernando Ramonet[17], Athos Agapiou[18], Stylianos Hadjipetrou[19], Kyriakos Michaelides[20], Stavros Patsalidis[21], Phaedon Kyriakidis[22], Apostolos Papakonstantinou[23], Demetrios Athanasoulis[24], Christos Maris[25], Themistoklis Vakoulis[26], Tomoki Nagata[27], Katrin Beyer[28], and Savvas Saloustros[29]

[1]Athena Research Center, Greece; 0000-0002-9909-1584
[2]Athena Research Center, Greece; 0000-0001-9862-7335
[3]Athena Research Center, Greece; 0000-0003-4948-255X
[4]Athena Research Center, Greece; 0000-0001-8302-5665
[5]Athena Research Center, Greece; 0000-0001-9348-8786
[6]Athena Research Center, Greece; 0000-0003-4320-3740
[7]University of Cyprus, Cyprus; 0000-0001-6071-4767
[8]University of Cyprus, Cyprus; 0000-0001-9841-8023
[9]University of Cyprus, Cyprus; 0000-0002-7621-9821
[10]Fraunhofer FIT, Germany; 0000-0001-9778-9164
[11]Fraunhofer FIT, Germany; 0000-0001-7662-5523
[12]Roma Tre University, Italy; 0000-0003-0654-6162
[13]Roma Tre University, Italy; 0000-0002-7279-5856
[14]Worldsensing, Spain; 0000-0003-0471-269X
[15]ITEFI-CSIC, Spain; 0000-0003-4069-015X
[16]ITEFI-CSIC, Spain; 0000-0001-6075-593X
[17]ITEFI-CSIC, Spain; 0000-0002-7517-0894

[18]Cyprus University of Technology, Cyprus; ⓘ 0000-0001-9106-6766
[19]Cyprus University of Technology, Cyprus; ⓘ 0000-0002-8808-3319
[20]Cyprus University of Technology, Cyprus
[21]Cyprus University of Technology, Cyprus
[22]Cyprus University of Technology, Cyprus; ⓘ 0000-0003-4222-8567
[23]Cyprus University of Technology, Cyprus; ⓘ 0000-0002-6464-2008
[24]Ephorate of Antiquities of the Cyclades, Greece; ⓘ 0000-0001-7297-4320
[25]Ephorate of Antiquities of the Cyclades, Greece
[26]École Polytechnique Fédérale de Lausanne, Switzerland; ⓘ
[27]École Polytechnique Fédérale de Lausanne, Switzerland; ⓘ 0000-0002-4937-6055
[28]École Polytechnique Fédérale de Lausanne, Switzerland; ⓘ 0000-0001-8905-1514
[29]École Polytechnique Fédérale de Lausanne, Switzerland; ⓘ 0000-0002-9513-8373
*Corresponding author: gpavlid@athenarc.gr

Abstract

The preservation of cultural heritage faces increasing challenges from environmental, climatic, and anthropogenic pressures. The ARGUS Horizon Europe project addresses these challenges by proposing an innovative predictive preservation approach that leverages AI-driven digital twins and multimodal data fusion to assess and mitigate risks to heritage sites. Our research focuses on developing a sustainable, dynamic decision support system (DSS) that integrates multi-scale on-site and remote sensing data, enabling holistic heritage management, while focusing on the preventive rather than the reactive aspects. The primary research question treated in this paper relates to how digital twins incorporating multi-dimensional data and an ontology background enhance the preservation and adaptive management of cultural heritage in a changing environment.

1. Introduction

Cultural heritage is increasingly endangered by a convergence of natural, climatic, and anthropogenic threats. Earthquakes, floods, wildfires, freeze-thaw cycles, and coastal erosion regularly affect heritage structures and landscapes, while human-driven pressures such as urbanization, pollution, mass tourism, and neglect accelerate the deterioration of sites and weaken their resilience (Agapiou et al. 2015; Hadjimitsis et al. 2013; Agapiou 2017). The combined impacts of climate change and societal transformation amplify these risks, threatening both tangible assets—monuments, buildings, archaeological remains—and intangible values such as identity, memory, and cultural continuity. This is particularly acute in remote or exposed sites, where monitoring capacity is limited and local conservation resources are scarce.

Traditional preservation strategies often operate reactively, intervening only after visible damage has occurred. Monitoring approaches, when available, are typically fragmented across institutions, data silos, and disciplinary practices. While important progress has been made in documenting heritage through digitization, 3D modeling, and GIS-based inventories, these outputs frequently remain static and disconnected from real-time condition monitoring or decision-making processes,

particularly in a preventive manner. In order to safeguard cultural heritage under increasingly volatile conditions, there is a pressing need to move from reactive conservation toward preventive and predictive management, grounded in continuous evidence and structured risk assessment (Michalski and Pedersoli 2016).

The notion of the *digital twin*, originating in Industry 4.0 and cyber-physical systems, offers a compelling paradigm shift. A digital twin is a dynamic, data-rich replica of a physical asset, continuously updated with multimodal data streams and capable of simulating future conditions, supporting diagnostics, and guiding interventions. In a sense, it is a living digital entity. In cultural heritage, this implies moving beyond static digital models or Heritage Building Information Management (HBIM) representations toward living, responsive systems that integrate sensing, semantics, and simulation (Quattrini et al. 2015; Jouan and Hallot 2019; 2020; Gabellone 2022; Dang et al. 2023). Such twins can host multimodal datasets—structural, environmental, remote sensing, and intangible—and provide management professionals with predictive scenarios for threats, as well as tools for communication with the public.

In parallel, Niccolucci and collaborators have proposed the Heritage Digital Twin Ontology (HDTO) and its extension, the Reactive Heritage Digital Twin Ontology (RHDTO), which formalize semantic representations of assets, sensors, activators, and decision processes for heritage contexts (Niccolucci et al. 2023; Niccolucci and Felicetti 2024). These works demonstrate how cultural heritage digital twins can evolve from static documentation to reactive systems, linking monitoring data directly to conservation actions.

