Open Technologies for the 3D Cultural Heritage Digitisation Pipeline

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Abstract

This paper introduces the 3D-4CH project and its open framework, i.e. a sustainable ecosystem of tools designed to overcome the fragmentation and limited maintainability of previous EU-funded 3D heritage initiatives. Aligned with the European Collaborative Cloud for Cultural Heritage (ECCCH), the framework integrates an end-to-end pipeline for 3D data generation and processing, semantic enrichment and long-term dissemination, including metadata and paradata inclusion. The 3D-4CH initiative bridges the gap between ICT research and operational heritage practices, ensuring the scalability and reproducibility of 3D digital assets for cross-institutional data sharing and preservation. All software components, including GitHub repositories and online processing frameworks, are openly available, in accordance with open science principles and FAIR data practices. Further information is available at https://www.3d4ch-competencecentre.eu/en/tools/.

1. Introduction

Within the framework of the Common European Data Space for Cultural Heritage and the European Collaborative Cloud for Cultural Heritage, a growing ecosystem of EU-funded initiatives is actively advancing the development of innovative Information and Communication Technology (ICT) solutions aimed at transforming and streamlining cultural heritage workflows. These efforts are particularly focused on enabling scalable and interoperable approaches for 3D data acquisition, processing, semantic annotation and dissemination, thereby supporting enhanced documentation practices, remote accessibility, advanced analytical capabilities and cross-institutional data sharing.

In this rapidly evolving context, several interdisciplinary and international projects, such as the 3D-4CH - The Online Competence Centre in 3D for Cultural Heritage[1], are contributing to the consolidation of a comprehensive digital ecosystem for cultural heritage. These initiatives aim to strengthen the digital competencies of heritage professionals, while simultaneously developing robust and user-oriented 3D processing pipelines, generating high-quality and standardized 3D content, and fostering synergies between academic research and operational practices. The emphasis is not only on technological innovation but also on capacity building, reproducibility, and long-term accessibility of digital resources.

Previous European projects, such as EPOCH and 3D-ICONS, have addressed related challenges by proposing methodological frameworks and processing pipelines tailored to the specific needs of the heritage domain (e.g., Nocerino et al., 2017). However, despite their significant contributions, the sustainability, maintainability and long-term availability of the developed research tools and platforms have often remained limited, hindering their widespread adoption and reuse by public and private end-users.

Against this background, the present paper provides a technical overview of the ongoing collaborative developments within the 3D-4CH initiative. In particular, it focuses on the design and implementation of an integrated, open and sustainable framework for 3D digitization, semantic enrichment, management and dissemination of 3D heritage assets. The proposed 3D-4CH framework aims to ensure interoperability, scalability and long-term preservation of both data and services, in alignment with current European strategies for digital heritage.

1.1 The 3D-4CH project

The EU-funded Online Competence Centre in 3D for Cultural Heritage - 3D-4CH[1] - brings together 22 beneficiaries, 2 affiliated and 5 associated partners to empower cultural professionals with reliable 3D tools, training and resources for 3D digitization, AI, and XR applications, fostering innovation across education, tourism and research. 3D-4CH (2025-2028) builds on the shoulders of past successful EU projects like 4CH[2] and 5Dculture[3] and aims to help cultural heritage (CH) end-users to effectively adopt 3D and other advanced technologies for preserving and utilizing cultural heritage in various ways, including conservation, education and tourism.

2. Related works

The digitisation of CH assets through 3D reconstruction has become a fundamental practice for documentation, conservation and dissemination (Remondino and Campana, 2014; Guidi and Frischer, 2020; Guillem et al., 2025). Many good examples and best practices at various scales have been presented in the past years (Levoy et al., 2000; Guidi et al., 2005; Remondino et al., 2009; Menna et al., 2016). At the same time, open-source technologies have emerged as feasible alternatives to proprietary solutions, offering transparency, reproducibility and cost-effectiveness. The typical 3D digitisation workflow (Remondino

[1] https://www.3d4ch-competencecentre.eu/
[2] https://www.4ch-project.eu/
[3] https://5dculture.eu/

et al., 2013) consists of sequential stages including design and planning, data acquisition, point cloud processing, semantic enrichment, visualization and metadata curation. The design phase is crucial to meet the digitisation project requirements and needs, and to ensure that the outcomes meet the expectations in terms of accuracy and data quality. The choice of the most suitable sensor (active-range, passive-image based) and technique is constrained by several factors, including digitisation scope and specifications, object size and complexity, accessibility and portability, time and budget (Guidi and Remondino, 2012). Each stage is supported by a set of diverse tools, often developed independently, which must be integrated into coherent frameworks. However, despite their increasing need and adoption, the open ecosystem remains fragmented, requiring critical analyses across the entire digitisation pipeline, from data acquisition to visualization and dissemination.

