

Developing the ArchAIDE Application: A digital workflow for identifying, organising and sharing archaeological pottery using automated image recognition

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Cite this as: Anichini, F. *et al.* 2020 Developing the ArchAIDE Application: A digital workflow for identifying, organising and sharing archaeological pottery using automated image recognition, *Internet Archaeology* 52. <https://doi.org/10.11141/ia.52.7>

Summary



Overview of the ArchAIDE workflow (60 seconds). Taken from [ArchAIDE consortium \(2019\)](#)

Pottery is of fundamental importance for understanding archaeological contexts, facilitating the understanding of production, trade flows, and social interactions. Pottery characterisation and the classification of ceramics is still a manual process, reliant on analogue catalogues created by specialists, held in archives and libraries. The [ArchAIDE project](#) worked to streamline, optimise and economise the mundane aspects of these processes, using the latest automatic image recognition technology, while retaining key decision points necessary to create trusted results. Specifically, ArchAIDE worked to support classification and interpretation work (during both fieldwork and post-excavation analysis) with an innovative app for tablets and smartphones. This article summarises the work of this three-year project, funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement N.693548, with a consortium of partners representing both the academic and industry-led ICT (Information and Communications Technology) domains, and the academic and development-led archaeology domains. The collaborative work of the archaeological and technical partners created a pipeline where potsherds are photographed, their characteristics compared against a trained neural network, and the results returned with suggested matches from a comparative collection with typical pottery types and characteristics. Once the correct type is identified, all relevant information for that type is linked to the new sherd and stored within a database that can be shared online. ArchAIDE integrated a variety of novel and best-practice approaches, both in the creation of the app, and the communication of the project to a range of stakeholders.

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- Keywords: pottery, ceramic, digitisation, machine learning, app development, image recognition, archaeology, identification, classification
- Related digital archives: ArchAIDE consortium (2019) ArchAIDE Portal for Publications and Outputs [data-set]. York: Archaeology Data Service [distributor] <https://doi.org/10.5284/1050896> and the [ArchAIDE software on Github](#)
- This open access publication was funded by the European Union's Horizon 2020 Research and Innovation Programme under grant agreement N.693548.

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1. Introduction

Every day, archaeologists are working to discover and tell stories using objects from the past, investing considerable time, effort and funding to identify and characterise individual finds. Pottery is of fundamental importance for the comprehension and dating of archaeological contexts, and in order to understand the dynamics of production, trade flows, and social interactions. Today, characterisation and classification of ceramics are carried out manually, through the expertise of specialists and the use of analogue catalogues held in archives and libraries. While not seeking to replace the knowledge and expertise of specialists, the [ArchAIDE project](#) worked to optimise and economise identification processes, developing a new system that streamlines the practice of pottery recognition in archaeology, using the latest automated image recognition technology. At the same time, ArchAIDE worked to ensure archaeologists remained at the heart of the decision-making process within the identification workflow, and focused on optimising tasks that were repetitive and time consuming. Specifically, ArchAIDE worked to support the essential classification and interpretation work of archaeologists (during both fieldwork and post-excavation analysis) with an innovative app for tablets and smartphones.

The ArchAIDE project was funded by the European Union's [Horizon 2020 Research and Innovation Programme](#) under grant agreement N.693548, with a consortium of partners representing both the academic and industry-led ICT domains, and the academic and development-led archaeology domains. The archaeological partners within the consortium were the [MAPPA Lab](#) at the University of Pisa (coordinator) which has relevant experience in mathematical and digital applications in archaeology and archaeological communication; the [Material Culture and Archaeometry research unit](#) at the University of Barcelona, which is focused on promoting studies of material culture, especially relating to archaeological ceramics and archaeometric approaches; the [Digital Archaeology Laboratory](#) at the University of Cologne, which manages ARACHNE, a highly structured object database in partnership with the [German Archaeological Institute](#) (DAI); and the [Archaeology Data Service](#) (ADS) at the University of York, which is a world-leading digital data archive for archaeology. The consortium also includes two companies carrying out rescue and development-led archaeological investigations: [Baraka Arqueólogos S.L.](#), which has particular expertise in the study of archaeological ceramics, and [Elements S.L.](#) which is experienced in the application of digital technologies related to ceramic studies. Finally, the consortium's technical ICT partners were the [Visual Computing Lab at CNR-ISTI](#), an institute of Italian CNR devoted to research on Visual Media and Cultural Heritage; the Deep Learning Lab at the [School of Computer Science](#) at Tel Aviv University, which focuses on document analysis, image textual description, and action recognition; and a private software company, [Inera s.r.l.](#), which has development experience in the field of protocols and web apps.

The collaborative work of the archaeological and technical partners created a pipeline where potsherds are photographed, their characteristics compared against a trained neural network, and the results returned with suggested matches from a comparative collection with typical pottery types and characteristics. Once the correct type is identified, all relevant information for that type is linked to the new sherd and stored within a database that can be shared online. This goal has been implemented through the creation of the following practical elements:

- A digital comparative collection for multiple pottery types, incorporating existing digital collections, digitised paper catalogues and multiple photography campaigns.
- An automated-as-possible workflow to digitise paper catalogues accurately and improve the search and retrieval process (Figure 1).
- A multilingual thesaurus of descriptive pottery terms, mapped to the Getty Art and Architecture Thesaurus including mappings in French, German, Spanish, Catalan, English and Italian.
- Two distinct neural networks for appearance-based and shape-based recognition.
- An app using digital comparative collections to support archaeologists in recognising potsherds during excavation and post-excavation analysis, with an easy-to-use interface and efficient image recognition algorithms for search and retrieval, based on either shape or decorative characteristics.
- Once a sherd has been recognised, the app can be used to automatically populate the relevant type information about the sherd into a virtual assemblage for a site, including the generation of an identity card as a formatted, digital or printable document.



Figure 1: Overview video of the ArchAIDE workflow (2 mins 21 seconds) Taken from [ArchAIDE consortium](#) (2019)

The underlying technologies developed for the app were also implemented as a desktop application, which is a web-based, real-time data visualisation resource, to improve access to archaeological heritage and generate new understanding. Both the desktop application and the app can also be used as a tool to aid learning about pottery identification, either for students or when specialists are not available.

1.1 Methodology, specification and design

As suggested by (Orton and Hughes [2013](#), 48), 'wherever possible it is much better to have a finds specialist at hand on site'. The specialist can give instant advice and identification, allowing (1) dating and (2) quantification. Dating allows the formulation of working hypotheses for the phasing of a site, whereas quantification is a way to record general pottery characteristics, i.e. the proportions of the different ceramic types that comprise an assemblage. This allows archaeologists to interpret and understand the dynamics of production, trade flows, social interactions, etc. Pottery recognition requires complex skills, is heavily dependent on human inspection and interpretation, while also being a very time-consuming and often repetitive activity.

To address the time-consuming and repetitive aspects of pottery recognition, the ArchAIDE system was designed to support a more automated pottery identification workflow, meeting real user needs and reducing time and costs within both academic and professional archaeology (Figure 2). Although similar in methodological approach, the goals, costs, and types of available expertise between academic and professional archaeology can vary tremendously. The first is less bound by time pressures, and typically allows more time for post-excavation documentation. The second, often related to development-led archaeology, is usually closely bound by time pressures, and often carried out by teams composed of professional archaeologists, where specialist training and/or access to specialist knowledge is at a premium.

As a discipline, archaeology is often an early adopter of novel technologies, but on the whole, maintains a conservative approach when it comes to replacing well-established methods. As such, ArchAIDE has been careful to support good practice, rather than seek to change existing workflows, and the ArchAIDE system was designed to follow specialist methodologies: recognising a pottery type via observation of the profile/cut section shape, and/or through analysis of the decorative surface treatment.

As both speed and accuracy are important in pottery identification, the ArchAIDE system was designed to support the classification and interpretation work of archaeologists (during both fieldwork and post-excavation analysis) through the creation of an innovative app designed for mobile devices and desktop computers. The app features an interface that facilitates the identification of a potsherd from a photograph, acquired using a camera from a typical mobile device. Within the app, the ArchAIDE system supports efficient and powerful algorithms for pottery characterisation. This allows search and retrieval of the possible visual/geometric correspondences against a complex database built from comparative data, derived from digital and analogue resources. In order to create the database, and the training data for the deep learning image-recognition algorithms, it was necessary to acquire robust comparative data for the specific pottery types chosen for the ArchAIDE proof-of-concept.

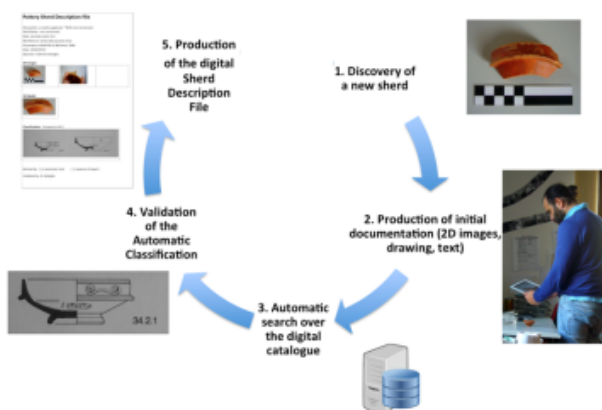


Figure 2: Illustration of the basic ArchAIDE workflow

The ArchAIDE database is composed of (1) a Reference Database and (2) a Results Database. The Reference Database contains a number of born-digital and digitised paper catalogues of pottery typologies, which have been combined to create a coherent comparative resource. The Reference Database was designed with a core catalogue, containing basic information about pottery classes and types that are common across different thematic and period-based pottery catalogues, with additional media (drawings, photographs, 3D models etc.) to aid the main recognition application. The Reference Database includes spatial data related to each type entity to allow data analysis and the creation of data visualisation, such as distribution maps.

To create the Reference Database, in addition to openly licensed resources (e.g. [Roman Amphorae: a digital resource](#), held by the ADS; University of Southampton [2014](#)), use of materials protected by copyright (e.g. paper catalogues) and/or by *sui generis* right (e.g. digital resource, held by the University of Cologne) required meticulous analysis of European InfoSoc Directive (Information Society Directive 2001/29/EC of 22 May 2001 on the harmonisation of certain aspects of copyright and related rights in the information society) and Database Directive (Directive 96/9/EC of 11 March 1996 on the legal protection of databases). While use of the necessary resources was possible thanks to the research exceptions justified for non-commercial purposes, copyright issues proved problematic for any commercial exploitation of the app, even when photography of a sherd or digitisation of resources in a paper catalogue were carried out by the ArchAIDE project itself.

The Results Database was intended to facilitate the capture of user-generated text and images in the field/laboratory. Once a sherd is identified using the automated image recognition algorithm against the reference dataset, the diagnostic information matched to the type of sherd was then associated with the sherd and stored within a larger 'results dataset' which records the classes and types, to create a 'digital assemblage'. Search and retrieval is based on shape-based and appearance-based deep learning algorithms for classification. In summary, the workflow of the ArchAIDE App is: download onto a mobile device; take pictures of a pottery sherd using the device's built-in camera; edit its known attributes and classify it using comparative images returned using the automated image recognition functionality provided within the app; and save the relevant information about the sherd into a digital assemblage associated with a particular archaeological site or intervention. This workflow combines technological innovation while retaining the well-established methodologies used by archaeologists and the ability to agree or disagree with the classification, with the potential to generate economic benefits by reducing time spent and costs.

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2. Development of the Reference and Results Databases

The Reference Database is a core component of the ArchAIDE system and provides data to all the other components. The design and analysis phase involved input from all the archaeological specialist partners to gather the necessary design requirements. The development of the software tools were implemented using 'Agile' software development methodologies, in order to continuously deliver versions of the final system to the partners for testing. Each design-develop-test-refine cycle (about 2 weeks) included a partial revision of the requirements and functionalities of the system. The tight cooperation with the partners allowed the creation of both useful and robust tools. The Reference Database contains the definitions of the pottery types, the decorations, stamps, fabrics, and other information needed by archaeologists during sherd analysis.

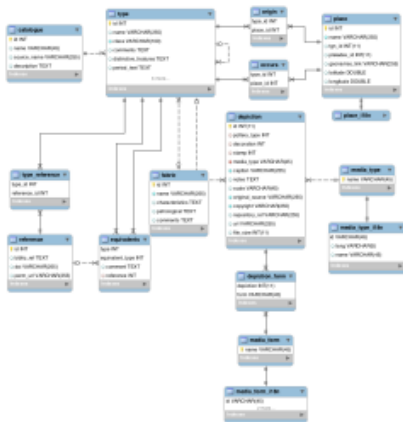


Figure 3: Model of the ArchAIDE Reference Database

The Reference Database includes data created and managed by different users, from a variety of sources, concerning different ceramic classes and historical periods; thus the data are organised in catalogues or archives created and managed by and for specific groups of users (Figure 3). The main entities within the Reference Database are:

- **Pottery types:** known types usually described in printed catalogues and used as a reference to recognise sherds. A type may have one or more origins and many occurrences. A type may have many different depictions (i.e. photo, drawing, 3D model, etc.) each representing different parts of the object (i.e. rim, whole vessel, handle, etc.).
- **Decoration:** these are classifications of decoration types that can be found on different pottery objects. The description contains information such as colour, period, location, references and images.
- **Stamps:** the way in which workshops/potters used to sign their products. As with the previous entities, stamps are defined by descriptive information (i.e. a transcript of the stamp) and multimedia attachments.