Europe has invested heavily in this direction through research infrastructures and innovation actions. The ARIADNE and ARIADNEplus projects have demonstrated large-scale integration of archaeological datasets following CIDOC CRM-based standards (Geser et al. 2023), while E-RIHS is consolidating facilities, labs, and digital services to provide advanced research infrastructure for heritage science across the continent (Striova et al. 2017). The 4CH project has articulated the concept of a European Competence Center for Cultural Heritage, focusing on cloud-based services and standardization (Medici et al. 2022). In parallel, the Time Machine initiative envisions massive digitization and AI-based analysis of European history (Aigner 2022), and EUreka3D has recently advanced large-scale 3D digitization pipelines aligned with FAIR principles. Together, these initiatives underscore the importance of data integration, interoperability, and shared infrastructures—yet they typically emphasize either documentation, access, or interoperability, without fully embedding environmental monitoring and risk analysis in their digital frameworks.

The ARGUS Horizon Europe project builds on this ecosystem but addresses a distinct gap: the lack of integrated, risk-driven digital twins that combine environmental sensing, AI-based threat analysis, and semantic reasoning for preventive preservation. ARGUS focuses explicitly on remote and vulnerable heritage sites, where risks from climate change, environmental processes, and human activities intersect. Its approach integrates multimodal on-site sensing, remote sensing, and legacy data into a geospatial backbone, enriched by a new ontology (titled *PANOPTES*) and aligned with existing well-established ontologies like CIDOC CRM (Doerr 2003). The system operationalizes the ICCROM/CCI *ABC method* for risk assessment (Michalski and Pedersoli 2016) and adheres to the FAIR principles for scientific data stewardship (Wilkinson et al. 2016). By doing so, ARGUS creates digital twins that not only mirror the present condition of heritage assets but also simulate future

scenarios, inform conservation decisions, and promote inclusive engagement through Living Labs and participatory activities.

In this paper, we present the conceptual framework of ARGUS' digital twin. We describe the vision and objectives, the five pilot sites and their risk contexts, the architecture of the data management and digital twin system, and the integration of the ABC methodology into digital workflows. We conclude with a discussion of challenges and outlook, positioning ARGUS as a contribution toward future-proofing cultural heritage through multimodal digital twins.

2.   Vision and Objectives

The overarching vision of ARGUS is to establish a next-generation monitoring ecosystem for cultural heritage that enables preventive, rather than reactive, preservation. This vision rests on three pillars: (i) scientific integration of multimodal data streams; (ii) technological innovation in sensing, modeling, and visualization; and (iii) social sustainability through participatory and inclusive practices. By addressing these dimensions together, ARGUS aims to transform cultural heritage management from fragmented and reactive interventions to coherent, evidence-based strategies.

To realize this vision, ARGUS develops a multi-scale, multi-modal digital twin for heritage assets. This twin integrates heterogeneous sources—in-situ sensors, remote sensing, legacy GIS datasets, and archival records—into a living digital representation that can be dynamically updated, reasoned upon across scales from building detail to landscape context, and used to simulate future risk scenarios. The project also deploys portable, non-destructive sensing systems that are complemented by remote sensing datasets, including Copernicus Earth Observation data, aerial imagery, and UAV-based surveys. These provide an observational ecosystem capable of capturing both localized and regional processes.

Central to the project is the implementation of AI-powered threat analysis and risk assessment pipelines. Building upon the ICCROM/CCI ABC methodology (Michalski and Pedersoli 2016), ARGUS develops machine learning workflows to analyze sensor data, detect anomalous patterns, and prioritize risks. The integration of AI and semantic ontologies allows these analyses to support both predictive simulations and explainable recommendations for management decisions. At the same time, advanced visualization services are designed to meet the needs of different stakeholders, ranging from GIS dashboards that support professional heritage managers to intuitive interfaces that communicate risks and conservation options to wider audiences. Finally, citizen engagement is embedded within the project through participatory formats such as Living Labs and co-creation events, where citizens, students, and local stakeholders contribute data, test applications, and shape narratives. This ensures long-term sustainability by embedding digital heritage management within community practices. Taken together, these objectives articulate a holistic approach that combines technical innovation with social responsibility. ARGUS seeks not only to improve conservation outcomes, but also to foster a sense of shared stewardship, ensuring that cultural heritage remains a living resource that is accessible and meaningful to diverse communities.

To ensure that the ARGUS framework is tested under diverse conditions, five pilot sites were selected across Europe, representing different geographies, chronological horizons, typologies of cultural heritage, and risk factors. Together, these pilots provide a robust testbed for validating data acquisition strategies, risk assessment methodologies, and digital twin implementations. The first

site, **Delos Island in Greece**, a UNESCO World Heritage archaeological site, is highly exposed to coastal erosion, salinity, and marine pollution. Rising sea levels and increasing storm intensity pose direct threats to its structural remains, and ARGUS explores how relevant data can be integrated with new sensing strategies to model threat dynamics. In **Baltanás, Spain**, a subterranean wine cellar town, vulnerabilities arise from ventilation issues, humidity imbalance, and landslide risks. Its distinctive underground architecture creates microclimatic instability, and ARGUS pilots wireless sensor networks and humidity monitoring strategies to evaluate thresholds for collapse and mold growth. The **Monti Lucretili area in Italy** represents an upland cultural landscape exposed to erosion, subsidence, and vegetation overgrowth. With its mix of natural and built elements, it offers an ideal case for testing landscape-scale integration of remote sensing and field-based data. Here ARGUS applies geomorphological modeling and vegetation indices derived from satellite imagery to assess conservation needs. The **Abbey of Sant'Antonio di Ranverso**, also in Italy, is a medieval monastic complex facing water infiltration, biodeterioration, and the pressures of visitor access. At this site, ARGUS examines the potential of structural and environmental sensors to diagnose infiltration pathways and monitor biological growth on stone surfaces. Finally, **Schenkenberg Castle in Switzerland**, a mountain fortress, is threatened by freeze–thaw cycles, vegetation-induced damage, and long-term structural stability challenges. ARGUS tests vibration sensors and UAV-based thermal imaging here to capture the seasonal effects of freeze–thaw dynamics on stone integrity.

Figure 1: Geographical distribution of the five ARGUS pilot sites across Europe.