2.1 Image-based 3D reconstruction and rendering

At the core of most CH digitisation workflows lies photogrammetry, typically implemented through automated procedures nowadays called Structure-from-Motion (SfM) and Multi-View Stereo (MVS) (Remondino et al., 2017). These methods reconstruct sparse and dense geometry from overlapping image sets, forming the backbone of 3D documentation pipelines. The most widely adopted open photogrammetry technologies include (Pamart et al., 2026a): COLMAP[4] (Schönberger, 2018), OpenMVG[5] + OpenMVS[6] (Moulon et al., 2016), MicMac[7] (Rupnik et al., 2017), AliceVision / Meshroom[8]. Other solutions only include the image orientation / SfM step, e.g., Theia (Sweeney et al., 2015), PixSfM (Lindenberger et al., 2021) or GLOMAP (Pan et al., 2024). Recent learning-based 3D reconstruction methods (Wang et al., 2026) are also promising - e.g. VGGSfM (Wang et al., 2024a), DUSt3R (Wang et al., 2024b), MASt3R (Leroy et al., 2024), VGGT (Wang et al., 2025), Spann3R (Wang and Agapito, 2025), MapAnything (Keetha et al., 2025), or FAST3R (Yang et al., 2025), although their metric aspects, reliability, and replicability are very low. Some research packages embed a combination or customization of the abovementioned solutions, such as GRAPHOS (Gonzalez-Aguilera et al., 2018) or PhotoMatch (Ruiz de Oña et al., 2023) while open libraries for tie point extraction are available in DIM[9] (Morelli et al., 2024). These frameworks are capable of handling quite large and unordered image datasets and provide full access to algorithmic parameters through the scientific literature, enabling reproducibility and project-based fine-tuning. COLMAP and Meshroom offer a GUI that exposes each processing stage, enhancing transparency and educational value. Despite their maturity, open photogrammetric pipelines generally exhibit several limitations, such as slow processing for large datasets due to the lack of algorithmic optimization and limited support for metric scaling / georeferencing via ground control points (GCPs).

The recent advances in neural rendering have introduced new methods for representing 3D scenes or objects using implicit or explicit representations. Among them, Neural Radiance Fields - NeRF (Mildenhall et al., 2020) and 3D Gaussian Splatting - GS (Kerbl et al., 2023) recently emerged as particularly influential methods. These methods do not use explicit geometry (points or meshes) but learn how the object looks from any viewpoint. Most of these tools are open (LichtFeld Studio[10]; Nerfstudio[11] ; Liu et al., 2025[12]; Ye et al., 2025[13]).

2.2 Range-based 3D surveying techniques

Often called laser scanner or LiDAR (Shan and Toth, 2008; Vosselman and Maas, 2010), they enable the creation of accurate digital representations of objects, monuments and sites by directly capturing their geometry in a non-contact, non-invasive manner. The quality and resolution of the resulting 3D data depend on several factors, including the choice of scanner, the intended use of the data and the resources available for the project. 3D recordings are performed through triangulation or time-of-flight measurement principles, following an optimal acquisition planning to ensure the lowest number of scans (for static acquisitions) while covering the entire object surface, with sufficient overlap for data registration for achieving the required geometric accuracy.