The information associated with a pottery type includes:

- **Context information:** each type requires specifying the catalogue it belongs to and, optionally, the list of secondary catalogues in which it appears. The secondary catalogue allows the

archaeologist to work with types that are described in more than one source (i.e. a book). The parent type relation is used to specify that a given pottery form is a variant of a more general one, for example, 'Conspectus form 7.1' belongs to the family of the type 'Conspectus form 7'.

- **Classification and tagging:** terms used for classification (single value) and tagging (multiple values) of a type are derived from a multilingual vocabulary pre-loaded in the database. In particular, for types, the available terms are:
 - Class type (i.e. terra sigillata, amphorae, ...)
 - Primary function (i.e. transport, food preparation & consumption, ...)
 - Form (i.e. cup, jar, dish, mortaria, ...)
 - Characteristics (i.e. base: flat, body: ovoid, handle: arched, ...)
- **Textual data:** descriptive data usually found in references (books or databases). It is important to note that textual information captured for a type in many cases is converted into structured metadata (machine-readable) and relations. For example, if the description of the type (distinctive features) includes a typical collar rim, the user will add 'Rim: collar' to the 'Characteristics' field. If the source contains a description with an equivalence between the type and other types, the archaeologist can add a new entry in the 'Equivalent type' tab of the editor.
- **Relations:** the relations of a type with other entities within the database are:
 - Decorations
 - Stamps
 - Origins (where it was produced by period and fabric)
 - Occurrences (places where the type was found)
 - References
 - Equivalent type
- **Multimedia:** the system allows the upload of multimedia files associated with a type. The types allowed are:
 - Photograph
 - Drawing
 - 3D Model
 - Thin section

The content of the media may be verified by specifying its media form such as: Whole vessel, Rim sherd, Base sherd, etc. The field 'External id' is the handle connecting the reference database to the machine-learning models for automatic classification. The deep-learning model, resulting from a classification request, returns a list of codes corresponding to types (shape recognition) or decorations (image recognition); the codes used are the same as those present in the type definition as an external id.

2.1 Reference Database technical specifications

The ArchAIDE Reference Database application was developed in Java using the Grails Application Framework and runs on the following stack (from top to bottom):

1. Apache HTTP Server
2. Tomcat 8 (with AJP protocol)
3. MySQL Server
4. Elasticsearch Server

5. Debian Linux

The data are stored in a relational database (MySQL) and indexed for advanced search and API support (Elasticsearch). All the multimedia files related to database entities, such as depictions and 3D models, are stored in the file system.

The reference database is integrated with the following:

- External sources/sync of data to import and export information.
- Geographic systems to define the origin and the occurrences of specific objects.
- OCR Tools to support the digitisation of books.
- 3D rendering tools to enhance the media content of each pottery type.

In order to make the Reference Database able to exchange data with external systems, the ArchAIDE partners defined a data exchange format based on JSON, and to define an API interface allowing external data to be sent and received. The availability of a well-defined data format allowed the partners to export it mapped to the ArchAIDE schema using existing digital comparative data and see it imported in the Reference Database. This was the case for *Roman Amphora* and *CERAMALEX*. The format was also used in the process of extracting information from printed pottery catalogues.

The definition of an API interface is essential for the Reference Database, in order to provide information to the ArchAIDE App and to external systems that need to synchronise their data with ArchAIDE. To include geographical information in the database, it was decided to use GeoJSON as a format to represent geographical features (both points, lines and polygons). Location in GeoJSON is represented by a small amount of text in JSON format, thus it is easy to store in the database.

The mappings were supplied to Inera (as JSON and CSV) for incorporation within the reference database. The multilingual vocabularies have been implemented as the basis for establishing a clear level of semantic interoperability within the reference catalogues imported into the database.

2.2 Development of comparative collections to populate the database

The choice of the pottery classes, and consequently the catalogues to be used for the ArchAIDE project, was one of the main issues to be considered in order to create a system that must have a real-world implementation. The decision was made to choose three types: amphorae manufactured throughout the Roman world between the late 3rd century BCE and the early 7th century CE; Roman Terra Sigillata manufactured in Italy, Spain and Gaul; Majolica produced in Montelupo Fiorentino (Italy) from the 15th to 18th centuries, and medieval and post-medieval Majolica found in Barcelona. The choice of pottery types was based on the availability of collections to the ArchAIDE partners and their areas of specialist expertise, and the need to find types that relied on both shape-based and decoration-based characteristics for identification.

In addition to the *Roman Amphorae* and *CERAMALEX* digital collections, the database was also populated with analogue catalogues, which had to be digitised (see [Section 2.2.2](#)). These were in the form of catalogues, books and papers (Berti [1997](#); Bustamante-Alvarez [2016](#); Ettliger and Römisch-Germanische Kommission [1990](#); Dragendorff [1895](#); Gascón *et al.* [2017](#); Fornaciari [2016](#); Gempeler [1992](#); Peacock [1972](#); Keay [1984](#); Simpson [1985](#); Medri [1992](#); Montes *et al.* [2010](#); Wilson [2002](#)).

2.2.1 Digital comparative data

Databases are common tools for archaeological work, but for different reasons (e.g. technical, legal or historical research traditions) each project, excavation or research community develops their own database structures, naming conventions and data workflows. This leads to a very heterogeneous situation for data provision, even within the same field of research. This is reflected in the two digital sources imported into the database:

- *Roman Amphorae: a digital resource* (<https://doi.org/10.5284/1028192>) is a comparative digital archive created by Simon Key and David Williams of the University of Southampton, funded by the UK Arts and Humanities Research Council, and deposited with the ADS in 2005 (updated in [2014](#) with additional amphorae types). The database encompasses most of the principal types manufactured throughout the Roman Empire between the late 3rd century BCE and the early 7th century CE.
- The *CERAMALEX* database was created by the Deutsche Forschungsgemeinschaft (DFG) in cooperation with the French Agence National de la Recherche (ANR) to integrate the databases of the German and French excavations in Alexandria, Schedia and Marea, and in order to create a common typology and terminology. Therefore, the [CERAMALEX database](#) holds information on different types of amphorae produced in Egypt and traded from other parts of the Roman Empire that expand the range of *Roman Amphorae: a digital resource*.

In order to enable data exchange between the ArchAIDE database and existing external sources like *Roman Amphorae: a digital resource* and CERAMALEX, the project partners decided to define a JSON-based data format, derived from the ArchAIDE database schema, to be used in both import and export transactions. The JSON format was intended to represent the content of a catalogue (i.e. 'Roman Amphorae') and contains definitions of pottery types, fabrics, decorations, stamps, places, etc.. The external sources should provide a JSON file or a compressed (zip) file containing the JSON file, plus all the multimedia resources associated with the described entities.



Figure 4: Screenshot of *Roman Amphorae: a digital resource* <https://doi.org/10.5284/1028192>

Using the import tool provided by INERA as part of the ArchAIDE Reference Database Management System it was possible to import both the ADS and CERAMALEX catalogues. In particular, the *Roman amphora* catalogue from ADS was the first external source integrated because of the similarity between the conceptual schema of the databases (Figure 4). The work on the CERAMALEX database was more complex because the database schema and architecture led to a different focus of pottery research. The differences between the two systems required complex mapping and normalisation activities, ending

with the creation of an ArchAIDE catalogue imported from the CERAMALEX/CeramEgypt database, with the mapping and normalisation process leading to the revision of the ArchAIDE database. Therefore the already structured database with totally different data structure, CERAMALEX/CeramEgypt, was used as proof of concept for the import approach.

2.2.2 Digitising paper catalogues

Paper catalogues contain all the geometric and semantic information needed to populate the reference database and train the image recognition algorithm. This information is presented as both textual description and diagnostic drawings. Digitising these catalogues transforms them into structured/annotated data that can be used within a database, and is also searchable and machine-readable.

The paper catalogues were scanned as images, and then textual information was extracted corresponding to the relevant fields within the database, along with the drawings of the pottery types (which were then processed to trace their profiles, as explained in [Section 2.2.3](#)). While the drawings were more standardised, in terms of uniformity and information content, the structure of the textual description varied greatly between catalogues. It was possible to find both highly structured catalogues, where each type is described individually with a series of fields (very similar to a database), and non-structured catalogues, where the various types are verbosely described as free text, without any recurring, definable structure. It was therefore necessary to create a tool able to deal with both structured and unstructured catalogues.

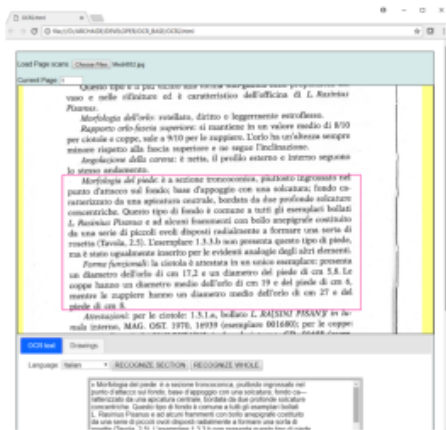


Figure 5: Screenshot of the digitisation tool developed by CNR-ISTI Visual Computing Lab

This division made it easier to create the interface for the digitisation tool (Figure 5). JavaScript worked well with the web database backend and the metadata structures, as HTML/JavaScript supports images and text manipulation, and rendering of components. Text recognition functions were implemented using the [Tesseract OCR](#), a widely used open source OCR tool, available on multiple platforms, including JavaScript. The 'structured catalogue' digitisation tool worked by combining OCR with the structure used in the catalogue, to describe each type (e.g. the number and order of paragraphs, their position within the pages, recurring keywords and section titles, and/or the presence of bulleted and numbered lists). Starting from the output of the OCR, which contains all the columns/sections/lines/words in the page, the tool automatically splits the description into chunks following the catalogue structure template. The chunks are used to fill the database fields representing a pottery type.

Unfortunately, each catalogue may employ a different structure to describe the types: it then becomes necessary to adjust the parsing process to accommodate the new template. This task of creating a new

'structure parsing template' must still be carried out manually, as the number of structured catalogues was so small it was not useful to create a higher level description of these templates. The output of this processing tool was a series of JSON data structures (containing the different data fields extracted from the catalogue) and images (cropped from the scans), describing each type of pottery. These data were then directly imported into the database, generating the types and associated visual depictions. This was a one-time batch operation, due to the limited number of structured catalogues; thus the tool was used as a stand-alone process, not integrated into the database backend.

The 'unstructured catalogue' digitisation tool was integrated directly into the database backend, to be used by the archaeological partners when creating a new pottery type. In this instance, a fixed structure could not be used, but it was still possible to use OCR to digitise chunks of text from the catalogue scans, speeding up the data entry. The interface lets the archaeologist load multiple scans and browse them. The user reads the text, and when they find a part of the text that can be used to fill one of the database fields, they select it and the tool selectively applies OCR to the selected section. The text may then be edited, to correct errors, or add user-created content. When the text is ready, the user chooses to which database field this text should be assigned. Similarly, from the same interface, images may be marked, cropped from the original images, and inserted directly into the database as visual depictions associated with the new type.

2.2.3 Vectorisation and generation of 3D models from section drawings

Pottery profile drawings in catalogues use a standardised geometry, but the semantic information is flattened in a single raster layer, and encoded following specific representation rules. Designed for human interpretation, this representation is not machine readable. A vector-based representation allows the separation of different semantic and diagnostic elements. It was suitable for use in the Reference Database, but was also found to be useful for training the neural network. Using image processing techniques developed by CNR-ISTI for ArchAIDE, and exploiting the common representation rules of pottery profile drawing in archaeology, it was possible to vectorise and create semantic elements in an automated way (Figure 6).

