CORPVS VASORVM ANTIQVORVM

BELGIQUE

SUPPLÉMENT

N°I

The Corpus Vasorum Antiquorum 1922-2022

A Century of Exploring Greek Vases : Typologies, Readings and Debates

Edited by Stefan Schmidt and Athena Tsingarida
with the collaboration of Anne Coulié

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PREFACE

The volume presents the proceedings of the international symposium that took place in October 2022, in Brussels at the Royal Academy of Sciences, Letters and Arts of Belgium. It was organized following a suggestion of Didier Viviers, Secrétaire Perpétuel of the Royal Academy and General Secretary of the Union Académique Internationale, to celebrate the Centenary Anniversary of the publication of the first volume of the Corpus Vasorum Antiquorum which is the oldest project of the Union Académique Internationale, initiated in 1919 by Edmond Pottier, curator at the Musée du Louvre.

This ambitious international enterprise was initially thought by Pottier as a comprehensive study of ancient pottery from three continents, Asia, Africa and Europe, including some undecorated samples, and with a special emphasis on the Mediterranean, Near and Middle Eastern productions. The project, conceived in the frame of the late 19th-century tradition of large corpora, in a truly international spirit, aimed to provide the academic community with a well-documented and scientifically accurate publication of pottery collections kept in museums. Many years after the death of Edmond Pottier, members of the CVA committees, many of them Hellenists, met in Lyon in 1956, and decided to narrow its focus to make Greek painted pottery (and related Greek influenced productions) the main subject of the series, a choice that is still largely followed today. Despite this narrowed focus, the series continued to be published and have become a landmark in the studies of ancient pottery. However, as the material of the corpus is not only decorated with ornaments, but often also with sophisticated images, the collection is at the same time basic research in the field of Bildwissenschaften and cultural history.

The Centenary Anniversary was a unique opportunity to discuss the state of the discipline in the field of ancient Greek pottery studies through its history, on-going research and future perspectives. The proceedings follow the four main sessions of the symposium, reflecting major subjects and trends of the research through papers based on selected case studies. The first part, entitled History of scholarship and collections, focuses on the developments of the discipline during the pionneering years in the late-19th-early 20th-century, in a period earlier or contemporary to the first volume of the CVA. It further considers the impact of new tools of research and important collections of vases on specialists and a wider audience throughout time. The second part [II. Classification: regional productions, workshops and individual styles] focuses on the different criteria of classification applied to this material. Typology has been and still is a critical component of pottery studies. It is taken here in its wide sense, including a large variety of approaches such as the study of regional productions, potter's workshops and individual painters. A third part [III. Images: agency, interpretation, effects] is concerned with images and raises questions related to their agency, components (including decorative patterns and inscriptions), meanings and impacts both from the workshop and the consumer. The fourth and last session [IV. Contexts and Uses] aims to contextualize ancient Greek pottery following a trend especially developed in recent studies which have been increasingly interested in the consumer's choice and impact. In this section, shapes, uses and archaeological contexts are taken into account, completed by papers on the role of middlemen and traders along with questions about craftsmen's mobility related to markets and demands.

The conference was organised by the three editors, Anne Coulié (Musée du Louvre), Stefan Schmidt (Bayerische Akademie der Wissenschaften) and Athena Tsingarida (Université libre de Bruxelles). It was made possible thanks to the generous funding of the Royal Academy of Belgium, the Bayerische Akademie der Wissenschaften, the Union Académique Internationale, the FNRS, the ULB and with the collaboration of the Musée du Louvre. During the preparation of the symposium and the volume for publication, we further benefited from the support of the CReA-Patrimoine (ULB, Brussels) and the team of the Royal Academy, especially Alberto Fernandez Munoz for his help on technical matters.

We owe special thanks to Didier Viviers for his constant support in the organization of the symposium and publication of the Proceedings. Special thoughts are addressed to the late Nathalie Bloch, infographist of the CReA-Patrimoine who prepared the program and the announcement, and who is no more with us. For her assistance in English language editing we owe great thanks to

Melanie Mendonca. Our task as editors was facilitated by the skills and expertise of Etienne Depasse, infographist at the CReA-Patrimoine, who prepared the manuscript for publication. We are also very grateful to all participants to the symposium, speakers and audience, who enthusiastically took part to the exchanges and enriched the discussions.