As shown on the map in the

Figure 1, pilots span distinct climatic zones and geomorphological settings, which is essential for validating generalizable workflows. By covering such a wide spectrum of risks—from coastal erosion to subterranean collapse and alpine freeze-thaw—the pilots ensure that ARGUS methodologies are validated across contexts. They also highlight the importance of tailoring digital twin strategies to the specific vulnerabilities, scales, and data availability of each site.

3. Materials and Methods

3.1. *Ontology-Driven Multimodal Digital Twins*

The notion of a digital twin represents a major conceptual and technological shift for cultural heritage. Unlike static digital models, a digital twin is a dynamic, data-rich representation of a physical asset that evolves over time, incorporating multimodal data streams and enabling predictive simulation. For heritage management, this means that the digital representation of a monument or site is not limited to geometry or appearance, but actively reflects its condition, vulnerabilities, and risks (Gabellone 2022; Jouan and Hallot 2020; Dang et al. 2023). ARGUS adopts a multimodal digital twin architecture tailored to the needs of cultural heritage.

The integration of ontologies into the digital twin framework is not merely a technical detail, but a conceptual choice. Digital twins in engineering domains often operate as closed cyber-physical replicas, focusing on synchronization between a physical asset and its digital model. In cultural heritage, however, the problem space is broader: the asset is not only a material object but also a bearer of historical, social, and cultural values; risks are not only physical but also interpretative and managerial; and preservation actions must be accountable and transparent.

The digital twin paradigm extends the ontology approach by adding temporality, real-time data ingestion, and simulation. While ontologies traditionally describe classes and relationships, digital twins bring temporality, real-time data ingestion, and simulation into the picture. The ARGUS digital twin thus transforms PANOPTES from a static semantic schema into a dynamic semantic

infrastructure, where data are not only curated but also continuously updated, reasoned upon, and acted upon. *This mutual reinforcement—using ontologies to make digital twins meaningful, and digital twins to make ontologies actionable—is central to ARGUS.* It allows cultural heritage management to move beyond fragmented datasets or isolated 3D models toward integrated, risk-aware, and decision-supportive systems.
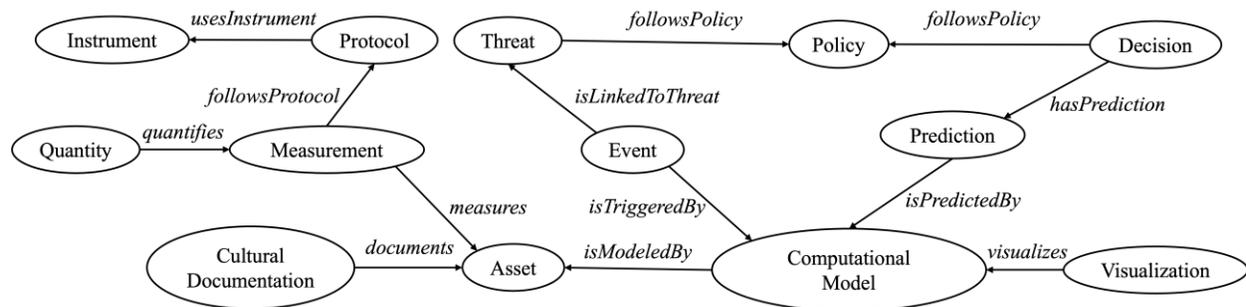

Figure 2: The PANOPTES core ontology concept in ARGUS: connecting measurements, risks, and decisions into a semantically integrated digital twin.

Building on this line of reasoning, ARGUS introduces the *PANOPTES ontology*, to move beyond geospatial integration toward semantic reasoning. PANOPTES extends the CIDOC CRM standard (Doerr 2003) and integrates ontologies from the sensor and data provenance domains (SOSA/SSN (Janowicz et al. 2019), PROV-O, OWL-Time, GeoSPARQL). This provides a semantic backbone for representing assets, measurements, diagnoses, predictions, threats, and policy-driven decisions in a machine-readable and interoperable manner. By capturing not only data but also their meaning, provenance, and temporal context, the ontology allows AI modules to reason about risks and propose actions in a transparent and explainable way.

The conceptual rationale of PANOPTES aligns with and extends the current research trajectory. While HDTO and RHDTO (Niccolucci et al. 2023; Niccolucci and Felicetti 2024) have established important precedents for embedding sensors, activators, and decision logic into semantic frameworks, PANOPTES emphasizes interoperability with established standards (CIDOC CRM, SOSA/SSN, PROV-O, OWL-Time, GeoSPARQL) and integration into multimodal digital twin predictive (and not reactive) workflows. This positions PANOPTES not only as a semantic schema, but as a dynamic infrastructure where ontological reasoning, real-time monitoring, and predictive preservation converge.

The rationale and the core ontology concept of PANOPTES is illustrated in Figure 2. The model integrates instruments, protocols, threats, rules, policies, events, measurements, diagnoses, predictions, and decisions, connecting them to assets and cultural documentation. This semantic structure ensures that multimodal data streams can be interpreted in terms of risks, policies, and conservation actions, rather than remaining disconnected technical records. This representation is simplified for illustration purposes and the deep technical specifics are included in the following analysis.

Beyond its alignment with CIDOC CRM and related standards, PANOPTES provides a conceptual framework that grounds the digital twin in semantically meaningful structures. At its core,

PANOPTES centers on the **heritage asset**, which may be a movable object, monument, site, or region. Each asset is represented through a sequence of **asset states**, understood as temporally and spatially situated snapshots of its existence. An asset state embodies the current manifestation of the asset at a specific location and time, and serves as the live instance of the digital twin.

Every asset state is associated with **cultural documentation**, i.e. domain experts' descriptions spanning history, conservation, provenance, and other disciplinary perspectives. The state is also linked to **measurements**, obtained through instruments and protocols and reflecting physical quantities such as temperature, humidity, vibration, or spectral reflectance. Measurements may be point values from sensors, multi-dimensional datasets such as thermography, or remote-sensing imagery. These are interpreted by **computational models**, which infer meaningful **events** (e.g. a rainfall episode, an earthquake shock, or a humidity excursion) and produce **predictions** about possible future conditions (e.g. structural tilt, stone erosion, or mold formation).