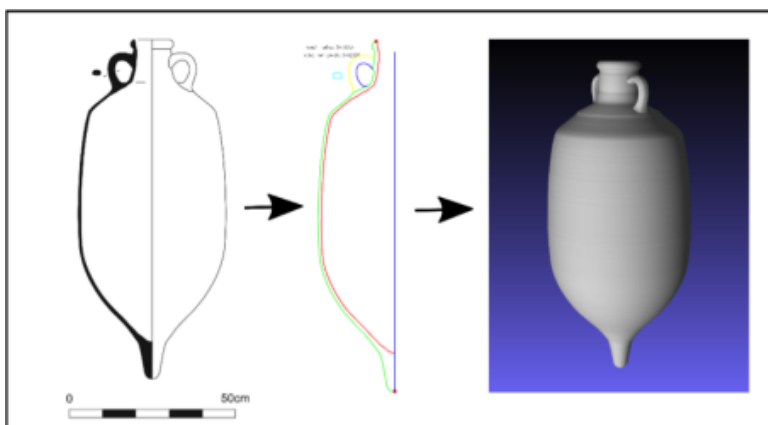


Figure 6: Illustration of the conversion process carried out by the CNR-ISTI Visual Computing Lab. Standardised profile drawings of archaeological pottery were converted into vector files in SVG format, from which 3D scale models were derived

The aim of this process was the extraction of several geometric and semantic features (body/handles profiles, rim, base, rotation axis). The extracted profile was then stored as an SVG file, and annotated with semantic information. In this way, it was possible to create a digital visual representation (for human access), but the data were also machine-readable. Image-processing techniques also made it possible to generate a 3D model of the traced vessel. The profile extraction was automated, but was

able to accommodate small inconsistencies in drawing style across different catalogues, and required only minimal adjustments. The tracing process was implemented as a Matlab function, which could be a batched execution, generating SVG tracings and 3D models for all the drawings in a single catalogue in a matter of minutes.

The tracing of profiles followed a series of steps. First, the scanned image of the archaeological pottery profile was cropped and binarised. Then, a *dilate* and *erode* operator was applied to remove any possible pixel outliers resulting from scan noise and printing imperfections. The rotation axis of the vessel was then found, using a Hough transform, isolating the longest vertical line in the drawing. From this axis, the 'profile' side of the drawing was isolated: typically, pottery drawing conventions dictate profiles are drawn on the left side, while the external surface is described in the right part of the drawing, while characteristics such as orientation and drawing style (filled, empty, hatching) may not be consistent between catalogues.

It was then necessary to extract the actual profile regions: external profile, internal profile and handles. The drawing was segmented to extract all the edges. Starting from the axis, the inner profile curve was found, then using a 'marching' process the whole inner profile was traced, going from the top point to the axis. The outer profile was slightly trickier, as it might contain a handle. If a handle was detected, its profile was isolated and trimmed from the outer vessel profile, using an energy function that provides a trimming surface that is smooth with respect to the rest of the outer vessel profile. The cut-through section of the handle, if present, was isolated and traced separately. In addition to the axis and inner/outer/handle profiles, other metric and semantic information (position of rim and base point, mouth radius) were automatically computed and stored in the SVG. The physical size of the profile could be extracted automatically if a scale bar is present in the image, or recovered starting from the DPI value of the image, and if the information was present in the catalogues (each catalogue/page might be drawn at a specific scale).

Once all the elements were traced and saved in the SVG, a further step produced a 3D model (Figure 7). This 3D model is a simple representation, aimed at visual presentation. The body of the vessel is a simple rotating object, generated from the profile. For vessels with handles, 3D models for the handles were generated as parametric extrusion along with the handle profiles. Then, the main body is trimmed, and the 3D models of the handles were welded in place. Managing the handles was not always straightforward, as the information in the drawing may be incomplete (e.g. only the profile of the handle is shown, with a middle cross-section, or sometimes not shown at all). These 3D models are available in the desktop Reference Database and can be interactively visualised in the pottery type database page.

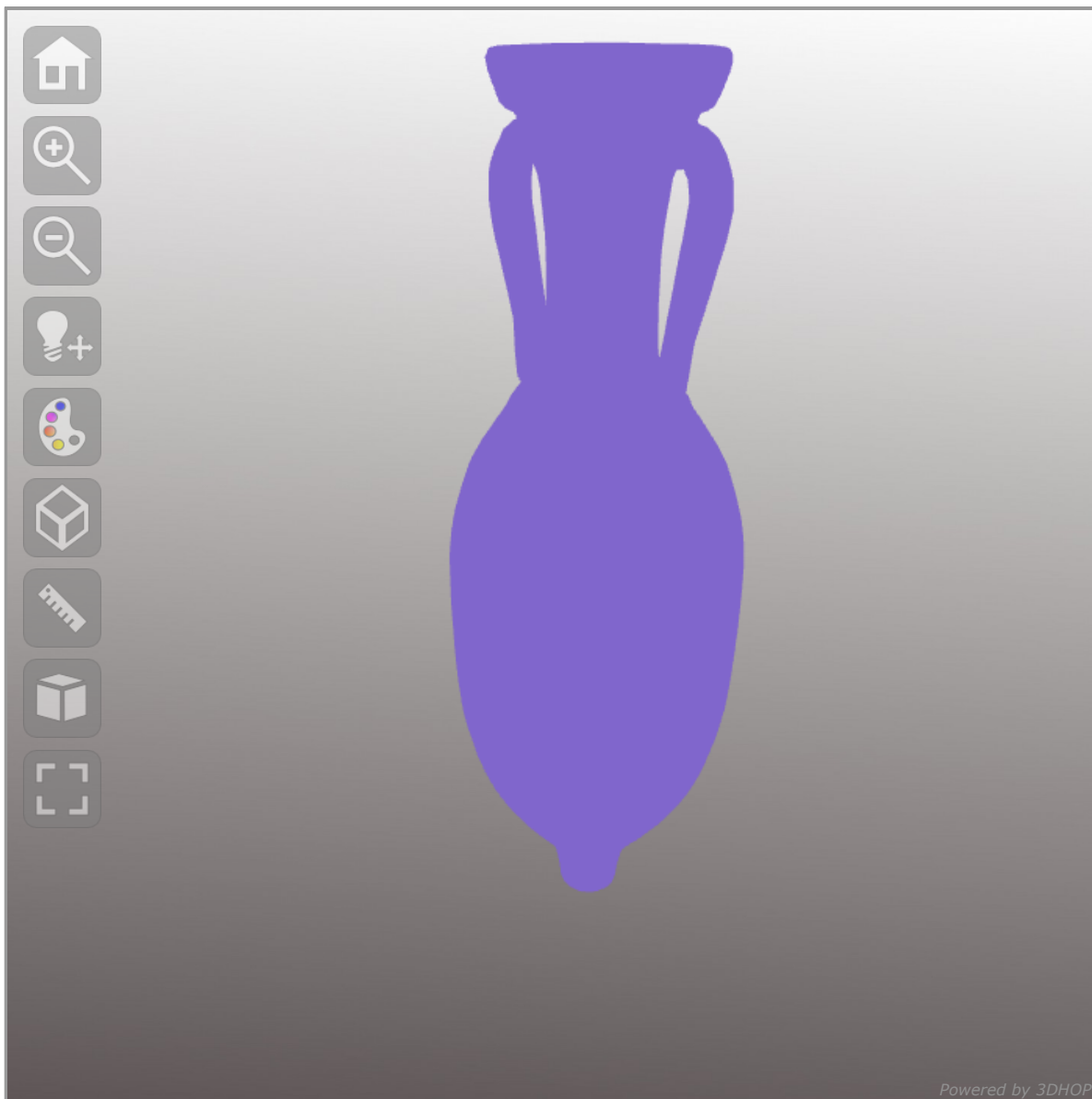


Figure 7: 3D interactive model of amphorae type Dressel 12 created from a profile drawing.

https://archaeologydataservice.ac.uk/archives/view/archaide_2019/downloads_amphora.cfm?amph=Dressel_12_DR109

2.3 Multilingual vocabularies

From the outset of the project, it was clear that a significant component of the ArchAIDE Reference Database would be the ability to contain multilingual vocabularies, to enable linguistic interoperability within the dataset being assembled. However, early in the discussions, project partners quickly identified semantics difficulties when faced with the task of describing either a fragment, or a whole vessel. For example, the difference between what may be referred to as a 'dish', 'plate' or 'platter', even though the physical shape may be similar or the same. Furthermore, it was necessary to establish a scheme of recording that was not only consistent across languages, but also archaeological traditions.

Archaeologists working in different countries may not only use different words but also varying hierarchies or classifications for how they categorise an object. As a hypothetical example, one tradition may have four different words to categorise a candlestick, while another tradition may simply have one. These issues around semantics apply broadly across most areas of archaeological research, not only within the pottery specialism, so this solution is likely to be useful for a wide range of archaeological material.

The solution was the creation of a discrete set of vocabularies to account for, and reconcile these differences (Figure 8). These were used as the data forming the backbone of the ArchAIDE Reference Database, allowing different catalogues, and therefore different classification schemes, to be cross-searched and then presented by the ArchAIDE application. Following the precedent set by the EU Infrastructures ARIADNE project (Aloia *et al.* 2017), the vocabularies were built to create a resource with maximum interoperability for current initiatives and future projects. This was achieved through taking a Linked Data approach. The initial mapping exercise established a concordance between ArchAIDE and a neutral Linked Open Data (LOD) vocabulary. The creation of LOD for ArchAIDE allowed project data to be easily cross-searched as part of the wider Semantic Web, a format that lends itself to use through a range of methods and processes that utilise established web protocols and standards to interact with and retrieve data.

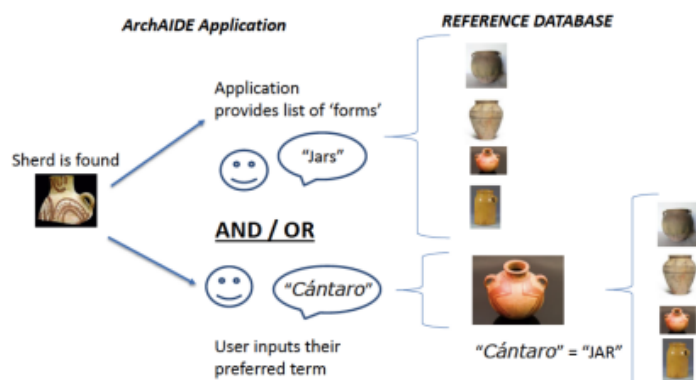


Figure 8: Illustration of how use of multilingual vocabularies allow searching not only terms, but also through browsing the Reference Database, leading to the same results

Each of the ArchAIDE archaeological partners worked through their catalogues and identified the descriptive terms that refer to, or classify, significant elements of a ceramic form. Learning from the methodology and using the tools developed for the ARIADNE project by the [Hypermedia Research Group](#) at the University of South Wales (Binding and Tudhope 2016), using a neutral spine to which partners could map these terms was deemed a preferable solution to establishing a new thesaurus bespoke to the project. As with the ARIADNE project, use of [Getty Institutes Art and Architecture Thesaurus \(AAT\)](#), proved a suitable candidate, with the added value of interoperability with [ARIADNE](#) and *any other data* also mapped to the AAT, thus giving the mapping work done by ArchAIDE a strong sustainable base. In the initial phase of the project all partners agreed on a subset of AAT terms that could be used for this neutral spine, describing the following methods of recording pottery from archaeological excavations:

- The sherd type
- The vessel form
- The decoration type
- The decoration colour

Later in the project, partners established a need for controlled terminologies to describe the type or characteristics of specific parts of a ceramic vessel. As an alternative, and as a concerted effort to ensure that ArchAIDE data was interoperable with past and future projects, the project used the concepts of recording established by the original creators of the *Roman Amphorae: a digital resource*. The ArchAIDE multilingual vocabularies are now freely available for download and reuse from the

[ArchAIDE Portal for Publications and Outputs](#). They are available in Catalan, Dutch, French, German, Italian, Portuguese, Spanish and English, in both CSV and as LOD in Windows NT format.

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3. Development of Deep Learning Image Recognition Algorithms

The use of image recognition on archaeological material is a very new research area, but other work has been done in this field, showing the potential usefulness of this application to other types of archaeological resources. This includes projects such as DADAISM, which focused on the identification of types of Palaeolithic stone tools (Power *et al.* [2017](#)) and Arch-I-Scan, which is also working to create an easy-to-use, handheld interface for archaeological pottery recognition, but uses 3D scans rather than 2D images as the basis for its image recognition algorithms (Tyukin *et al.* [2018](#)).

For ArchAIDE, two complementary machine-learning tools were developed to identify archaeological pottery. One method relied on the shape of a sherd's profile while the other was based on decorative features. For the shape-based identification tool, a novel deep learning methodology was employed, integrating shape information from points along the inner and outer surfaces. Fabric type is also an important tool for identification, but after considerable discussion it was deemed to be less promising and more problematic than shape and decoration-based tools. This was largely due to differences in lighting conditions found across thin-sections, and the difficulty in deriving a sufficient amount of training data.

The decoration-based classifier was based on relatively standard methods used in image recognition. In both cases, training the classifiers presented real-world challenges specific (although not limited) to archaeological data. This included a paucity of exemplars of pottery that were well identified, an extreme imbalance between the number of exemplars across different types, and the need to include rare types or minute distinguishing features within types. The scarcity of training data for archaeological pottery required multiple solutions, the first of which was to initiate large-scale photo campaigns to increase these data.