At the first stages of the organization of this symposium, the late François Lissarrague kindly accepted to be part of the project and to deliver the keynote lecture. We would like to heartfully thank Alain Schnapp who generously accepted the difficult task to replace François and who gave a lecture in form of a tribute to his work and the studies initiated by the group of scholars behind the "Cité des Images". This volume is dedicated to the memory of François Lissarrague.

Anne Coulié, Stefan Schmidt, Athena Tsingarida

ABBREVIATIONS

The abbreviations used for the periodicals are those of the *Année Philologique*

AIBL : Académie des Inscriptions et Belles Lettres

ABV : J.D. Beazley, *Attic Black-Figure Vase-Painters*, Oxford, 1956.

Add²: T.H. Carpenter, *Beazley Addenda. Additional References to ABV, ARV² & Paralipomena* 2nd ed., Oxford, 1989.

ARV²: J.D. Beazley, *Attic Red-Figure Vase-Painters* 2nd ed., Oxford, 1963.

AVI : Attic Vase Inscriptions Database

BAPD : Beazley Archive Pottery Database

CEG 1: P. A. Hansen (Hrsg.), *Carmina epigraphica Graeca* 1*, Saeculorum VIII - V a. Chr. n.*, Berlin, 1983

CVA : *Corpus Vasorum Antiquorum*

DAI Archiv : Deutsches Archäologisches Institut, Archiv der Zentrale

GstA : Geheimes Staatsarchiv, Stiftung Preußischer Kulturbesitz

INHA : Institut National d'Histoire de l'Art

LCS : A.D. Trendall, *The Red-Figured Vases of Lucania, Campania and Sicily*, Oxford, 1967.

LCS Suppl. 1 : A.D. Trendall, *The Red-Figured Vases of Lucania, Campania and Sicily, First Supplement*, London, 1970 [*BICS Supplement* 26].

LCS Suppl. 2 : A.D. Trendall, *The Red-Figured Vases of Lucania, Campania and Sicily. Second Supplement*, London, 1973 [*BICS Supplement* 31].

LCS Suppl. 3 : A.D. Trendall, *The Red-Figured Vases of Lucania, Campania and Sicily. Third Supplement Consolidated*, 1983 [*BICS Supplement* 43].

LIMC : *Lexicon Iconographicum Mythologiae Classicae*, Paris-Zurich.

Para : J.D. Beazley, *Paralipomena. Additions to Attic Black-Figure Vase-Painters and to Attic Red-Figure Vase-Painters* 2nd ed., Oxford, 1971.

RVAp : A.D. Trendall, A. Cambitoglou, *The Red-Figured Vases of Apulia*, Oxford, 1978 and 1982.

SMB-ZA : Zentralarchiv, Staatliche Museen zu Berlin

UAI : Union Académique Internationale

IV

CONTEXTS AND USES

'Capacity', the ULB Solution for Vessel Capacity Calculation

Laurent Bavay, Rudy Ercek, Cydrisse Cateloy

Long neglected by pottery studies, vessel capacity is increasingly recognised as an important element for the definition of the use and function of ceramic containers, as well as for classification purposes. It also offers a relevant way to approach standardisation and variation, a topic which has seen renewed interest and considerable advances in recent years.[1]

It is well known that the capacity of archaeological vessels can be measured by different methods.

The most accurate is by filling the vase directly with a liquid (typically water) or a free-flowing solid, such as polystyrene microbeads. This method is only possible under specific conditions, which are rarely met. In most cases, the fragmentary condition of the vessel does not allow for this direct measurement, while the physical filling may cause damage to the preservation of the container due to pressure and the materials used.

Indirect methods based on mathematical calculation of the volume from scale drawings are therefore more widespread and commonly used. These methods and the different formulae used to calculate the volume have been discussed repeatedly.[2] The most common consider the vessel volume as the addition of cylinders stacked one above the other, known as the "stacked cylinders" method, or the more accurate "bevel-walled cylinders" technique.