The framework introduces a policy layer to connect data interpretation with preventive action. **Policies** define thresholds and acceptable conditions (e.g. humidity outside 45-60% for more than 48 hours is a threat to mural stability). By evaluating events and predictions against such policies, the system identifies **threats** and formulates **decisions**—recommendations for preventive interventions, recorded in formal decision contexts. Visualizations at each stage (maps, 3D models, heatmaps, dashboards) integrate measurements, events, and predictions into intuitive forms for both experts and the public.

In this way, PANOPTES operationalizes the digital twin not only as a technical data hub but as a semantically grounded ecosystem. Assets, states, measurements, models, events, policies, threats, and decisions are explicitly represented, ensuring that ARGUS twins remain transparent, interoperable, and capable of supporting accountable conservation strategies. In simple words, PANOPTES' rationale can be summarized into the following:

To preserve a heritage asset, its temporally and spatially situated state is culturally documented and continuously monitored, through structured measurements derived via instruments and protocols. These measurements are interpreted by computational models to identify events and generate predictions, and intuitive visualizations. Events are evaluated in light of policy constraints to assess threats, and predictions are incorporated into decision contexts to support semantically grounded preventive actions.

To complement the conceptual rationale, PANOPTES is implemented as an OWL ontology with a compact set of core classes and object properties aligned to CIDOC CRM, SOSA/SSN, PROV-O, OWL-Time, and GeoSPARQL. Table 1 and Table 2, together with Figure 2, summarize the structure. PANOPTES aligns

- `Asset/CulturalDocumentation` with CIDOC CRM classes;
- `Measurement/Instrument/Protocol/PhysicalQuantity` with SOSA/SSN;
- provenance of `Measurement` and `ComputationalModel` with PROV-O;

temporal anchors of `AssetState`, `Measurement`, `Event`, and `Prediction` with OWL-Time;

- geospatial anchors with GeoSPARQL.

Table 1: PANOPTES core classes (with two optional provenance record classes).

Class	Role in PANOPTES
`Asset`	Cultural entity under stewardship (movable or immovable: object, monument, site, region). Root of the twin.
`Assetstate`	Time-space specific manifestation of an `Asset`; live instance of the twin at a given instant and location (the place to which time/geometry anchors attach).
`Culturaldocumentation`	Domain-expert descriptions linked to an `Asset` or `AssetState` (history, conservation, provenance), which may vary across states.
`Physicalquantity`	Measurable property relating to an `AssetState` (e.g., temperature, RH, electrical conductivity).
`Measurement`	Observation/acquisition about an `AssetState` (point sensor value, image, 3D model, thermography, satellite scene).
`Instrument`	Device/system producing a `Measurement` (e.g., thermistor, humidity sensor, UAV, multispectral camera, satellite).
`Protocol`	Procedure/recipe used by an `Instrument` to obtain a `Measurement`.
`Computationalmodel`	Formal method that interprets measurements to infer `Events` and produce `Predictions`; may also drive `Visualization`.
`Event`	Interpreted occurrence at an `AssetState` (e.g., rainfall episode, humidity excursion, earthquake shock); not necessarily damaging.
`Prediction`	Forward-looking estimate of a possible future state or condition (e.g., structural tilt, stone erosion, mold formation).
`Policy`	Formalized domain rule expressing acceptable ranges, thresholds, or objectives for evaluation (e.g., RH 45–60% for murals).
`Threat`	Semantic interpretation that an `Event` (evaluated against a `Policy`) indicates potential risk/degradation.
`Decision`	Preventive action recommendation derived by evaluating a `Prediction` against a `Policy` (optionally recorded in a `DecisionContext`).
`Visualization`	Spatio-temporal presentation aggregating measurements, events, predictions (maps, 3D, heatmaps, dashboards).
Policyeventlink (optional)	Record node linking a specific `Event` to a `Policy` with evaluation timestamp and resulting `Threat`.
Decisioncontext (optional)	Record node linking a `Prediction` to a `Policy` with evaluation timestamp and resulting `Decision`.

Table 2: Key PANOPTES object properties (relationships).

Object Property	Semantics (domain → range)
hasState	Asset → AssetState
isStateOf (inverse)	AssetState → Asset
documentedBy	Asset/ AssetState → CulturalDocumentation
hasMeasurement	AssetState → Measurement
usesInstrument	Measurement → Instrument
followsProtocol	Measurement → Protocol
observedProperty	Measurement → PhysicalQuantity
interpretedBy	Measurement → ComputationalModel
infersEvent	ComputationalModel → Event
producesPrediction	ComputationalModel → Prediction
evaluatedAgainst	Event/Prediction → Policy
resultsInThreat	Event → Policy → Threat
resultsInDecision	Prediction → Policy → Decision
visualizedAs	AssetState/Measurement/Event/Prediction → Visualization
hasTime	AssetState/Measurement/Event/Prediction → time:Instant
hasGeometry	AssetState/Measurement → geo:Geometry
linksEvent/linksPolicy/ (optional record)	PolicyEventLink → Event/Policy/Threat
linksPrediction/linksPolicy/ (optional record)	DecisionContext → Prediction/Policy/Decision

To illustrate how the ontology operates in practice, we present a concrete example from the pilot site of Delos, where coastal salinity poses a major conservation risk. In this scenario, PANOPTES structures the full monitoring and decision-support workflow as linked entities, from the asset and its cultural documentation through measurements, instruments, protocols, events, predictions, policies, threats, and preventive decisions.

To make the workflow more intuitive, we briefly narrate the example here. At Delos, conductivity sensors detect a spike in salinity on the marble shoreline during a high-wind marine spray event. The system automatically correlates sensor readings with microclimate data and satellite observations, triggering a salinity excursion event. The ABC-based policy thresholds classify this as a crystallization risk, leading to a preventive recommendation (rinsing and windbreak intervention). Table 3 and Table 4 then show how each step is formally represented in PANOPTES.

Table 3: Example instantiation of PANOPTES entities for a Delos coastal salinity episode (illustrative values).