2.3 Point cloud processing and classification

The resulting image- or range-based dense point clouds require further processing, including cleaning, simplification, and analysis. Key open-source tools include CloudCompare[14] - specifically dedicated to point cloud processing, segmentation and comparison, MeshLab[15] - widely used for mesh editing, simplification and quality assessment (Cignoni et al., 2008), Open3D[16], a library for programmatic 3D data processing and algorithm development or CGAL[17], an software project that provides easy access to efficient and reliable geometric algorithms in the form of a C++ library. Generally, there is a fragmentation between GUI-based and programming environments, with low reliability and efficiency of tools in the case of large datasets. Further operations include semantic enrichment based on machine/deep learning methods (Grilli and Remondino, 2019; Grilli and Remondino, 2020; Cirigliano et al., 2025; Mazzacca and Remondino, 2026) and annotated data (Ponchio et al., 2020). Heritage 3D data classification is indeed becoming a requested solution as semantic enrichment opens many possibilities for analyses and understanding that only geometric data cannot offer. The geometric complexity and class variability (without standards) in the heritage sector, together with the difficulty of obtaining large, annotated datasets, represent significant challenges, especially in the context of deep learning (Teruggi et al., 2020). Supervised machine learning methods played an important role some years ago (Matrone et al., 2020), while nowadays the research community is investigating more on 3D deep learning approaches (Matrone et al., 2023).

2.4 3D modeling

The processed geometric data are afterwards typically refined and visualized using general-purpose 3D software, such as Blender[18]. These tools enable the creation of high-quality visual outputs, including physically-based rendering (PBR), relighting, and immersive experiences.

[4] https://colmap.github.io
[5] https://github.com/openMVG/openMVG
[6] https://github.com/cdcseacave/openMVS
[7] https://micmac.ensg.eu/
[8] https://alicevision.org/#meshroom
[9] https://github.com/3DOM-FBK/deep-image-matching
[10] https://github.com/MrNeRF/LichtFeld-Studio
[11] https://github.com/nerfstudio-project/nerfstudio
[12] https://github.com/RongLiu-Leo/beta-splatting
[13] http://www.gsplat.studio/
[14] https://www.cloudcompare.org/
[15] https://www.meshlab.net/
[16] https://www.open3d.org/
[17] https://www.cgal.org/
[18] https://www.blender.org/

2.5 Annotations and metadata enrichment

The enhancement of 3D documentation practices is generally achieved by two complementary approaches. The first concerns hard data (e.g. sensor-based and quantitative aspects) when a 3D model is augmented by visual or geometric features. The second concerns soft data (e.g., semantic and qualitative aspects), where observations and expert knowledge enhance the documentary value of a digital resource. The literature also reports the use of metadata and paradata, the former to describe the content and structure of data or how they are acquired, the latter to documents the process and methodology used to create, collected or manipulated the digital heritage asset (Lorenzini et al., 2021: Ammirati et al., 2025; Guillem et al., 2025). Today, promising approaches are emerging to bridge the gap between all this information and data, and open tools are becoming available (Abergel et al., 2023[19]; Anamnesis[20]; De Luca et al., 2026).

2.6 3D content management

The management, storage and dissemination of 3D assets remain significantly less mature than for traditional 2D or textual resources. Large-scale aggregators such as Europeana, currently contain only a very limited proportion of 3D models, highlighting persistent challenges such as heterogeneity of formats, large file sizes, incomplete or inconsistent metadata, insufficient documentation of provenance and paradata, and the lack of harmonised standards for online publication (EuropeanaTech Task Force on 3D, 2020). Effective 3D content management requires repository infrastructures capable of supporting the full lifecycle of 3D assets - including ingest, validation, structured metadata enrichment, versioning, long-term preservation, semantic annotation, transformation and web delivery - while ensuring interoperability and compliance with FAIR principles (Wilkinson et al., 2016). The increasing demand for 3D datasets for research, conservation, AI-based, education and XR applications further reinforces the need for robust systems that can deliver 3D content in machine-actionable, reusable formats (Guidi and Frischer, 2020). In this context, these gaps are addressed by developing advanced tools for structured, scalable 3D data management and publication: examples include Repox[21], a platform for comprehensive 3D asset lifecycle management, and Share3D Dashboard[22], a user-friendly web-based tool for the interoperable publication of 3D cultural heritage models to Europeana. Zenodo[23] has recently been adopted as a primary input source for storing 3D models, despite its limited support for structured metadata.

3. 3D-4CH tools for the 3D digitization pipeline

3.1 Online 3D reconstruction framework

Based on several active open-source projects related to Photogrammetry and neural rendering technologies, together with existing libraries and front-end solutions for supporting 3D visualization of open formats, a 3D reconstruction pipeline is developed. The framework combines the COLMAP, OpenMVG and OpenMVS for the photogrammetric part, whereas Nerfstudio and Beta Splatting for the radiance field part. From a user's perspective, images are uploaded to the server, parameters and processing methods are selected and, once the 3D reconstruction is performed, results can be downloaded in an open format or visualize it in a web assembly-based online 3D viewer. All services can be accessed through a REST API and there is an Android application allowing smartphone image uploading to the server and retrieving or visualizing the generated 3D model (Figure 1). The communication between components, services and online 3D viewers is based on the XRCulture[24] open middleware protocol.