In recent years, a number of studies have also used a third method based on 3D modeling softwares (such as Autodesk 3Ds Max®) to generate a tridimensional model from which the volume of the container is calculated. However, most of these solutions create the 3D model on the basis of a scale drawing of the vessel. They therefore offer no significant difference, in terms of precision, from the 2D methods based on the drawing since the result still relies on the accuracy of the graphic document. However, they require more time since it is necessary to generate the 3D render from the drawing, while the 2D method that we promote only requires the conversion of the original drawing as a jpeg file. Some other methods are based on the digital capture of the vessel, either using photogrammetry or a 3D scanner.[3] While it definitely provides a more accurate result, notably when the vessel presents irregularities, it requires a lot of handling and processing, as well as specialised competences and direct access to the containers. For these reasons, we do not consider 3D methods as a *significant* improvement over 2D capacity calculation, at least not for daily practice in pottery studies.

The ULB web-based application, from version 1.0 to 'Capacity': 15 years of evolution

In 2006, a new web-based solution for vessel capacity calculation was presented at the international conference "Formes et usages des vases grecs" held at the Université libre de Bruxelles (ULB).[4] The development of this solution was the result of a collaboration between civil engineers of the ULB Polytechnic School and archaeologists of the Archaeological Research Centre, as part of a research project led by Athena Tsingarida on "Ceramics in Ancient Societies: Production, Distribution and Uses".[5] The solution was designed as a free, easy-to-use application to calculate the capacity of a vessel based on its scale drawing. Its advantage was that it required nothing else but the graphic documentation commonly available for archaeological pottery collections or assemblages. The application had to meet the following specifications: the possibility of using vessel drawings with minimal adaptations, to automate the measurements as well as the calculations, to provide a user-friendly interface, and to offer the greatest possible availability and accessibility. This website has been online without interruption since 2006 and it has been widely used by the scientific community, as illustrated

1 See in particular the contributions in Kotsonas 2014; Cateloy 2022.

2 Notably Senior, Birnie 1995; Thomas, Wheeler 2002; Engels, Bavay, Tsingarida 2009, 129-130; Rodriguez, Hastorf 2019; Moreno, Arévalo, Moreno 2019.

3 Velasco Felipe, Celdrán Beltrán 2019; Tavella et al. 2022.

4 Engels, Bavay, Tsingarida 2009.

5 ARC research project (2004-2009) funded by the Fédération Wallonie Bruxelles.

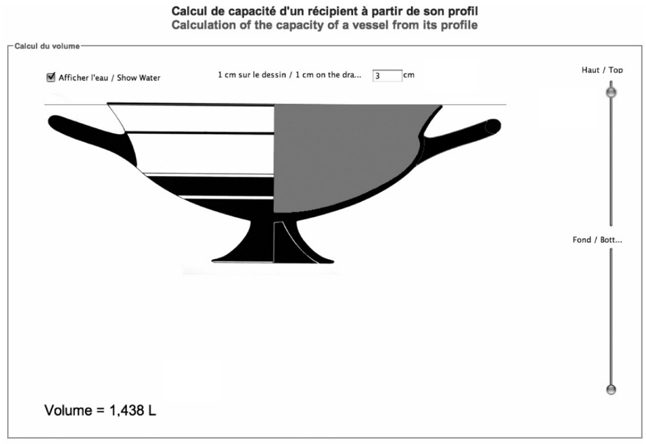

Fig. 1. The original version of the capacity viewer (2006) (ULB, LISA & CReA-Patrimoine)