PANOPTES entity	Example instance (Delos, salinity monitoring)
Asset	`asset:delos_shore_zone`; Delos coastal archaeological zone (UNESCO WH).
AssetState	`state:delos_2024-06-25T14:00Z_shore_A`; spatial/temporal snapshot. Space: WKT `POINT(25.268 37.394)` in EPSG:4326; Time: `2024-06-25T14:00:00Z`
CulturalDocumentation	`doc:delos_shore_notes_v3`; conservation notes on marble erosion susceptibility; references local reports and site registers.
PhysicalQuantity	`pq:electrical_conductivity_surface`; proxy for salinity at 2cm depth (field).
Measurement	`meas:cond_probe_A_2024-06-25T14:00Z`; observedProperty = `pq:electrical_conductivity_surface`; value = `53.2 mS/cm`; uncertainty = `±0.3 mS/cm`; depth = `2 cm`; co-located SST = `23.1°C`; coincident Sentinel-2 L2A pixel noted.
Instrument	`instr:YSI_ProDSS_SN20417`; handheld conductivity/temperature probe; calibration record `cal:2024-06-20`.
Protocol	`prot:ISO_7888_in-situ`; ISO 7888 field conductivity; 3 replicates averaged; rinse between readings.
ComputationalModel	`model:salinity_risk_v1`; rule-based + temperature compensation; correlates EC to practical salinity; integrates tidal stage + wind.
Event	`event:salinity_excursion_2024-06-25_A`; detected saline spray event at shoreline sector A; duration window: `13:40–14:20Z`.
Prediction	`pred:surface_salt_crystallization_7d`; 7-day horizon forecast for crystallization risk on marble surfaces under current microclimate.
Policy	`policy:stone_RH_salinity_limits_v2`; "If EC>50mS/cm at surface & RH>70% for >24h, then material stability at risk; trigger inspection/mitigation."
Threat	`threat:salt_crystallization_risk_rank_high}`; policy evaluation marks the event as a *threat* for marble granular disintegration.
Decision	`dec:rinse_windbreak_monitor_2024W26`; prescribe deionized gentle rinse on affected statues; pilot windbreak; follow-up measurements every 12h (72h).
Visualization	`viz:delos_salinity_map_heat`; heatmap + time-series dashboard (EC, RH, wind), linked to the above entities.

Table 3 summarizes the core entities involved in a salinity monitoring episode, showing how a specific *asset state* of the Delos shoreline is linked to conductivity measurements, instruments and protocols, cultural documentation, and computational models that infer events and generate predictions. Each element is temporally and spatially anchored, with explicit provenance and standards-based encoding (e.g. ISO-8601 for time, WKT for coordinates).

Building on this, Table 4 demonstrates how the ontology records the evaluation chain in which events are assessed against domain-specific policies, producing threats and triggering preventive decisions. In the Delos case, measured electrical conductivity values exceeding thresholds defined in conservation policies lead to the classification of a high salt crystallization risk, which in turn generates a preventive decision recommending rinsing protocols and protective measures. Provenance links ensure that each decision is transparently grounded in the preceding measurements, models, and policies.

Table 4: Policy evaluation workflow for the same Delos case: from event to threat and a preventive decision.

Step	Instance/content
Event detection	`event:salinity_excursion_2024-06-25_A` inferred by `model:salinity_risk_v1` from `meas:cond_probe_A_2024-06-25T14:00Z` (+ nearby replicates; wind=11m/s NNE; tide=high).
Policy reference	`policy:stone_RH_salinity_limits_v2` with thresholds: EC>50mS/cm at surface & RH>70% sustained >24h.
Evaluation (*Event→Policy*)	Conditions met: EC=53.2mS/cm; RH median=74% (last 26h); temperature=23°C; duration satisfied. $\Rightarrow$ *Threat*.
Threat assignment	`threat:salt_crystallization_risk_rank_high` created (via policy–event evaluation; provenance to event, policy, measurements, model, timestamp).
Prediction context	`pred:surface_salt_crystallization_7d`: persistence probability 0.62 (ensemble); highest-risk sectors: "shore_A", "colonnade_SE".
Decision (*Prediction→Policy*)	`dec:rinse_windbreak_monitor_2024W26`: (i) deionized gentle rinse; (ii) pilot windbreak screen; (iii) 12h monitoring cadence for 72h; review ABC scores next cycle.
Visualization links	`viz:delos_salinity_map_heat`: map layers (EC points, RH tiles), time series, event/policy badges; permalink URIs to all entities.

These examples highlight how PANOPTES moves beyond abstract modeling by capturing the entire lifecycle of heritage risk management in a machine-readable structure. Assets are not only documented but also continuously observed, interpreted, and acted upon within a semantic framework, ensuring both transparency for experts and interoperability with external infrastructures (see subsection 3.3 for the risk assessment framework that complements this ontology-based representation).

The integration of those various layers of documentation transforms the ARGUS digital twin into more than a passive repository. It becomes an *active decision-support system* that combines multiple functions. Through continuous ingestion of sensor streams the system supports **real-time monitoring** of asset conditions. Automated workflows then provide **AI-supported diagnostics**, detecting anomalies and inferring their potential causes—for instance, correlating increases in humidity with rainfall events or patterns of visitor traffic. On this basis, the twin enables the **predictive assessment** of future risks, including sea-level rise, freeze-thaw cycles, or vegetation overgrowth and structural threats, drawing upon both historical trends and trajectory forecasts.

This approach also addresses a long-standing challenge in digital heritage: the disconnection between scientific monitoring data and management decision-making. By embedding the ICCROM/CCI ABC risk model directly into the semantic layer, ARGUS ensures that quantified risks can be linked to both measurements and management actions. Moreover, by adhering to FAIR principles (Wilkinson et al. 2016) and leveraging established ontological standards, the system aligns with European efforts toward interoperable, federated infrastructures for heritage science (Geser et al. 2023; Striova et al. 2017; Medici et al. 2022). In this way, ARGUS advances the field from documentation-oriented digital models toward *multimodal, risk-aware, and semantically-enabled digital twins*. These not only record the present state of heritage assets but also anticipate future challenges, support preventive interventions, and foster inclusive cultural stewardship through transparent and participatory digital ecosystems.

3.2. Data Architecture and Processing

A central innovation of ARGUS lies in its data architecture, designed to capture, integrate, and manage highly heterogeneous datasets across scales and modalities. Cultural heritage sites are complex socio-ecological systems, and monitoring them requires combining long-term archives with new sensor observations and large-scale Earth Observation products. The ARGUS framework therefore implements a layered approach, structured around three main data categories and a unified processing pipeline.