3.1 Training data photo campaigns

Multiple photo campaigns were conducted across the life of the project to produce a complete dataset of images for all the ceramic classes under study. The aim of the photo campaigns was to provide a sufficient number of images to train the algorithms for both the appearance-based (Majolica of Montelupo and Majolica from Barcelona) and the shape-based image recognition neural network (Roman amphorae, Terra Sigillata Italica, Hispanica and South Gaulish). ArchAIDE partners led the collection of photos, involving researchers both beyond the consortium and within their own photo campaigns. All partners worked with colleagues, institutions, museums and excavations to acquire the required number of samples. As not all types were stored in a single site, it was necessary to access multiple resources involving more than 30 different institutions in Italy, Spain, and Austria.

To train the shape-based neural network, it was necessary to take diagnostic photos of sherd profiles, so detailed guidelines were prepared for use by the consortium partners and project associates. Finding, classifying, photographing and creating digital storage for the necessary sherds was very time-

consuming, as images of at least 10 different sherds for every type were needed to provide enough training information for the algorithm. The ArchAIDE archaeological partners had to verify that the selected sherds were identified correctly, which on occasion also helped institutions (such as museums, research centres, etc.) correct mistakes in the classification of their assemblages. The first approach was to search for at least 10 sherds for each of the 574 different types and sub-types identified in the reference catalogues. It became apparent, however, that not every top-level type and sub-type could be represented. In some instances this was because the type was rare, or because sherds of different types were mixed together when stored, and it was very difficult to locate them. This is a challenge across all forms of pottery studies, not just for a digital application like ArchAIDE. Partners reorganised the search to focus on top-level types, which reduced the number of processed types from 574 to 223.

Overall, 3498 sherds were photographed for training the shape-based recognition model (Figure 9). This included 1311 sherds of Roman amphorae representing 61 different types, including more than 10 sherds photographed for each type. The Terra Sigillata types included 2187 sherds, representing 54 'top level' types, including more than 10 sherds photographed for each type (many with more than 30 sherds).

For appearance-based recognition (Majolica of Montelupo and Majolica of Barcelona), using every image where decoration was visible, it was possible to collect photos originally taken for different purposes, e.g. graduate or PhD theses, archaeological excavations, etc. In these cases, photos were collected, classified, tagged and stored on the basis of the genres of decoration to which they belonged. A larger corpus of photos was collected through photo campaigns in Pisa (at the Superintendency warehouse), in Montelupo Fiorentino (at the local Museo della Ceramica) and in Barcelona (Archaeological Archive of the Museu d'Història de Barcelona and ceramic collection of the Museu del Disseny de Barcelona). In Montelupo Fiorentino, activities were conducted with the help of Francesco Cini, one of the ArchAIDE project associates, a professional archaeologist who collaborates with the Museum, together with a group of local volunteers who manage an archaeological warehouse that stores the largest collection of sherds of Majolica of Montelupo in the world. The final dataset included 10,036 items.

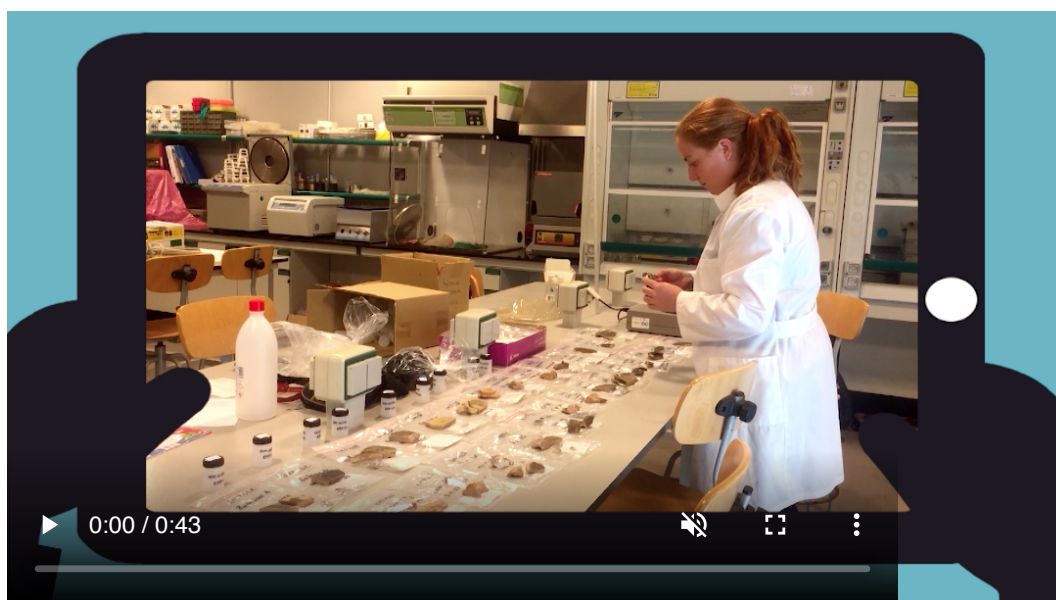


Figure 9: Video of ArchAIDE partners undertaking photo campaigns (43 seconds). Taken from [ArchAIDE consortium](#) (2019)

In the case of the Majolica from Barcelona, photo campaigns were attempted not only to create a dataset in order to train the algorithm, but to also create the first structured catalogue for this type of pottery. For this reason, in order to manage the work economically, the choice of assemblages was crucial. First, attention was focused on green and manganese ware, as there was a preliminary study in progress done by some members of the consortium on a large assemblage stored at the Archaeological Archive of the Museu d'Història de Barcelona. This may be the cornerstone for others to create a full catalogue that will include the other types of decoration for the Majolica pottery of Barcelona and their corresponding typologies. A total of 597 different vessels were documented generating a dataset of 3640 photos.

3.2 Technical description of training the image recognition classifiers

The creation of training data for both the shape and decoration-based image recognition classifiers (algorithms) was ongoing throughout the ArchAIDE project, but as the decoration-based work proceeded much more quickly, it became the main focus for solving the image-based search and retrieval workflow developed by the Deep Learning Lab at Tel Aviv University. As such, the discussion that follows concerns primarily the decoration-based work. As such, the discussion that follows concerns primarily the decoration-based work. Shape-based recognition will be discussed in more technical detail elsewhere (Itkin *et al.* [2019](#)). When defining classes of pottery, the definition of a class does not follow a fixed structure; it may be defined by the use of specific colours or their combination, by the type of patterns, by the areas being embellished, and more. While this sort of variability in the set of defining features is not uncommon in other image classification systems, such as ImageNet (Deng *et al.* [2009](#)), when combined with the limited number of images readily available for training purposes it poses challenges for training a new classifier.

Training classifiers for deep learning applications typically rely on very large datasets to find meaningful patterns within the data. The arts and humanities typically create datasets that are quite small and often heterogeneous in comparison, and the training data available for ArchAIDE was no exception. Training classifiers from a small dataset has often been tackled using transfer learning: performing the training on a somewhat similar domain, and then fine-tuning the last layers of the neural network (after features have been extracted) to perform inference for the given set of classes. To perform the classification, a classifier was therefore trained based on a Residual Neural Network, commonly known as a ResNet model (He *et al.* [2016](#)) trained on ImageNet. Specifically, the variant chosen for the ArchAIDE network was the ResNet-101 network, as it had the best reported accuracy from all variants tested by He *et al.* ([2016](#)). The network operates on RGB (colour) images, which must be resized to 224×224 pixels in size in order to be fed into the network.

To utilise features at various scales and complexity, features from multiple levels of depth were relied upon in addition to the final feature vector of ResNet. ResNet-101 is composed of a sequence of five blocks, where the features emitted by the last block undergo a linear transformation to obtain the score ranking of the various classes for each input. This was solved based on concatenating the features from blocks 2-5 in order to obtain one large feature vector, representing features at various complexity levels and receptive fields.

As the output of each layer in ResNet represents the activation of a feature in a specific region of the image, to reduce the size of the feature activation vector while also obtaining more 'global' information

on features without referring to their specific location in the image, the activation of each feature over the entire image was averaged ('average pooling'), to produce the final feature vector for our classification system.

To classify the vectors into classes, an SVM classifier was used. As SVM is typically used to separate vectors between two classes, in order to enable support for multiple classes, a One Versus Rest (OVR) technique - training one SVM classifier per class was used, to decide whether a feature vector belongs to a class or not. The classes were then ranked based on the confidence scores of their respective classifiers, to obtain an ordering between the different classes. It is important to note that as the features from different layers in the network are concatenated, their expected range of values is likely to change, therefore each feature is separately normalised to have a mean of 0 and a standard deviation of 1 over all the training dataset, before being used in the SVM classification process.

The pottery training images were typically rectangular, and so in order to fit them to the neural networks they were scaled to 224 pixels (along the long axis) and cropped to the middle to make them square. However, this meant omitting certain parts of wide sherds that failed to fit the central square of the image.

To train the network to work with varying amounts of decoration/background, the original image dataset was enriched by adding augmented versions of each image:

- Each image was scaled to four different sizes (224 pixels and larger sizes).
- On each scaled image, three orientations were created (unflipped, horizontally flipped and vertically flipped).
- Finally, all the images were cropped, leaving the centre.

Thus from each image, 12 training images were created.

3.3 The creation of the decoration-based training data

For appearance/decoration based classification, work was mainly carried out on the Majolica of Montelupo pottery. The collection of the dataset was led by the University of Pisa (UNIFI), using existing images (from archaeological excavations, PhD theses, etc.) and through multiple photography campaigns that had been carried out since 2016 (see [Section 3.1](#)). The classification of the images was based on that made by Berti ([1997](#)) and updated by Fornaciari ([2016](#)), with more than 80 decoration genres.

Most of the photos in the corpus were collected in dedicated photography campaigns in Pisa (at the Superintendency warehouse) and in Montelupo Fiorentino (at the local pottery museum). Despite the fact that the photo campaigns were carried out in a warehouse containing the largest collection of sherds of Majolica of Montelupo in the world, not every genre was represented by a high number of sherds. For 19 genres, fewer than 10 potsherd images were obtained, with six of them exhibiting only a single example.

The majority of the images were collected during the autumn of 2017, with more than 8000 sherds being photographed, covering 67 genres with more than 20 sherds, and many of them with more than 100 sherds. All the pictures have been classified by UNIFI. Finally, a social media campaign was

launched to involve the world archaeological community, and obtain more images of Montelupo's Majolica from Portugal, Mexico, and Italy.

The methodology went through a comprehensive evaluation. A detailed test bed for the proposed appearance model was carried out by UNIPI, including about 400 pictures of sherds classified through a desktop application, and about 250 pictures of sherds taken and classified with mobile devices. The pictures captured with mobile devices were taken in different positions and varying amounts of environmental light. In this test the desktop version provided 42.5% top-1-accuracy and 77.9% top-5-accuracy, whereas the mobile version reported significantly lower accuracy: 33% for top-5, and only 12.8% for top-1.

3.4 Complications around the creation of the training data

Additional findings reported by the partners using the model indicated multiple factors that had varying effects on the classification results, including noticeable differences when altering the lighting conditions and/or background colours, and additional changes when using different cameras, or even between pairs of images that looked quite similar. This indicated a lack of stability in the classification system, which had to be addressed if it was to be used successfully in the field.

The evaluation results reported accuracy metrics that were significantly lower than the accuracy measures obtained on the test set during training, thus indicating a potential difference between the domain of the dataset images and the domain of images acquired in the field. Owing to the amount of effort already invested in the creation of the dataset, it was not possible to recapture the dataset images in 'more realistic' scenarios. Therefore, a solution was needed for retraining the model using the existing data.

Of all the factors that affect the classification results, altering the lighting had the most impact and therefore had to be addressed first. Looking at samples from the dataset, it was observed that most images were captured during the photo campaigns and under similar lighting conditions, whereas no colour augmentation was done throughout the training. The rationale for the lack of augmentation was the belief that features extracted from images, using the robust ResNet model, should already have been sufficiently resilient for these sorts of changes in the image.

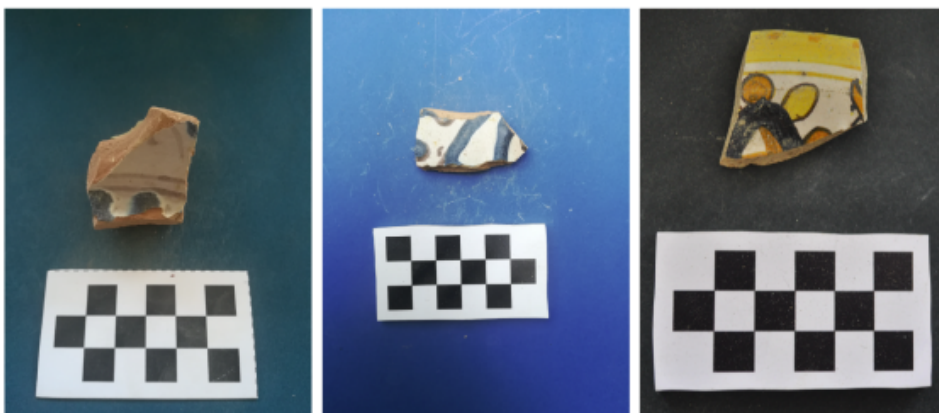


Figure 10: Three typical images captured during the photography campaign

While going over the training dataset, a potentially larger cause for the failure of the classifier to generalise from the training set to images captured in the mobile app was observed (Figure 10). Within each photo campaign, most images were captured in very similar conditions, including similar

backgrounds and similar ruler size/shape/position. This means the classifier may have learned features that are only relevant to the specific photo campaign (background and ruler) and used these in the classification process. This may explain the significant gap in the performance on images in the desktop app (images from the photo campaigns) and images in the mobile version (images captured in new conditions).