Figure 1. Examples of heritage artefacts produced with the online 3D reconstruction framework of 3D-4CH.

3.2 Metadata and annotation-based semantic enrichment

3.2.1 Aioli

Aioli is a collaborative spatial annotation platform enabling users to construct custom descriptive structures and perform 2D-to-3D annotations from photogrammetric scenes (Abergel et al., 2023). For each observation, users draw an annotation on an oriented image, which is then automatically projected as a 3D annotation onto the point cloud (Figure 2). Each annotation can be enriched by free-from attributes (text, date, data, or linked resource). At the end of an annotation process, users can export 2D and 3D labels along with their description sheets and geometric descriptors. This approach is highly relevant for facilitating multidimensional semantic labelling to feed AI-based classification (Croce et al., 2023). A major advantage of Aioli is that a single annotation is automatically propagated to all images where the corresponding 3D region appears. Aioli has been extensively used on the scientific worksite of Notre Dame de Paris, providing more than 14,000 spatialised annotations to enrich the multidimensional model of expert observations (Roussel et al., 2023). Aioli ingests, through Python scripting, image-based reconstruction results from various photogrammetric tools (Pamart et al, 2020). Users can structure their labelling classes freely in groups and sub-groups completed with custom descriptive fields (text, number, date, or joint file). After the interactive annotation process, an export function delivers all geometric outputs (segmented point cloud in PLY, 2D and 3D mask in SVG) and semantic files (CSV, JSON etc).

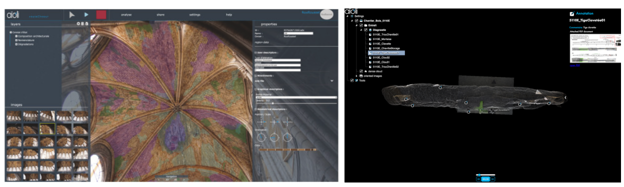

Figure 2. Examples of Aioli online platform for image annotation.

3.2.2 Anamnesis

Anamnesis is a web application dedicated to documenting data provenance within the digitization workflow. It enables the structuring and management of metadata and paradata using the W7 model (Liu and Ram, 2017). The platform offers cultural heritage practitioners a dedicated tool to enrich their digital

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[19] https://www.map.cnrs.fr/en/research-activities/projects/aioli/
[20] https://anamnesis.espadon.net/
[21] https://repox.io/en
[22] https://www.share3d.eu/en/
[23] https://zenodo.org/
[24] https://xrculture.eu/

https://doi.org/10.5194/isprs-archives-XLIX-B2-2026-787-2026

workflows by documenting protocols in a structured way, following the FAIR principles. The platform provides an intuitive framework to record the digital scaffolding of workflows without requiring expertise in metadata schemes and standards. Its main advantage is that it brings together, at the moment of creation, all information needed to reinforce data provenance and ensure data lineage (Pamart et al., 2026b). At the end of a digitization workflow, metadata and paradata can be automatically shared to repositories, bridging the gap between data providers and data curators (Guillem et al., 2025). The core engine of Anmnesis relies on orchestrated PIDs management to share and link resources using external (GeoNames, CORDIS, Orcid) and internal resources (OpenTheso, OntoPortal), enlarging interoperability capacities. Users can manage technical schemes related to conventional imaging workflows (image and range-based modelling), organize and share a collection of assets, or create templates for instrumental set-up or reproducible datasets to accelerate metadata ingestion. At the end of a documentation process, user can export curated metadata in JSON format combined with an advanced mapping export function to enlarge metadata compliance with standard schemes (EDM, GoTriple, DublinCore, etc).

3.2.3 Point cloud annotator

Semantic segmentation of 3D data (mainly point clouds and meshes) relies on supervised AI solutions that rely heavily on high-quality training (annotated) data. Although zero-shot and unsupervised approaches have been presented (Alami and Remondino, 2026), their applicability in the heritage sector is very limited. Pre-trained AI models are therefore the most used, although they are sufficient only for similar tasks (and classes) that resemble on which they are trained on. However, in domain-specific applications, training on custom datasets is essential and new (manual) annotations by humans are mandatory.