1. **Pre-existing datasets.** These include cartographic and GIS layers, seismic records, digital elevation models (DEMs), climate series, orthophotos, archaeological surveys, and thematic geoscientific datasets. Extensive use is made of open European infrastructures such as the European Soil Data Centre (ESDAC), the European Marine Observation and Data Network (EMODnet), the European Geological Data Infrastructure (EGDI), and Copernicus services (e.g., CAMS). Historic aerial photographs and legacy surveys are also incorporated, where available. The challenge lies in harmonizing diverse coordinate systems, resolutions, and metadata quality while ensuring provenance documentation and temporal annotation.

2. **New sensor data.** Early-stage prototypes were designed to capture environmental and structural parameters, including gas sensors (CO_2, NO_2, SO_2), soil moisture, vibration and acoustic emission sensors, thermal and multispectral cameras, GNSS nodes, and microclimate loggers. Both static in-situ stations and drone-mounted platforms were tested to evaluate static versus dynamic monitoring configurations. Particular emphasis was placed on low-power protocols (e.g., LoRaWAN) and open data standards (SensorML,

OGC SWE), ensuring that new data streams can be ingested seamlessly into the ARGUS backend.

3. **Remote sensing data.** Multispectral satellite imagery and time-series data and aerial photography provide landscape-scale coverage. For instance, legacy orthophotos (where available) allow diachronic change detection, while Sentinel-2 and Landsat imagery support site-wise diagnostics, like vegetation monitoring and erosion modelling. These data complement in-situ sensors by capturing broader environmental dynamics (Agapiou 2017).

To operationalize these inputs, ARGUS implements a high-level data pipeline that (i) transforms heterogeneous formats into standardized geospatial data structures; (ii) normalizes temporal and spatial resolution to enable multi-scale analysis; and (iii) integrates sensor streams with legacy datasets in a GIS-compatible backend. Semantic enrichment and risk reasoning are performed through PANOPTES (see subsection 3.1), ensuring interoperability with heritage standards and sensor ontologies.

ARGUS adopts the FAIR data principles not as an abstract guideline, but through concrete and verifiable data management practices.

- Findable: all datasets, software, and publications are deposited in a dedicated Zenodo community with DOIs, DataCite metadata, and controlled keywords, following project-wide naming conventions.
- Accessible: open-access datasets are shared through Zenodo and OGC-compliant services, while sensitive data follow restricted or embargoed access with metadata always publicly available.
- Interoperable: data are structured using international standards such as SensorML, OGC, and DataCite, and semantically aligned through CIDOC CRM, SOSA/SSN, PROV-O, and controlled vocabularies including AAT, TGN, and LCSH.
- Reusable: ARGUS ensures full provenance, contextual descriptions, uncertainty metadata, licensing transparency, and long-term preservation via trusted repositories.

The PANOPTES ontology builds on these foundations by enabling machine-actionable heritage data that remain semantically meaningful, interoperable, and reusable across digital twin infrastructures. The ARGUS architecture, combined with this operational FAIR strategy, ensures that data are not only collected but also contextualized, discoverable, and reusable within a standards-based semantic backbone (Wilkinson et al. 2016). This overall data flow is summarized in Figure 3, which illustrates how heterogeneous inputs are semantically integrated through the PANOPTES ontology and subsequently linked to applications such as risk assessment, simulation, visualization, and decision support. By explicitly grounding multimodal data in CIDOC CRM and FAIR-aligned workflows, ARGUS provides a reusable blueprint for future heritage digital twins and European-scale cultural data spaces.
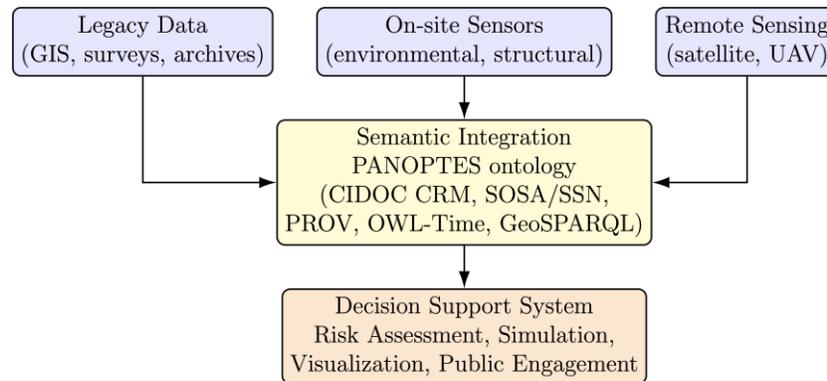
Figure 3: Simplified ARGUS data pipeline: heterogeneous inputs are semantically integrated via PANOPTES (see subsection 3.1) and then drive decision support, simulation, and visualization.

3.3. Risk Assessment Methodology

Risk assessment within ARGUS is grounded in the ICCROM/CCI *ABC method* (Michalski and Pedersoli 2016), which has been widely adopted in cultural heritage management as a structured, comparative approach for prioritizing conservation actions. The ABC framework enables managers to move beyond ad hoc or reactive interventions and to systematically identify, rank, and communicate risks. Its appeal lies in its relative simplicity, transparency, and adaptability to very different heritage contexts, from archaeological sites to museums and archives.

The method quantifies risk through three parameters:

- **A (Frequency):** The estimated likelihood of occurrence of a specific threat or hazard within a given time frame.
- **B (Loss of value):** The expected loss of cultural significance or value should the threat materialize. This can include historical, artistic, scientific, or social values.
- **C (Fraction affected):** The proportion of the heritage asset (object, collection, or site) that would be impacted by the threat.

Each parameter is scored on a five-point scale (1 = minimal, 5 = maximal), and combined to produce a *Magnitude of Risk* (MR):

$$MR = A + B + C, \qquad MR \in [3, 15]$$

The interpretation of MR follows a quasi-logarithmic model, where each unit increase represents a significant escalation in risk level. This supports the ranking of risks across multiple sites or collections, and facilitates decision-making when resources are limited. For example, an MR of 12 indicates a qualitatively much higher level of concern than an MR of 9, even if the numerical difference seems small.