The solution to the first problem (lack of robustness to lighting/colour changes) was to add automatic augmentation, simulating different white balance results, and various brightness and contrast adjustments. This was applied during the generation of the training dataset by multiplying the luminosity ('brightness') of all the pixels within each image, using a randomised factor (between 0.8 and 1.2) per image, to simulate different lighting conditions. To compensate for different white balances, a similar random multiplicative factor was applied to each channel in the image; each of the Red/Green/Blue channels was multiplied by a separate random constant factor, in order to change the ratio between colours in the image.



Figure 11: Images with the foreground removed using the GrabCut algorithm

To solve the second problem (learning from details specific to a photo campaign), the ideal solution would have been to remove the image of the sherd from the background, to provide an isolated view of the relevant part in the picture (Figure 11). To automatically remove the foreground, the GrabCut algorithm for interactive foreground extraction was integrated (Rother *et al.* 2004) into the application used by the archaeologists. This enabled the users, with a few simple clicks, to reliably extract the foreground from most images.

3.5 The training data workflow

While it was sufficient for images captured in the app, the training dataset contained thousands of images that had to be extracted from the background in order to fix the training process. To avoid the human labour required to perform segmentation manually, an automated solution was developed which benefits from the same phenomenon that originally hampered the training — the homogeneous capture process. The images, as can be seen in Figure 10, have a mostly uniform background, a potsherd and a ruler. For these images, a heuristic technique was devised to provide an automatic input for the GrabCut algorithm, instead of requiring manual input.

First, colour samples from the background were obtained, by sampling pixels around the border of the image, relying on the fact that both the ruler and the potsherd are centred in the image, and do not touch the image edges. Using the samples of background colour, the distance of each pixel in the image

from the nearest background colour we sampled was measured. A threshold operation was then applied to obtain two large connected regions to correspond to the ruler and the potsherd. To make sure the image was indeed segmented correctly, it was necessary to verify whether one of these items is a ruler. As the rulers have a checkerboard pattern, corner detection algorithms were able to detect corners with strong activation scores at the corners of each square. To detect the corners, Harris corner detection was applied, with at least five corners needing to be present after dropping defections near the edges of the area. To distinguish between the ruler and the potsherd (which may exhibit details with 'corners'), a 'checkerboard error' was applied at the corners of the ruler, so each image patch should be roughly identical to its rotation in 180 degrees. By computing the geometric mean on the difference of the rotated patches around the corners, it was possible to rank how likely it was that each image patch had the checkerboard pattern, and was therefore the ruler. Finally, when the segmented area containing the potsherd was identified, GrabCut was applied to obtain a finer segmentation.

After obtaining the processed training dataset, which was much larger than the original due to the augmentations, the SVM classifier was replaced by a neural network. The network contained two dropout layers, which should make the model learn using a more robust representation, and decrease the chances of overfitting the training data. Furthermore, in order to boost the application performance (runtime), the 'heavy' ResNet-101 model, was replaced by a much lighter ResNet-50 model. The image recognition classifiers (algorithms) developed for ArchAIDE are also freely available on GitHub at <https://github.com/barak-itkin/archaide-software>.

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4. Development of ArchAIDE Application and Desktop Comparative Database User Interfaces

In order to create the appropriate software for the ArchAIDE mobile app and desktop applications, partners analysed the archaeologist's existing workflows, from the excavation to documentation, including the context in which the activities were carried out and the related constraints. Feedback on how elements of these workflows might be automated, and the research implications of this automation were also extensively discussed and implemented where possible. ArchAIDE partners worked to respond to the variety of needs identified by potential users, who may want to use the application simply as a tool for recognition or more comprehensively for collecting and storing data in digital assemblages (Figure 12).



Figure 12: Video introducing the ArchAIDE database (1 min 40 seconds) Taken from [ArchAIDE consortium](#) (2019)

The design phase was carried out as a User-Centred Design process, prioritising intuitive access and ease of use. The software development methodology was based on an iterated production of prototypes, submitted to the project partners for evaluation. The feedback given by partners and archaeologists involved in workshops, training open days and multiplier events, were used to review the design decisions and generate new prototypes. Application design began with the creation of the general architecture of the system and covered the details of each component, while the development activities began first on the mobile app, and then moved on the desktop application. The design and software development used the Agile methodology and was based on the Scrum framework. The final result was an ecosystem composed of mobile and server-side applications interacting through an API server mediating all the communications and activities.

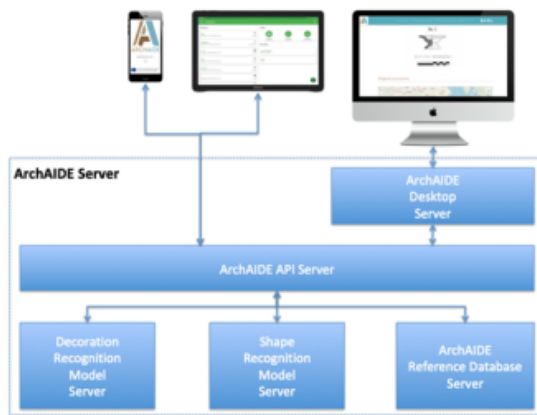


Figure 13: Model of the mobile and server-side applications interacting through the API server

On the client side, the mobile application and the desktop web server call the API services to register and authenticate users, download snapshots of the database, search and retrieve information, store user collected data, and request automatic classification, etc. (Figure 13). Access to the ArchAIDE API Server was secured via an OAuth2 authentication method, serving clients through an HTTP/REST protocol. This provides a uniform and consistent interface on which to implement any kind of client application, such as open-data server, bulk uploading, monitoring tools, and data-mining tools, etc.

The components of the ArchAIDE Server were the following:

- **ArchAIDE Desktop Web Server** serves a website where content management and interactive tools coexist in the same context. The site contains information about the tools developed for ArchAIDE, and provides the same search and classification functionalities implemented in the mobile app.
- **ArchAIDE Reference Database** is the cornerstone of the classification process and defines the reference classes for types, decorations and stamps.
- **Shape Recognition Model Server** is a web server implementing the pottery type prediction as a unique service. The input is an SVG file representing the internal and external profile of a sherd fracture. The result, returned as a JSON array, is a list of ceramic type identifiers paired with a probability index. This server is hosted on a dedicated virtual machine.
- **Decoration Recognition Model Server** is a web server implementing the type prediction as a unique service. The input to the prediction transaction is an image of the sherd surface. The result, returned as a JSON array, is a list of decoration class identifiers paired with a probability index. This server is hosted on a dedicated virtual machine.

4.1 The ArchAIDE mobile application

The development of the mobile application was carried out by Inera with the collaboration of ArchAIDE partners at CNR-ISTI and Tel Aviv University. In particular, CNR-ISTI provided the required support to integrate the libraries for the image manipulation used to prepare the images for the shape and decoration recognition tools. Tel Aviv University also supported the Inera team in installing and integrating the deep-learning models used by the prediction functions.

The ArchAIDE mobile application was designed to be used in many contexts, including where archaeologists often work but where connectivity may not be available, such as storehouses or remote rural areas. In such conditions, the use of the app may be limited to the acquisition of materials (i.e. creating new sherds from pictures taken with the device) or browsing the Reference Database to check characteristics of a specific ceramic type, decoration or stamp (Figure 14). When opened for the first time, the mobile app initialises the local database with all the data from the Reference Database, excluding the images. Users are not

required to register to access the Reference Database or automatic classification tools. This approach allows anyone to use the tools, but registration is required for users who wish to store information about their own sherds.

Registered users can save a variety of information about their own pottery (e.g. classification information obtained from the automatic classification tools), and access information about their own sites/assemblages/sherds (a sherd belongs to an assemblage that comes from a site) that are stored in the local memory of the device and, if the device is online, on the ArchAIDE server. The app registers the information locally when offline, but will be saved to the server when online. The synchronisation process between the device and the server is bi-directional.

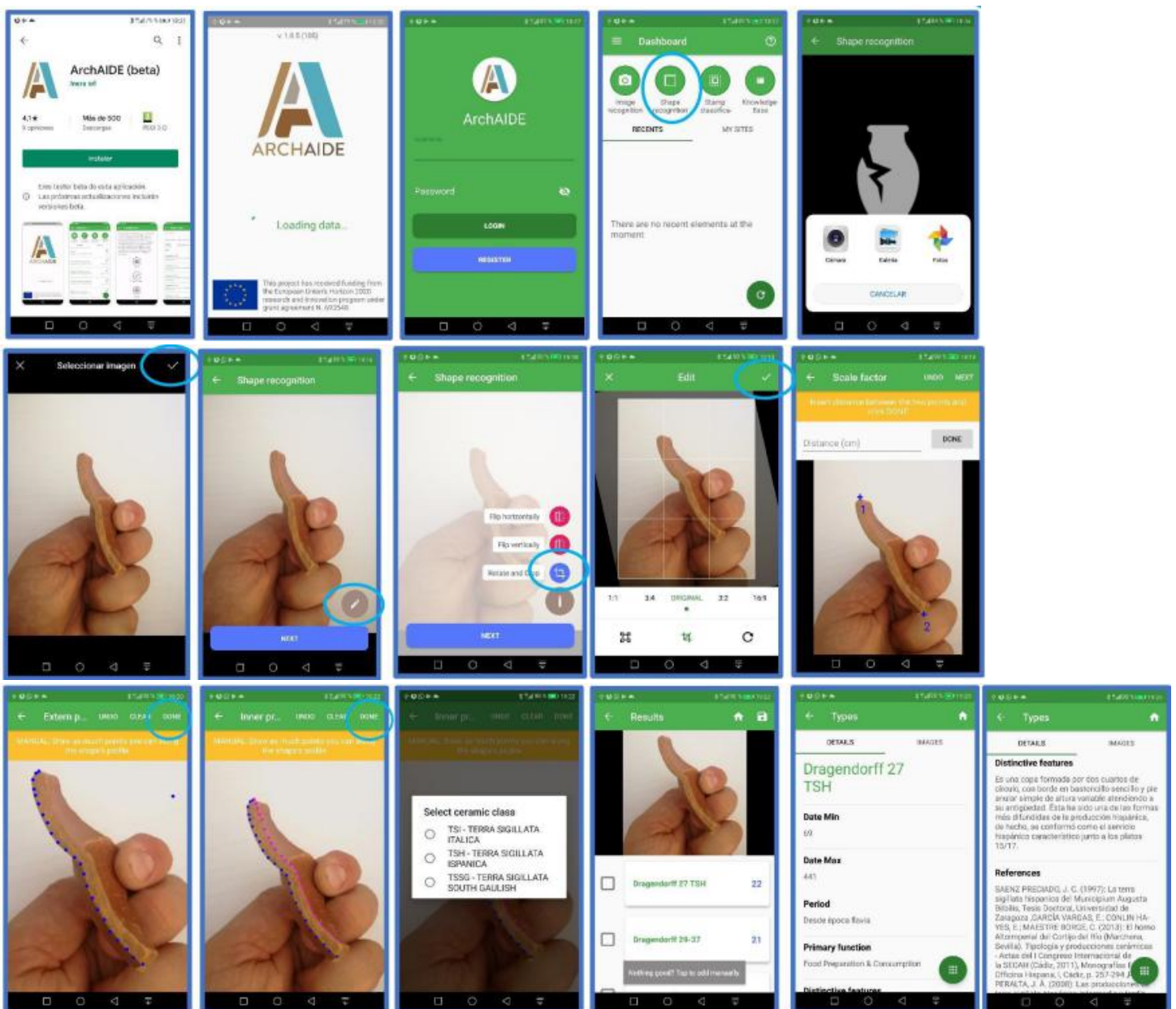


Figure 14: A series of screenshots showing the workflow for recognising a sherd by shape using the ArchAIDE app

Data collected by users are by definition private, and are not published. All system components are designed and implemented to comply with this privacy statement. At the same time, an important goal of the ArchAIDE Project was to openly publish pottery data resulting from cooperation across a community of archaeologists from all around Europe. The partners envisioned thousands of sherds stored in the ArchAIDE Database, together with pictures, profiles, classification information, etc. that could be openly published through a specific API and/or as Linked Open Data. To allow this, future versions of the application may

include a boolean option for users to 'publish as open data', so users may choose to provide their contribution to the community.