The 3D-4CH Annotator (Figure 3) is a platform that integrates web-based 3D point cloud visualization technologies (Potree library[25]) and extends it further by implementing server-side mechanisms for performing low-level data alterations, in order to offer users a collaborative, multi-user and multi-platform tool that can enhance 3D point clouds with semantic annotations. The Annotator allows for manual labelling of data that can then be used to train a neural network model. Afterwards, the inference on an unseen part of the cloud is run on the server and the classified results are converted into the Potree format for the online visualization. Users can review the output of the AI-based classification and proceed again with further annotation, fine-tuning and inference adjustments, if needed.

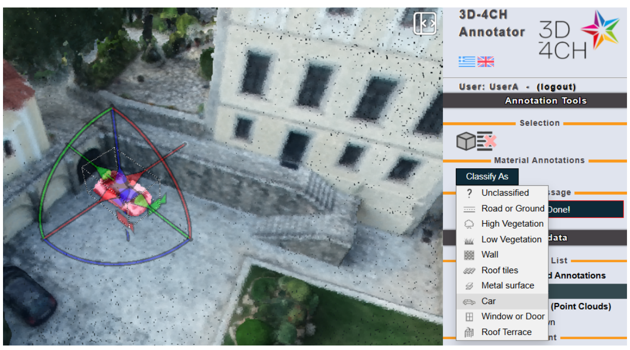

Figure 3. A point cloud visualized in the annotation tool: a user identifies and selects areas of the point cloud requiring annotation using volume boxes.

3.3 Point cloud classification

Beside the classification capabilities inside the Annotator tool (Section 3.2.3), two other 3D classification methods are available for offline processing (i.e. model training based on specific training data and inference): (i) a supervised machine learning method, based on Random Forest (Breiman, 2001) (Figure 4a) and (ii) a multi-level multi-resolution deep learning approach, based on Point Transformer (Wu et al., 2023), trained specifically for aerial archaeological applications (Cirigliano et al., 2025) (Figure 4b).

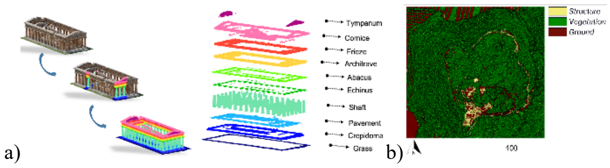

Figure 4. Machine (a) and deep (b) learning 3D classification results on terrestrial and aerial point clouds, respectively.

3.4 3D content management

3.4.1 3D assets lifecycle management

Repox is the core component of the 3D-4CH framework, to transform fragmented digital assets into structured and heritage assets. It treats 3D objects as cohesive information ecosystems, managing interconnected resources (e.g. raw data, processed models, metadata, etc.) within a unified environment, allowing institutions to manage, relate and preserve all associated assets within a single environment. The platform supports the full lifecycle of 3D content, from ingestion to dissemination, through a configurable data modelling engine with customizable schemas, controlled vocabularies and validation mechanisms, ensuring interoperability with established standards. Its storage abstraction layer, based on S3-compatible systems (e.g., AWS, Azure, MinIO), allows flexible deployment and scalability. Repox follows an integration-first approach, exposing all functionalities via REST APIs and supporting OAI-PMH for metadata publishing, facilitating interoperability with external systems. Advanced search capabilities (faceted, semantic, full-text) and fine-grained access control enable efficient data discovery and secure collaboration. An embedded web-based 3D viewer further enhances usability by supporting direct interaction with multiple 3D formats without additional software.