While the ABC method is not fully objective—its scoring depends on expert judgment and contextual knowledge—it provides a common language for conservation stakeholders. In ARGUS, this framework is coupled with multimodal sensing and AI analytics, enabling more evidence-based estimation of frequency (Aand fraction affected (C). By feeding monitoring data directly into the scoring process, ARGUS envisions to reduce subjectivity and strengthens repeatability.

Within the project, ABC evaluations have been piloted at all five sites, highlighting both common and site-specific threats. Common risks include fire, flooding, freeze--thaw cycles, and fluctuations in relative humidity, which were identified across multiple contexts. At the same time, local conditions reveal distinct vulnerabilities, like high salinity and coastal erosion in Delos, ventilation and landslide hazards in Baltanás, and abandonment-induced deterioration in Monti Lucretili. These results not only guide site-specific monitoring strategies but also help to establish a comparative risk hierarchy across pilots, demonstrating the versatility of the ABC method when integrated into a digital twin environment. In the broader architecture of ARGUS, ABC values act as a bridge between raw data and decision support. By quantifying risks in a standardized form, they can be directly linked to semantic models in PANOPTES, visualized through GIS dashboards, and used to trigger preservation policies or predictive simulations. Thus, the ABC method is not simply applied in isolation, but becomes a core component of the multimodal digital twin, connecting measurement, interpretation, and action.

4. Discussion

The ARGUS framework demonstrates the feasibility of integrating heterogeneous data sources into a unified digital twin for cultural heritage management. By combining GIS infrastructures, multimodal sensing, semantic ontologies, and risk methodologies, ARGUS advances the state of the art beyond static documentation or isolated monitoring projects. Its contribution lies in showing that diverse data streams—ranging from legacy surveys to real-time IoT sensors—can be meaningfully fused and contextualized to support preventive conservation.

The framework provides three areas of promise. First, **sustainability**: the use of low-power sensor prototypes, open-source GIS platforms, and modular ontology design ensures that the system can be scaled across different sites without prohibitive costs. This is essential for remote or resource-constrained heritage contexts, where expensive proprietary systems are rarely viable. Second, **interoperability**: ontology-driven integration (via PANOPTES) aligns with FAIR principles (Wilkinson et al. 2016), guaranteeing that collected data remain findable, accessible, interoperable, and reusable across institutions and infrastructures. By adopting standards such as CIDOC CRM, SOSA/SSN, and PROV-O, ARGUS ensures compatibility with existing European research infrastructures including ARIADNEplus (Geser et al. 2023), 4CH (Medici et al. 2022), and E-RIHS (Striova et al. 2017). Third, **adaptability**: real-time risk assessment enables preventive interventions that are responsive to evolving conditions rather than limited to post-damage repair. Participatory methods, ranging from Living Labs to broader community workshops, strengthen inclusivity, ensuring that digital twin infrastructures are not restricted to experts but can incorporate community knowledge and perspectives.

Our work builds upon earlier initiatives such as HDTO and RHDTO (Niccolucci et al. 2023; Niccolucci and Felicetti 2024), which underscored the value of semantic formalization in heritage digital twins. ARGUS extends these foundations by embedding the ICCROM/CCI ABC methodology and multimodal sensing into an ontology-driven architecture, thereby operationalizing risk-aware preservation across diverse European contexts. In this way, ARGUS moves from conceptual modeling to an implementable decision-support system tested in real-world pilot sites.

At the same time, several challenges remain. Semantic harmonization across highly diverse datasets is complex, particularly when dealing with inconsistent legacy records. Ensuring usability for non-expert stakeholders requires careful design of interfaces and visualizations, balancing

scientific precision with accessibility. Ethical considerations also arise, including questions of ownership of sensor data, representation of cultural values in digital models, and the potential commodification of heritage information. These issues demand critical reflection alongside technical innovation.

While ARGUS integrates AI-driven analytics in its broader architecture, the present contribution focuses on the semantic and structural foundations of the ontology-driven digital twin. The environmental impact of specific AI models will be examined in future work where model design, training strategy, and computational efficiency become the primary focus.

Overall, ARGUS illustrates both the potential and the limits of current digital twin approaches in cultural heritage. Its ongoing work will help refine how multimodal integration, risk modeling, and participatory practices can be scaled and generalized, informing future European and global infrastructures and shaping a new generation of heritage science tools.

5. Conclusion

ARGUS pioneers a multimodal digital twin framework tailored to the preventive preservation of cultural heritage. The project has already demonstrated the feasibility of unifying heterogeneous data streams within a GIS-based backbone, integrating early sensor prototypes, applying the ICCROM/CCI ABC methodology for risk assessment, and developing an ontology-driven semantic layer through PANOPTES. These achievements highlight the capacity of digital twins not only to represent the present condition of heritage assets but also to anticipate risks and inform conservation planning.

Looking forward, the focus of ARGUS is on consolidating these components into a fully operational decision support system. This involves the integration of AI-driven analytics for anomaly detection and predictive modeling, the deployment of dynamic workflows that connect monitoring with conservation actions, and the expansion toward federated digital twins capable of linking multiple sites and institutions. Equally important is the enrichment of the system with participatory tools that enable citizens, local communities, and heritage professionals to engage with complex data through intuitive interfaces and immersive experiences.

By bridging sensing, semantics, and simulation, ARGUS contributes to a paradigm shift in cultural heritage management, emphasizing predictive and adaptive strategies rather than post-damage responses. It extends the foundations of earlier digital twin efforts with explicit risk methodologies and multimodal data integration, offering a concrete pathway from conceptual models to actionable infrastructures. In doing so, it aligns with broader European initiatives for digital heritage, sustainability, and climate resilience, and provides a model for embedding digital heritage management within future European policies and research infrastructures, directly supporting the objectives of Horizon Europe and European Green Deal. The project thus charts a pathway toward future-proof stewardship of cultural heritage, where advanced technologies are embedded in socially inclusive and ethically grounded practices.

Supplementary Materials

No supplementary material accompanies this article.

Data Availability Statement.