The main features of the ArchAIDE mobile app are:

- **Knowledge-base tools.** Search and retrieval tools to access the type, decoration and stamp catalogues managed in the Reference Database.
- **Search and classification tools.** The collection of tools for automatic and supported classification of sherds: image recognition, shape recognition, stamp classification.
- **My sites.** Where registered users create and save information about their own sites and assemblages.

All tools are publicly available for evaluation and experimentation. The mobile app is available on App Store and Google Play.

4.2 The ArchAIDE desktop application

The ArchAIDE Desktop web site is a hybrid application mixing web content and interactive tools. The implementation is based on a Content Management System, but also provides a robust and flexible extension mechanism to incorporate plug-in interactive tools. The developers at Inera chose the open-source Portal Server technology: Liferay 7.1. Liferay Portal is enterprise level, feature rich, and widely used internationally to build medium/large web portals. Liferay constructs sites by composing and configuring user interface modules (Portlets). In order to share the same user archive between the app, the reference database and the desktop web site, a single sign-on infrastructure based on CAS (Central Authentication Server) was implemented.

The main features of the ArchAIDE desktop application are:

- **Web content.** A blog keeping users up-to-date on development plans, new features and activities added to the ArchAIDE platform.
- **Knowledge-base tools.** Search and retrieval tools to access the type, decoration and stamp catalogues managed in the Reference Database.
- **Data visualisation tools.** A collection of interactive tools for the visualisation of raw data and statistical data derived from the ArchAIDE database.
- **Search and classification tools.** A collection of tools for the automated and supported classification of sherds: image recognition, shape recognition, stamp classification.
- **My sites.** Where registered users create and save information about their own sites and assemblages.

All tools are publicly available for evaluation and experimentation via the [ArchAIDE Desktop](#).

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5. Data Analysis

The creation of the comparative data within the ArchAIDE Reference Database also allowed statistical relationships between the variables within the data to be considered as part of the work carried out by the Mappa Lab at the University of Pisa. Statistical techniques were used to explore and summarise the main characteristics of the data and identify outliers, trends or patterns. Specifically, Network Analysis was used to identify significant temporal breaks in the data. The network structure was created by linking together locations where ceramics were produced to locations where the same ceramic type was retrieved. This resulted in the formation of 3853 location vertices throughout Europe, the Middle East and North Africa. The structure included 16,820 different edges, joining together 322,764 different data points.

Network analysis allowed the identification of communities within the network, i.e. groups of vertices being densely connected internally but poorly connected externally. Such communities may represent commercial routes adopted by producers, or established for geographical or historical reasons. Temporal breaks were identified by an algorithm minimising the variance within intervals, while maximising the variance between intervals. Production and supply of ceramics had a natural context only in certain temporal intervals, making it possible to distinguish four main periods, characterised by different production centres emerging and declining in the different phases (Italian, South-Gaulish, Rhine productions) and showing different production dynamics.

The main area of interest related to networks, described and handled as mathematical graphs, obtained by linking locations where ceramics are produced to locations where (the same) ceramics were retrieved. This allowed the application of network theory techniques, specifically concerning link analysis, classification and clustering techniques. Roughly speaking, communities, or clusters, are defined as groups of vertices having a higher probability of being connected to each other than to members of other groups; this can of course be computed and checked in terms of network links. Identification of significant communities in the network draws attention to the main 'import-export' systems and their dynamics. Analysing pottery from a spatial point of view allows a better understanding of the economic connections underlying traffic flows.

This analysis is very valuable for archaeologists as it can provide information about aspects of economics and supply. For example, distribution maps permit the representation of areas where a particular ceramic type was in use. When a distribution map is associated with an area of production or origin, it represents the supply movement of pottery. Even where it is possible to describe the correlation between the origin and the destination (occurrence) to indicate a possible trade route, and so better understand the overall mechanism of the distribution process, it is better to analyse data on a larger scale than can be represented by a single site. In this way, as evidence grows, it is possible to create maps to understand the pottery supply and distribution in a region to be investigated.

For quantitative information attached to points (e.g. the number of items on a site) it was possible to create more complex distribution maps, but this must be undertaken carefully, as in many cases there is no information about the size of an assemblage, such that some sites may be over-represented. Moreover, working on the variation of the assemblages over time, it was possible to understand the correlation between origins and occurrences in order to visualise the variation of the main route of commercial exchange over the centuries. In fact, on the basis of the disparities exhibited by the ceramic chronologies, it was also possible to identify temporal intervals illustrating different network behaviours, and then analyse these temporal intervals separately. These analyses show the dynamics of the major production sites and main export areas, the increase and decrease of production, and the spheres of influence of the major production poles over time.

We focused on the following tools:

- Classification and Clustering techniques, used for understanding whether or not some features of the data possess useful classifications in a number of categories/groups, subsequently suggesting meaningful interpretation of such categories.
- Dimensionality Reduction techniques, used to extract a specific combination of features describing the greatest areas of information and variability contained within the data. These specific combinations together provide a way to summarise the data, and the identification of the major sources of variability.

Spatial statistical methods and related predictive modelling were applied directly within a GIS (geographic information system) module. These tools were used primarily to highlight possible patterns within the spatial distribution of data, and to suggest where to look for more data, more information, or optimal strategies to perform testing,

resulting in the application of particular clustering algorithms to the obtained graph. Two different alternatives were chosen. In the first algorithm (Newman [2006](#)), detecting communities in networks was approached using a benefit function known as 'modularity' over possible divisions of a network. In this particular algorithm, termed *leading eigenvalue clustering*, the maximisation is solved on the basis of the eigenspectrum of the modularity matrix. The second algorithm (Pons and Latapy [2006](#)), termed *walktrap clustering*, follows a completely different approach, being based on random walks on the graph. The walks are more likely to stay within the same community because there are only a few edges that lead outside a given community. In this way the walktrap algorithm captures the community structure in a network. The two algorithms give very similar results. This indicated that the communities identified were very well defined, and not dependent on the definition of the cluster algorithm.

After applying the clustering algorithm, an additional attribute was added to vertices of the graph, indicating the community. The attribute was also given a colour, so that it can be easily visualised. For the sake of visualisation, the first four communities were prioritised in terms of the number of vertices being the most important. Every other edge/vertex was associated with an additional (poor) community, made by vertices and edges not belonging to the four main communities identified by the clustering. Colours of vertices represent communities identified with clustering.

Another important feature concerning networks was the relative importance of the vertices, such as which vertices were more important and central in the network, and why? In this instance, a measure of such importance can be the *out-degree*, i.e. the quantity of ceramics 'exported' from a specific location, and another is the *in-degree*, i.e. the quantity of ceramics 'imported' in a specific location. Of course these two possibilities give a view of places having produced or imported many ceramics, but networks often have complex structures, so more refined measures of importance were derived. One of the most useful and effective is the PageRank (Brin and Page [1998](#)), an algorithm developed by Google's founders and now widespread. PageRank works by counting the number and quality of links to a vertex to determine an estimate of its importance. The underlying assumption is that more important vertices in a network are likely to receive more links from other (important) vertices. A vertex has a high PageRank score if there are many vertices pointing to it, or if there are some vertices pointing to it that have a high PageRank on their own. PageRank handles both these cases and everything in between by recursively propagating weights through the link structure of the network. According to these considerations, it was also possible to compute the PageRank score of vertices, giving a further view of most important

vertices. Confirming the complicated structure of the network, the results of PageRank differ significantly from those depending on in-degree or out-degree results.

The work carried out underlines how the availability of a high volume of data (which is often rare in archaeology), joined with explanatory analysis, allows new insights into archaeological research. More generally, this process was related both to the digitisation of existing data, such as the comparative catalogues, and to the datification of archaeological processes such as the data created to train the image recognition system within the ArchAIDE app. A key differentiating aspect between digitisation and datification is related to data analytics: digitisation uses data analytics based on traditional sampling mechanisms, while datification fits a Big Data approach and relies on the new forms of quantification and associated data mining techniques, permitting more sophisticated mathematical analyses to identify non-linear relationships among data.

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6. Data Visualisation

Using the data gathered by ArchAIDE, along with the data analysis, the Mappa Lab at the University of Pisa was able to apply data visualisation techniques. Data visualisation is of extreme importance to:

- Provide an efficient way to understand a vast amount of data.
- Allow for data-driven decision making.
- Communicate the results of the data analysis.

Data visualisation principles and good practices were followed, starting from the classification of data into types (categorical, ordinal, interval, ratio types) when imported into the programming platform. For each visualisation provided, it was determined which visual attribute represented the data types most effectively. The data visualisation component was integrated into the Desktop front-end. The data visualisation and data exploration modules show the data in different ways, with a lateral panel allowing users to add/remove different layers of data and/or tools.

The Reference Database contains basic visualisation and exploration tools; for example when viewing a stamp or a pottery type, a location map is available. In addition, for every location, it is possible to explore which and how many different stamps/types were found there. By interactively querying the tables, it is possible to switch from selected stamps to corresponding types and vice versa. By selecting a time interval, it is possible to visualise the map of types or stamps found in that specific timeframe. The online viewer for the 3D models of the pottery types was built using the [3DHOP](#) tool, an open-source framework for the interactive visualisation of 3D models online. By using HTML5 and WebGL it is possible to display interactive 3D without plug-ins on almost all desktop and mobile platforms. The viewer uses a simple turntable navigation that lets the user inspect in detail the whole geometry of the pottery, measure the 3D model, change lighting, and activate a cut-through section that shows the profile of the vessel with respect to the whole shape (see Figure 7).

To visualise pottery networks, clustering, and related data, the desk front-end was implemented using [OpenStreetMap](#) (OpenStreetMap 2018) and [Leaflet JavaScript](#) mapping library (Leaflet 2018), allowing simplification of the data visualisation and thematic mapping, and making it easier to turn data into compelling maps. In particular, for the visualisation of geographic networks, the [DVF Leaflet plug-in](#) was used, which is an open-source JavaScript extension of Leaflet, allowing the creation of very complex interactive thematic mappings.

The origin-occurrences map displays all the locations. Clicking on a location produces lines going to and from the point of origin and where the type is found (in different colours), as well as activating a pop-up containing descriptive information. This information can be organised as summary statistics for that particular location (about stamps and/or types, number of incoming and outgoing sherds, latitude and longitude, name of location), that can be navigated in order to gain more information. In addition, through the side menu, different locations can be selected and added to the network and kept 'fixed' within the network visualisation (Figure 15).

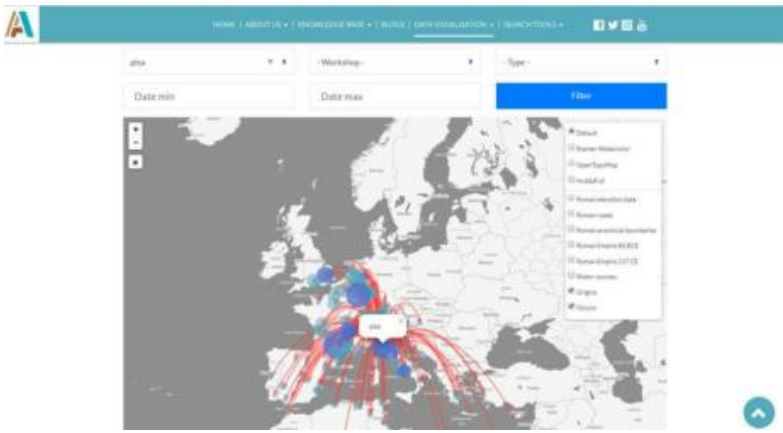


Figure 15: An example of a visualisation using the ArchAIDE data, showing trade networks for a particular pottery type

One layer of visualisation will mark locations with circles of a size proportional to the sum of incoming and outgoing sherds, while the proportion of incoming versus outgoing sherds are shown in blue and red. Additional queries can compute the PageRank of the network, or can 'colour' the locations according to the different workshops associated with a pottery type. To represent time, and therefore chronology, by clicking on a location, it is possible to see the 'history' of the exports/imports using an area graph. A separate tool can also generate an animation, based on time flow, with arrows and locations being formed and disappearing as time passes. For computational reasons, clustering of the graph can be made available only for a certain number of fixed choices, including the whole network and the networks identified by the four temporal intervals computed by the algorithm (described in [Section 3](#)).

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7. Feedback and Testing

Given the high degree of innovation expected by the project, the partners decided from the beginning to involve the archaeological community in the development of the ArchAIDE system, in order to create a tool that responded to user needs. For this reason, five 'Training Open Days' and two 'Multiplier Events' were held in order to effectively engage the project stakeholder communities, providing feedback, allowing users to test the functionality of the ArchAIDE tools and obtain information about technical specifications. These events were intended as one-day seminars with the aim of creating interaction between prospective ArchAIDE users and the project team before the completion of the expected results. These events also served as a first opportunity to encourage users with different archaeological backgrounds and interests to communicate effectively with each other, and to understand shared issues.