3.4.2 Publication and visualization of 3D data

The 3D-4CH framework is based on the open-source Share3D Dashboard (Figure 5), an open-source, standards-based platform designed for the structured documentation, visualization and publication of 3D cultural heritage assets. Its primary goal is ensuring interoperability with European aggregation infrastructures like Europeana. The legacy version (2018-2020) was developed in the Share3D project and integrated into the CARARE aggregation pipeline. It provided a metadata authoring environment for 3D models sourced from online repositories and utilized controlled vocabularies, supported serialization to the Europeana Data Model (EDM). The current version employs a modernized tech stack using OAuth 2.0 for secure repository integration and supports manual ingestion via direct file links for platforms like Zenodo. As Zenodo is not supporting metadata, the Share3D Dashboard enables manual ingestion of 3D models via direct file links, allowing data providers to host content externally while leveraging the platform for metadata enrichment and

[25] https://potree.github.io/

publication. The implemented metadata schema aligns with the latest European 3D guidelines, categorized into Identity, Place, Time, Copyright, Relations and Model Creation. Additional elements capture intended usage, the relationship between the digital model and its physical counterpart, as well as model typology and technical characteristics. For technical metadata extraction, the platform integrates the Metadata Extractor service of the 3d.repox.io ecosystem (Section 3.4.1), enabling automated metadata generation on a best-effort basis.

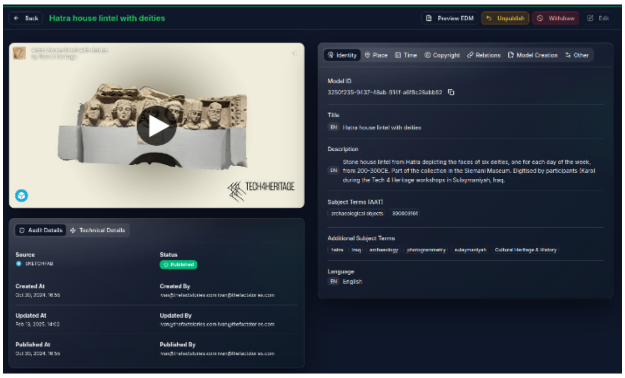

Figure 5. Metadata editing and visualization of a sample 3D model (originally hosted in Sketchfab) in Share3D.

Regarding visualization, the Share3D Dashboard dynamically selects the most appropriate rendering solution based on the source of the 3D model. When the source platform provides an embeddable viewer, it is used by default. In cases where no native viewer is available, the system utilizes the 3D Repox Viewer to ensure consistent visualization capabilities.

4. End-to-end experiment

All the previously described solutions, embedded in the 3D-4CH framework, are applied to a UAV dataset over an historic city centre (Old City of Xanthi). The dataset is composed of ca 400 nadir and oblique images (4000x3000 px). The generation of the mesh model in full resolution took ca 5h (Figure 6).

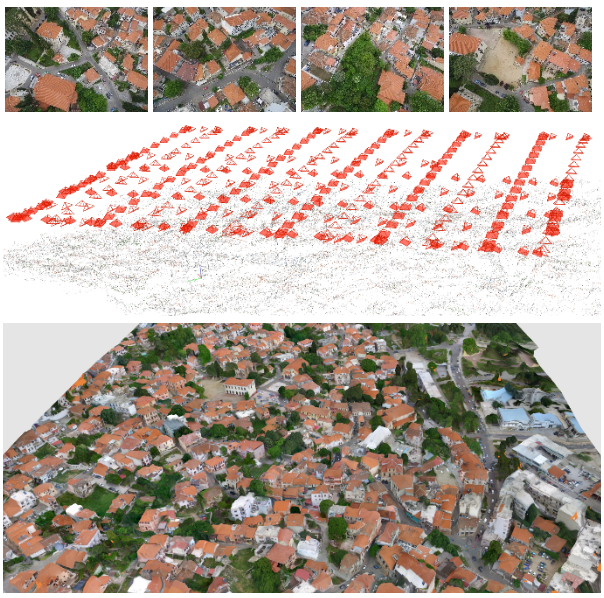

Figure 6. Some of the UAV images (top), the recovered camera poses and sparse point cloud (centre) and the mesh model of the historic city centre (bottom).

The successive 3D asset annotation is performed testing both Aioli and Annotator. Aioli revealed good stability and performances despite the large aerial drone dataset (Figure 7). The Aioli approach is particularly efficient to ease and fasten the creation of training sets thanks to its 2D-3D approach.