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: G.Pa., A.Ko., D.Ts., A.Sa., A.Ag., S.Sa.; methodology: M.Ka., V.Se., V.Ar., M.Po, V.Kl., A.Ag., P.Ky., K.Be., S.Sa., T.Na., T.Va.; software: V.Se., V.Ar., V.Kl., Z.Bo., L.Ko., E.Fa., F.M.N., I.Ka., S.Ap., J.O.H., F.Ra., A.Pa., K.Mi., St.Pa., S.Sa., T.Na., T.Va.; validation: G.Pa., A.Ko., D.Ts., M.Ka., A.Sa., M.Po., V.Kl., Z.Bo., L.Ko., A.Ag., P.Ky., J.O.H., K.Be., S.Sa., T.Na., T.Va., D.Ath., C.Ma.; formal analysis: G.Pa., D.Ts., M.Ka., V.Se., V.Ar., Z.Bo., L.Ko., S.Sa., T.Na.; investigation: all authors; resources: all authors; data curation: L.Ko., F.M.N., A.Pa., K.Mi., St.Pa.; writing - original draft preparation: all authors; writing - review and editing: all authors; visualization: G.Pa., V.Se., V.Ar.; supervision: G.Pa., A.Ko., A.Sa., Z.Bo., E.Fa., I.Ka., S.Ap., A.Ag., D.At., S.Sa.; project administration: G.Pa., A.Ko.; funding acquisition: G.Pa.. All authors have read and agreed to the published version of the manuscript.

References

Agapiou, A., V. Lysandrou, D. D. Alexakis, et al. 2015. "Cultural Heritage Management and Monitoring Using Remote Sensing Data and GIS: The Case Study of Paphos Area, Cyprus." *Computers, Environment and Urban Systems* 54: 230–39. https://doi.org/10.1016/j.compenvurbsys.2015.09.003.

Agapiou, Athos. 2017. "Remote Sensing Heritage in a Petabyte-Scale: Satellite Data and Heritage Earth Engine\copyright Applications." *International Journal of Digital Earth* 10 (1): 85–102.

Aigner, Thomas. 2022. "Big Data of the Past Comes True – The Time Machine Initiative." *Proceedings of the 27th International Conference on Cultural Heritage and New Technologies (CHNT 2022)* (Vienna). https://chnt.at/wp-content/uploads/2022/10/ID132_Aigner.pdf.

Dang, Xinyuan, Wanqin Liu, Xuemin Chen, Shuang Li, and Jian Yu. 2023. "Digital Twin Applications on Cultural World Heritage Sites in China: A State-of-the-Art Overview." *Journal of Cultural Heritage* 64: 1–14. https://doi.org/10.1016/j.culher.2023.10.010.

Doerr, Martin. 2003. "The CIDOC CRM—An Ontological Approach to Semantic Interoperability of Metadata." *AI Magazine* 24 (3): 75–92.

Gabellone, Francesco. 2022. "Digital Twin: A New Perspective for Cultural Heritage Management and Fruition." *Acta Imeko* 11 (1): 7-pp.

Geser, Guntram, Julian Richards, Douglas Tudhope, Andreas Vlachidis, Stuart Jeffrey, and Holly Wright. 2023. "Achievements of the ARIADNE Initiative for Archaeological Data Sharing and Research with the ARIADNEplus Project." *Internet Archaeology* 64. https://doi.org/10.11141/ia.64.2.

Hadjimitsis, Diofantos, Athos Agapiou, Dimitrios Alexakis, and Apostolos Sarris. 2013. "Exploring Natural and Anthropogenic Risk for Cultural Heritage in Cyprus Using Remote Sensing and GIS." *International Journal of Digital Earth* 6 (2): 115–42. https://doi.org/10.1080/17538947.2011.602119.

Janowicz, Krzysztof, Armin Haller, Simon Cox, Danh Le Phuoc, and Kerry Taylor. 2019. "SOSA: A Lightweight Ontology for Sensors, Observations, Samples, and Actuators." *Journal of Web Semantics* 56: 1–10. https://doi.org/10.1016/j.websem.2018.06.003.

Jouan, Pierre, and Pierre Hallot. 2019. "Digital Twin: A HBIM-Based Methodology to Support Preventive Conservation of Historic Assets through Heritage Significance Awareness." *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 42: 609–15.

Jouan, Pierre, and Pierre Hallot. 2020. "Digital Twin: Research Framework to Support Preventive Conservation Policies." *ISPRS International Journal of Geo-Information* 9 (4): 228.

Medici, Marco, Alessandro Costantini, and Franco Niccolucci. 2022. *D3.1 – Design of the CH Cloud and 4CH Platform*. 4CH Project. https://doi.org/10.5281/zenodo.7701438.

Michalski, Stefan, and José Luiz Jr. Pedersoli. 2016. *The ABC Method: A Risk Management Approach to the Preservation of Cultural Heritage*. ICCROM and Canadian Conservation Institute. https://www.iccrom.org/sites/default/files/2017-12/risk_manual_2016-eng.pdf.

Niccolucci, F, B Markhoff, M Theodoridou, A Felicetti, and S Hermon. 2023. "The Heritage Digital Twin: A Bicycle Made for Two. The Integration of Digital Methodologies into Cultural Heritage Research [Version 1; Peer Review: 2 Approved with Reservations]." *Open Research Europe* 3 (64). https://doi.org/10.12688/openreseurope.15496.1.

Niccolucci, Franco, and Achille Felicetti. 2024. "Digital Twin Sensors in Cultural Heritage Ontology Applications." *Sensors* 24 (12): 3978. https://doi.org/10.3390/s24123978.

Quattrini, Ramona, Eva S. Malinverni, Paolo Clini, Romina Nespeca, and Enrico Orlietti. 2015. "From TLS to HBIM. High Quality Semantically-Aware 3D Modeling of Complex Architecture." *The*

International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences XL-5/W4: 367–74. https://doi.org/10.5194/isprsarchives-XL-5-W4-367-2015.

Striova, Jana, Francesco Rosi, Luca Pezzati, Costanza Cucci, and others. 2017. "The European Research Infrastructure for Heritage Science (E-RIHS)." *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XLII-2/W5: 661–67. https://doi.org/10.5194/isprs-archives-XLII-2-W5-661-2017.

Wilkinson, Mark D., Michel Dumontier, I. Jsbrand Jan Aalbersberg, et al. 2016. "The FAIR Guiding Principles for Scientific Data Management and Stewardship." *Scientific Data* 3: 160018. https://doi.org/10.1038/sdata.2016.18.