7.1 Training and feedback

Entrepreneurs and users from professional associations also shared their perspectives with researchers about what the labour market needs, while students and PhD candidates in archaeology or related areas had the opportunity to explore the versatility of a tool also designed to be used as a training tool for those archaeology students learning how to classify pottery. The 'Training Open Days' were held in Italy (Spoleto and Pisa), in the UK (Brighton), and in Germany (Bonn), whereas the Multiplier Events were held in the UK and in Spain.

The first multiplier event was organised on 7 December 2017 by the ADS at the University of York. The event took the form of a discussion workshop to explain the aims and activities of the project, and to show the first release of the app using appearance-based recognition (Figure 16). As this was near the mid-point of the project, it was a key opportunity to collect important feedback from the participants while there was a tangible output to demonstrate, but with enough time to make changes based on this feedback. Around 25 professional and academic archaeologists attended the event, resulting in a very fruitful discussion around different issues. Significant feedback was collected and can be found [here](#).

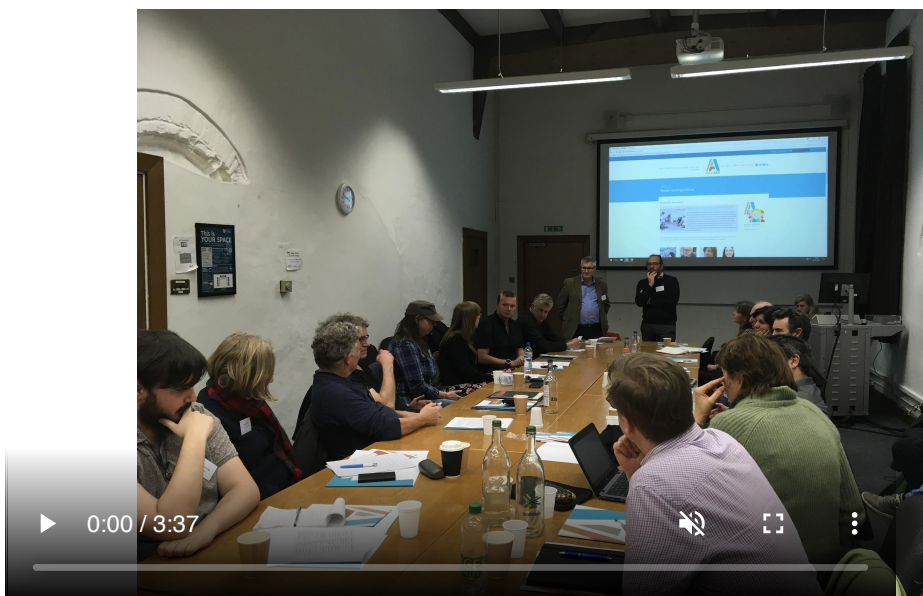


Figure 16: Video of feedback from archaeologists participating in ArchAIDE workshops around Europe (3 mins 37 seconds) Taken from [ArchAIDE consortium](#) (2019)

On 3 December 2018, the University of Pisa organised the second multiplier event, with 29 specialists from different museums, research institutions and professionals (Figure 17). During the event, it was possible to test the ArchAIDE app, both with the image recognition tool using Montelupo pottery, and with the new shape recognition tool, using Terra Sigillata Italica, thanks to the Archaeological Archive of the Museu d'Història de Barcelona, whose staff made its pottery assemblages available for the event. The specialists were able to test the ArchAIDE app over two hours, allowing the project to receive important feedback leading to further refinement. This approach showed the ways that ArchAIDE seeks not to become a substitute for pottery specialists, but to provide a useful tool that automates only the time-consuming and repetitive activities, ensuring archaeologists are the ones to confirm the identification. This created a generally open-minded and positive mood towards ArchAIDE, although some [scepticism persisted among senior archaeologists](#).



Figure 17: Professional and academic pottery specialists at the Pisa Workshop, 2018

7.2 Testing

The performance of the ArchAIDE tools was tested on both desktop and mobile devices. The performance checks were based on the following parameters:

- Percentage of cases where the correct type was returned by the app five times.
- Percentage of cases where correct type appeared as *the first* of the five outputs returned by the app.
- Frequency of outputs shown, taken independently of the input types.
- Number of comparative photos available for each type.
- Difference between consecutive scores shown by the app results.
- Frequency of mistakes.

These parameters were computed after testing the app numerous times on multiple different sherds, by following a randomisation procedure. The testing procedure allowed the identification of critical functions of the app, particularly during the first development phase, and helped to identify the main sources of errors and areas for improvement.

One of the main tasks of the project was devoted to creating two testing scenarios related to different applications. One type concerned small and medium sized enterprises (SME) involved in contract archaeology. These users are heavily constrained by constant digging activity, handling great volumes of

material and having short timeframes for their research. The second type of user is Higher Education Institutions (HEI) and research centres. These users may also face restrictions similar to archaeological SMEs, especially during fieldwork seasons abroad or in remote/isolated areas. In many circumstances, however, academic users have facilities (research buildings) with suitable equipment for post-excavation. Moreover, the second user group is not constrained by needing to undertake constant digging activity, as fieldwork is only scheduled during certain periods of the year. Thus, the objective was to test the app in these two different scenarios.



Figure 18: One of the many testing events carried out in Spain, Italy and Germany

The goal of the testing events was to assess the design of the mobile and desktop apps for the acquisition and identification of sherds, and the search and retrieval component to automatically match and classify a sherd according to the digital comparative collections produced during the project (Figure 18). For archaeological SMEs the tests were developed in the field or during post-excavation, while in the HEIs testing was carried out in their facilities with a selection of well-studied exemplars. Testing was conducted on large numbers of specimens that were automatically classified according to typology (shape recognition) but also according to decoration (image recognition). All on-site testing was performed during the final year of the project and in different urban excavations in Palma (Can Coll, Plaça de Cort, Convent de Sant Bartomeu d'Inca and La Misericòrdia), Andratx (Tower of Sa Mola and Castell de Son Mas) and Toledo (Real Street and Cuesta de los Portugueses Street). Different pottery assemblages included types chosen as case studies by ArchAIDE, such as pottery from the Roman city of Pollentia, Castle of Capdepera, Roman city of Ercávica, Roman city of Laminium, Roman city of Libisosa, Roman villa in Cabañas de la Sagra and different assemblages stored at the Archaeological Archive of the Museu d'Història de Barcelona, belonging to survey excavations within the city of Barcelona (Figure 19).



Figure 19: Testing at the ArchAIDE final conference in Pisa, 2019

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8. The ArchAIDE Archive

While the mobile and desktop apps were designed to be part of a proof of concept, the ArchAIDE project was committed to creating sustainable outputs where the project held copyright (ArchAIDE consortium [2019](#)). This included making the interoperable, multilingual vocabularies available (Figure 20).

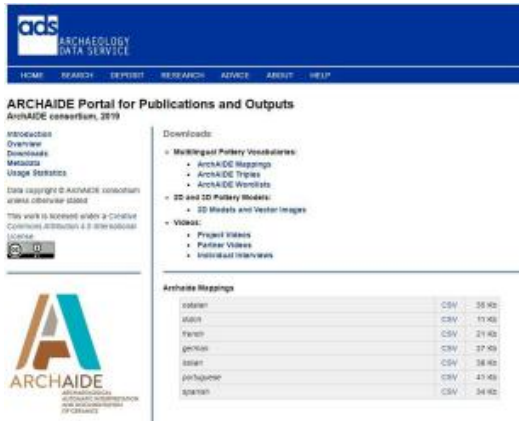


Figure 20: Screenshot of the ArchAIDE archive: <https://doi.org/10.5284/1050896>

The archive also includes the 2D and 3D models created by CNR-ISTI from the archive *Roman Amphorae: a digital resource* (University of Southampton [2014](#)), which were used to train the ArchAIDE deep learning algorithm for shape-based image recognition. This aspect of the archive represents a particularly good exemplar of best-practice reuse. *Roman Amphorae: a digital resource* was first deposited with the ADS in 2005, receiving a small update in 2014. As this archive is a comparative collection, allowing users to identify amphorae types, rather than the output of a particular archaeological project, it is widely used around the world as a resource. In fact, of the over 1000 'data rich' archives held by ADS, it is the single most popular resource, consistently receiving an average of 30,000 page-views every month. As such, the archive has become an authoritative resource, showing the potential of digital comparative collections when made freely and openly available.

When David Williams and Simon Keay of the University of Southampton first deposited the archive with the ADS in 2005, creating automated 2D and 3D models that could be used to create 'virtual sherds' to train the deep learning algorithm could not have been a use envisioned for the resource. As 2D and 3D models were created for every amphorae type and variant from *Roman Amphorae*, it was possible to link the two archives, amplifying the usefulness of both. With the kind permission of Williams and Keay, when a user now accesses the *Roman Amphorae* archive, and chooses an amphorae type to explore, in addition to the characteristics, pictures, drawings and petrology etc., there is now a link to 3D models, with the ArchAIDE logo to indicate it is a linked resource (Figure 21).



Figure 21: Screenshot of the archive *Roman Amphorae: a digital resource*, showing the ArchAIDE logo and a new link to 3D models on the right side of the menu bar for each type: <https://doi.org/10.5284/1028192>

Clicking through to the model for the desired type takes users directly to the page for that type in the ArchAIDE archive, which includes 2D vector drawings in SVG format for download, and 3D models for interactive use within the 3D viewer (created using [3DHOP](#)). The models can be manipulated and measured in a variety of ways (Figure 22). The 3D models are in OBJ format, and can also be downloaded for use with 3D software and for 3D printing (Figure 23).

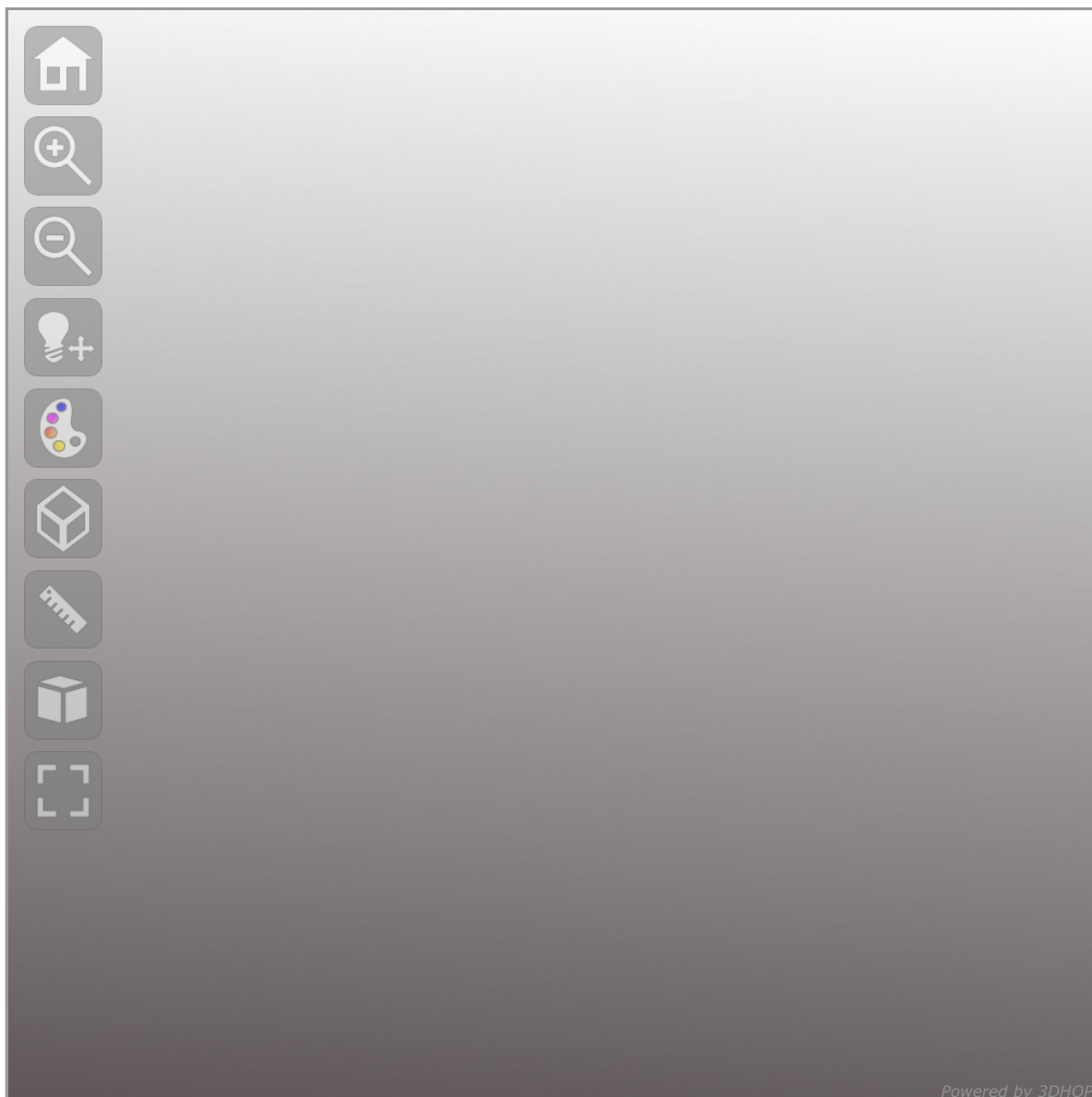


Figure 22: Carrot Amphora DR103 in the 3D viewer.
https://archaeologydataservice.ac.uk/archives/view/archaide_2019/downloads_amphora.cfm?amph=Carrot_Amphora_DR103

Finally, the ArchAIDE archive contains the video corpus created to both document and promote the project. Several of the videos from the archive are embedded within this article, which focused on the project generally, but there are many more in the archive that include individual interviews with partners, and self-shot partner profiles that were later professionally edited by the University of Pisa. The archive also includes the 30-minute ArchAIDE Documentary, created with footage shot over the course of the project. The ArchAIDE video archive not only represents a unique record of the project, but also an unusual record of the experience of implementing a European Commission-funded project with partners working across several countries.