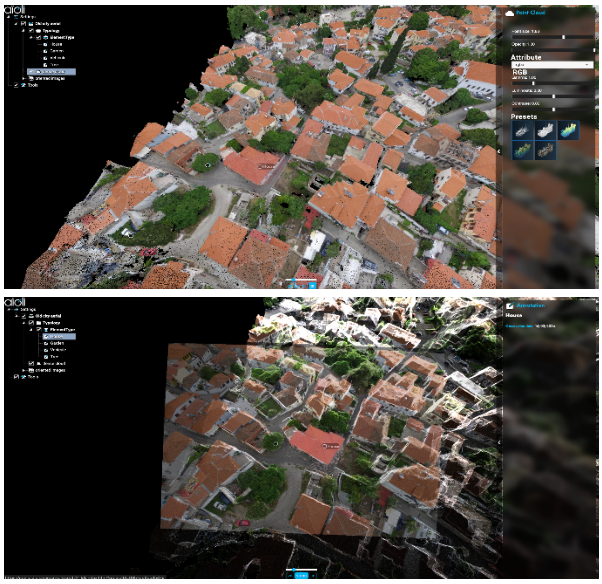

Figure 7. Example of annotations in Aioli.

Using Annotator a set of training data composed of 9 distinct classes is also created (Figure 8). Afterwards, three shallow classifiers (Logistic Regression, Support Vector Machines - SVM and Multi-Layer Perceptron - MLP), an ensemble of decision trees (Random Forest) and a deep neural network (PointNet) are used for point cloud classification. The shallow classifiers and Random Forest are trained on both geometric features (XYZ coordinates and normals) and radiometric features (colours) whereas the neural network is trained only using the XYZ coordinates.

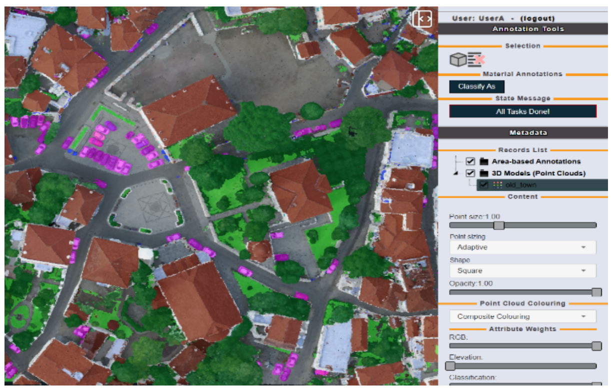

Figure 8. Point cloud semantic labelling using the 3D-4CH Annotator for machine/deep learning training.

PointNet achieved the best performance (Table 1, Figure 9), with consistently high accuracies (above 94%) for all classes. The model showed particularly strong results on the more dominant classes, such as roads, roof tiles and walls with accuracies exceeding 99%. In comparison, the shallow models performed adequately only on the dominant classes but struggled significantly on the less frequent ones. This highlights the advantage of the deep neural network approach, which not only avoids the issue of zero predictions but also offers a substantial improvement.

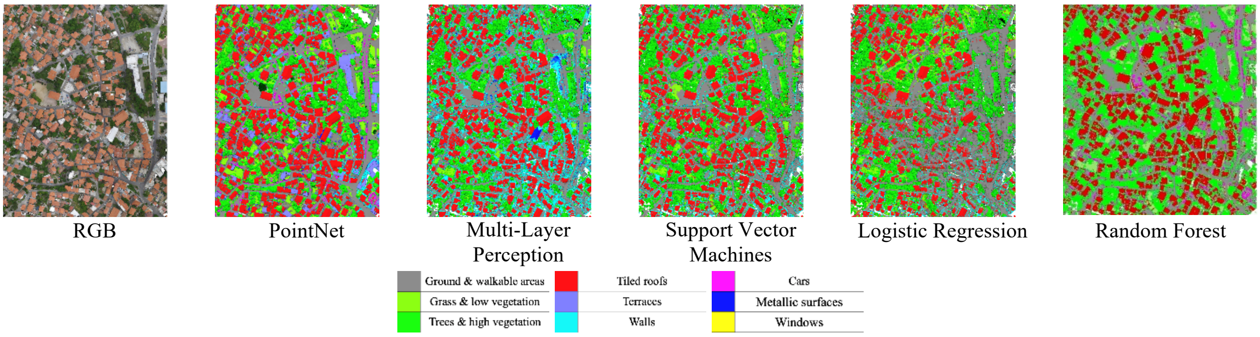

Figure 9. Visual results of the 3D classification process in the 9 shown classes.

Class\Method	PointNet	Multi-Layer Perceptron	Support Vector Machines	Logistic Regression	Random Forest
Ground	97.91	89.05	79.59	70.13	94.17
Low vegetation	96.98	91.82	88.51	80.23	66.65
High vegetation	99.01	92.24	87.31	78.09	99.55
Tiled roofs	99.76	97.51	95.75	89.13	94.26
Terraces	97.52	73.82	23.59	11.08	0
Walls	99.12	93.54	87.65	83.29	94.15
Cars	95.14	0	0	0	83.10
Metallic surfaces	94.53	41.83	17.25	2.1	0
Windows	96.04	0	0	0	60.79
Prediction Accuracy %	97.33	82.83	68.52	59.15	84.65

Table 1. Accuracy results (per class) for various 3D classification approaches.

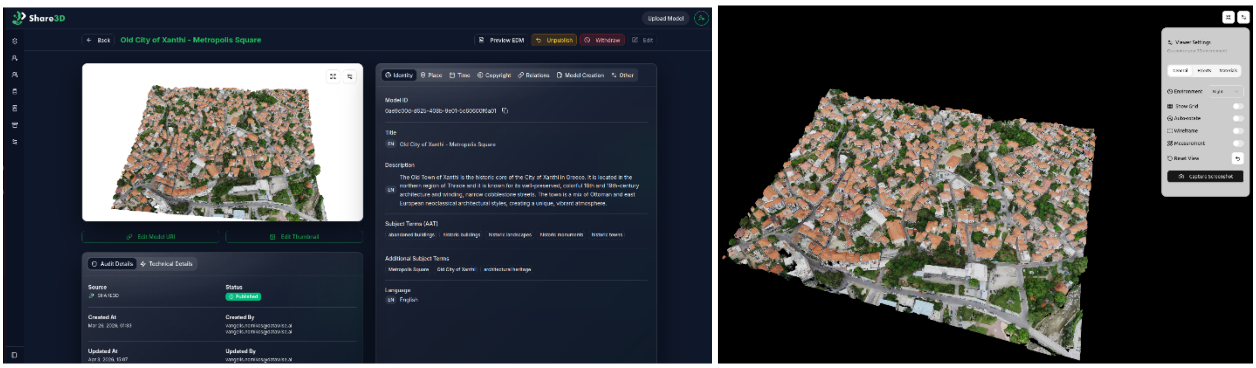

Figure 10. The record stored in Share3D Dashboard (left) and visualized with the Repox 3D viewer (right).

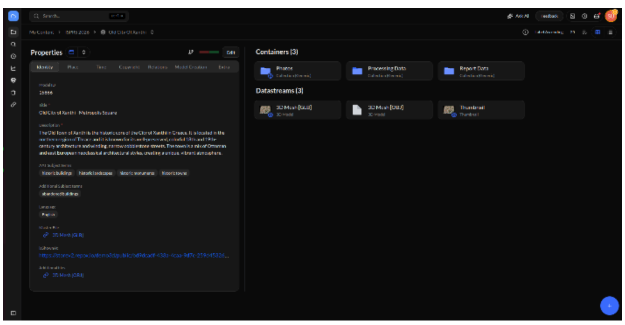

Figure 11. The complete information ecosystem of the 3D cultural heritage record as seen in Repox.

The heritage record is then ingested in Share3D (Figure 10) and Repox (Figure 11) to support content management, publication and visualization. Within the Share3D Dashboard, a direct link is provided to the output 3D model (e.g. GLB format) stored in Repox, enabling web visualization, metadata enrichment delivery to Europeana. The default Repox 3D viewer is used if no other embedded viewer is available. In Repox, a storage-based approach is followed, whereby files (e.g., input, processed and output data) are organized within a container/datastream hierarchy - similar to "folders" and "files" - with metadata assigned at each level.

5. Conclusions

The paper reports the ongoing technical developments for the realization of multiple ICT solutions for the 3D digitization, semantic enrichment, access, querying and visualization of 3D heritage assets. Within the activities of the 3D-4CH Competence Centre, all tools are developed in accordance with open science principles and FAIR data practices, trying to ensure scalability and reproducibility of processes for cross-institutional data sharing and preservation. The tools are made publicly available to empower cultural heritage professionals and organizations to use cutting-edge technologies for digital preservation and restoration, communication purposes and innovation, contributing to a digitally enriched cultural landscape in Europe.

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