Figure 23: 3D printed Roman amphorae from the ArchAIDE archive at the final project review in Brussels, 2019

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9. Conclusion and Future Work

The ArchAIDE project was ambitious and wide-ranging, but accomplished the majority of its aims over its three short years. Much was learned not only about the use of image recognition to identify archaeological pottery, but also the importance of access to comparative collections and intellectual property rights. ArchAIDE partners worked hard both to develop innovative technologies while still ensuring the knowledge and workflows of archaeological pottery specialists were respected. By being as outward facing as possible, both through the inclusion of Associate Partners and a comprehensive programme of communication and dissemination, contacts were made across the archaeological community who wanted to offer ongoing support and continue to contribute to the project, which has become a challenge now that it has formally ended. Along the way, several unexpected lessons were learned.

As the project progressed, it became evident that the comparative data necessary to implement the ArchAIDE database and app must be derived from a variety of sources, each with different advantages and restrictions. Comparative data (data that is meant to show typical pottery types and characteristics, against which pottery to be identified by the user is compared) is often useful only if it is considered authoritative. For instance, an analogue equivalent of the *Roman Amphorae* archive might be a particular comparative paper catalogue for Majolica of Montelupo that is accepted by specialists in that pottery type as a required citation in any peer-reviewed paper, and is also therefore considered authoritative. *Roman Amphorae* is free (as long as users abide by the appropriate terms and conditions of use). This is not the case for the paper catalogue described in the second example, where conversion into a dynamic digital resource was never envisioned.

While useful tools to help digitise the authoritative paper catalogues necessary to show the technical proof of concept of the ArchAIDE app were developed by CNR, this does not mean the ArchAIDE project necessarily now holds copyright to the newly digitised, remixed data (although the metadata created as part of this process by the ArchAIDE project can be argued to be new data, for which the project can claim copyright). Whether these data can be made available outside the proof of concept would need to be negotiated with each copyright holder, which represents a major logistical and (potentially) financial difficulty. This becomes even more complicated if the ArchAIDE app were to be monetised in any way. The issue cannot of course be solved by ArchAIDE, but instead provides another important proof of concept opportunity by the project. Showing the potential of digitising paper catalogues in a way that demonstrates how their content can be actively reused allows ArchAIDE to open a discussion with publishers and other data providers about the importance of making their resources available in new ways, with a tangible benefit (seeing their data in use within the app), thus furthering the long-term discourse around making research data open and accessible.

Another key lesson was the amount of training data necessary for the image recognition algorithm to return useful results. The researchers at Tel Aviv University were used to working with thousands of examples to train for a particular type, but ArchAIDE partners often struggled to obtain 10 per type. Ten per type was not ideal, but was determined to be the minimum amount that had to be acquired. This

resulted in far more time and effort spent on digitising the paper catalogues and undertaking the enormous photo campaigns to capture the necessary primary data. This effort helped partners to understand the importance of working together if the humanities wish to take advantage of the many machine-learning methods now available. Datasets are small, fragmented, and rarely optimised for machine-learning applications.

It was also hoped the photo campaigns might result in new comparative collections that could be made freely available as part of the ArchAIDE archive, but intellectual property rights in many European countries are restrictive, and did not allow photos taken by ArchAIDE partners of sherds held in national and regional collections to be made available. It is hoped that seeing the usefulness of these data within an example application such as ArchAIDE may also help convince the holders of these resources to move towards more open data policies.

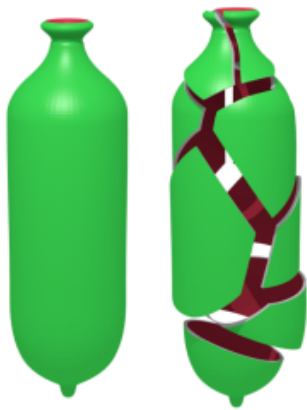


Figure 24: To address the paucity of training data available, 3D models were broken into 'virtual sherds' and used to train the shape-based algorithm

Once of the most fundamental lessons was that it was not possible to design an image recognition system that could identify pottery using both decoration-based and shape-based characteristics. It took considerable effort and discussion, but it became clear that it was necessary to separate them, developing two different algorithms. This allowed a creative outcome, as separating out shape-based recognition allowed the 3D models to be used to create desperately needed training data. By breaking the 3D models into 'virtual sherds' and using the sherds to train the shape-based image recognition algorithm, the accuracy rate was increased to an acceptable level (Figure 24).

ArchAIDE has shown the potential of using automated image recognition to identify archaeological pottery, while also illustrating some of the challenges that will need to be addressed in future. ArchAIDE has also shown it may be used for a variety of pottery types if the necessary comparative data can be gathered (and potentially other artefact types as well), as virtually all pottery identification relies on recognition based on either the shape or decorative elements of a vessel (or both). The ArchAIDE partners hope to continue working together, further developing the ArchAIDE mobile and desktop apps, but also working collaboratively across the archaeology community to build open comparative collections for use by all.

For other publications on aspects of the ArchAIDE project, please see (Anichini and Gattiglia [2017](#); Anichini *et al.* [2018](#); Banterle *et al.* [2017a](#); Banterle *et al.* [2017b](#); Dellepiane *et al.* [2017](#); Gattiglia [2018](#); Gualandi *et al.* [2016](#); Wright and Gattiglia [2018](#)) all of which can be downloaded from the [ArchAIDE Zenodo Community](#).

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Acknowledgements

ArchAIDE was born from a simple idea. Ten years ago, two archaeologists had a conversation about how difficult and time-consuming it was to classify their pottery, and how it might be possible to find ways to automate the process. Ten years ago ArchAIDE seemed impossible to create, a utopia, but we strongly believed in it, and are grateful for the opportunity to make it happen. ArchAIDE would still only be an idea without the effort and hard work of our great team. This skilled team includes archaeologists, computer scientists, IT specialists, mathematicians and videographers from across Europe who worked together over the last three years. The work was not always easy, having to take into account different cultures and approaches, but we found our common language by focusing on the same aim. Beyond the authors of this paper, we would like to thank all the other team members and people who took part in the project and helped us to reach our 'utopia'. In particular, from UNIPI: Antonio Campus and Sara Roberto; the Roman pottery specialists Paolo Sangriso and Simonetta Menchelli; the photo and video team including Nicola Trabucco, Simona Bellandi, Elda Chiriconi, Lorenzo Garzella, Serena Tonelli, Sonia Cerrai and Sandro Petri; Daniela Frediani, Massimo Bacci, Sandra Brondi and Michele Padrone. We would like to thank Mireia Pinto Monte from the University of Barcelona, and the ARQUB members Joan Sanmarti I Grego, Meritxell Tous Mata, Julia Beltrán de Heredia Bercero, Xavier Rubió, Cristina Fernandez de Marcos Garcia or the classification of Spanish Majolica; Felix Kußmaul and Michael Heinzelmann from the University of Cologne; the archaeologists and collaborators from Baraka, including Manuel Melero Serrano, Tomás Torres Gonzáles, Luis Alejandro García, Manuel Retuerce Velasco, Santiago Feijoo Martínez, José Luis Fuentes Sánchez, Jose Ignacio de la Torre Chávarri, Marian Arlegui Sánchez, Jacobo Fernández del Cerro, Rosario Cebrián Fernández, Olmo de Diego Pérez; and the developers of Inera Srl company, including Domenico Arenga, Alberto Cagetti, Bieder Muca and Christian Palombella.

The creation of the training dataset of photos of potsherds would not have been possible without the help of numerous colleagues who allowed us access to their finds warehouses and helped us to classify the materials. We would like to thank to Paola Olivanti, Maria Rosaria Barbera, Marcello Spanu, Emanuela Borgia, Francesca Romana Sabatini, Mara Elefante, Mara Sternini, Clementina Panella, Marta Casalini, Giovanni Altamore, Andrea Camilli, Claudia Rizzitelli, Eleni Shindler, Francesco Cini, Emili Revilla

Cubero, Joan Carles Lladó, Jaume Cardell Perelló, Elena Inglada, Miguel Ángel Cau, Judith Peix, Marta Valls, Júlia Coso, Laura Suau, David Prida, Núria Miró, Jordi Ramos, David Jimeno, Isabel Fernández del Moral and Francesco Cini.

Thanks also to Barbara Casalini, Antonella Fabbrini and Luisa Gaggini from Casalini Libri for working with us to find a sustainable solution to the difficulties surrounding catalogue copyrights.

ArchAIDE has also been a collaborative project involving many people around the world. We are grateful to all the ArchAIDE Associates, participants and volunteers who helped collect data, contributed to vocabularies and gave feedback during workshops and training days across Europe.

Many thanks to the ArchAIDE Associates: Alberto Martín Esquivel, Alfonso Forgione, Andreas Puhl, Astrid D'Eredità, Carlo Baione, Carlotta Bassoli, Claudia Sciuto, Cyrille Chaidron, Dagmara Łaciak, Darren Bentham, David Gallego Valle, Dennis Nicolas Lorenzo, Elisabeta Kodheli, Ellen Hallingstad, Enrico Giannitrapani, Erika Cappelletto, Ernesto Agustí García, Eslam Fawky, Francesca Grassi, Francesca Valbruzzi, Francesco Meo, Gabriel Rodrigues Barbosa, Gianfranco Israel, Concepción Tiza, Gimena Avalos, Giorgia Greco, Giuliana Mattos, Guilherme D'Andrea Curra, Guillaume Teillet, Hunter Provyn, Ivana Å kiljan, Ivana Ožanić Roguljić, James Byrne, Jesús Molero García, Jill Hilditch, Joan Frigola Torrent, Jona Petešić, Jorge Onrubia-Pintado, Laurence Cullen, Lorenza La Rosa, Luis Gonzalo Jaramillo Echeverri, Marco Antonio Aza Loza, Markus Nothegger, Matteo Lorenzini, Miguel Torres Mas, Mircea Masserini, Natália Botica, Ouafa Slimane, Pablo Medina Gil, Paula Alves Pereira, Penelope Allison, Rachel Opitz, Roy Towers, Sara Puggioni, Silvia Ferreri, Silvia Gazzoli, Silvia Lischi, Simona Morandi, Stephen Collins-Elliott, Ulrich Stockinger, Vincenzo Soria and Vittorio Fronza.

Many thanks to the ArchAIDE participants and volunteers: Agata Gattiglia, Alberto Caroti, Andrew Birley, Anacleto D'Agostino, Anna Taddei, Antonella Andaloro, Antonella Fabbrini, Antonio Fornaciari, Chiara Gatti, Chris Cumberpatch, Dan Miles, David Griffiths, Dominik Hagmann, Duncan Brown, Elisa Paperini, Elizabeth Greene, Ennio Casaglia, Fausto Berti, Filippo Sala, Francesca Simoncini, Francesca Toto, Francesco Pacetti, Gail Falkingham, Geoffrey Dannell, Germana Sorrentino, Giovanna Coppedé, Giuseppe Rigoli, Gloriana Pace, Hayden Strawbridge, Judith Peix, Júlia Coso, Julie Edwards, Keith May, Maria Duggan, Martina Fontanini, Matteo Vangeli, Miriam Torregrossa, Nick Cooper, Noemi Guadagni, Nora Sacco, Penelope Allison, Phil Holliday, Roberta Montesana, Sarah Colley, Silvia Lischi, Silvia Marini, Simone Sacco and Steve Roskams.

Finally, we dedicate ArchAIDE to the memory of Matteo Dellepiane, a bright scientist and gentle friend, who supported and helped shape our ideas from the beginning but left us too early in 2018.

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