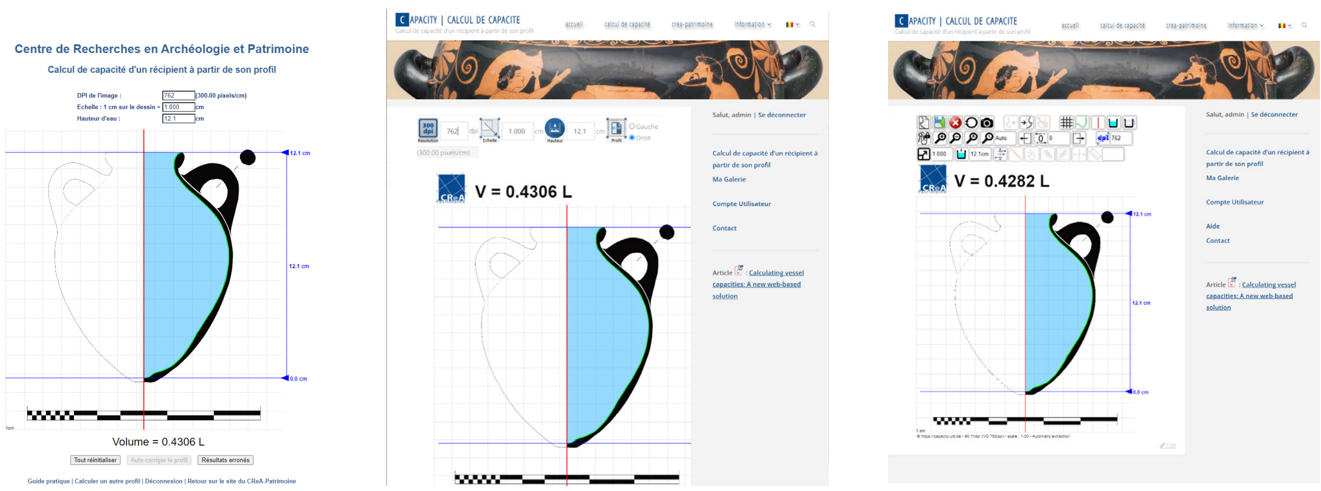

Fig. 2. (a) New javascript viewer in 2013 (b) WordPress site in 2020 (c) WordPress site with the new viewer in 2022 (ULB, LISA & CReA-Patrimoine)

by the range of publications referring to the use of the ULB solution. [6]

Over the years much feedback was received, mostly reporting problems encountered by the users. [7] The issues were fixed as far as was possible by the original developer of the application, engineer Laurent Engels, later followed up by Rudy Ercek of the Brussels Polytechnic School, who continues the technical maintenance and evolution of the solution.

Since 2006, some of the technologies used in the original version have become obsolete or are no longer supported, and some minor updates have been implemented. As an example, the Java applet (fig. 1) which supported the user's interface was replaced by Javascript (html 5) in 2013 as shown in fig. 2a. Another evolution had to be implemented in 2020 when the code running the user database was no longer supported by the new servers. This necessitated a major revision which was implemented in two phases, based on a WordPress website with a great deal of customisation and development. The first phase mainly focused on the new website design, user registration and capacity calculation using the original method with the Javascript viewer as shown in fig. 2b. This website was put online in November 2020. With the second phase of development, several new tools were added to the Javascript viewer allowing profile and axis corrections,

6 E.g. Böhr 2002; Molina Vidal, Corredor 2018; Steiner, Bidgood 2018; Sukhanov 2018; Phialon 2020; Mączyńska 2021; Sturge 2023.

7 Including valuable comments by Steiner, Bidgood 2018, 1015-1018.

WEBSITE	2006	Dec. 2013	Nov. 2020	Oct. 2022
Viewer	JAVA Applet	Javascript (JS) with Canvas	JS with minor changes	JS with major changes (tools,...)
Web Pages with User Management	PHP/HTML with DB Mysql	Minor changes	Wordpress CMS (PHP/Mysql) with plugins incl. 1 custom (capacity)	Major changes with custom gallery in the capacity plugin.
Profile/Axis Extraction	C++ Programme with OpenCV 1/2 Library	No change	No change	Webservice with C++ programme but axis corrected + Python for analysis
DEVELOPER	Laurent Engels	Rudy Ercek	Nextwave SPRL (consultancy)	Rudy Ercek
FEATURES	Original Version (OV)	Solve incompatibility issues with JAVA. Correct volume for vessels with bottle bottom. Scale can be adjusted with water height.	Automatic side detection when file uploaded. New modern web design. Basic gallery with uploaded files that can only removed. RGPD Compliant. New registration is mandatory.	Volume/side "validation". Axis position in the center, not on the axis edge (as OV). New gallery with search, filter, volumes, values, ... New viewer with many tools: profile & axis correction, save/snapshot results, measure, zoom, ...

Table 1. Technical evolution of the 'Capacity' solution 2006-2022

results saving, measurements, etc. A new gallery was also implemented which allowed users, for e.g., to review or delete drawings previously uploaded on the Capacity server. The complete website evolution with improvements and technologies used is presented in Table 1. The updated website has been online since October 2022.

Presentation and use of the revised website

The revised website, based on WordPress, is accessible at **https://capacity.ulb.be** using a recent web browser. The user interface is available in both French and English.
Even if a user already had an account on the original website, a new one has to be created using the registration button "Create a new account" (fig. 3). Registration is free but mandatory as it allows access to a personal library of the drawings previously submitted by the user. Once logged in, the right-hand panel gives access to the main calculation window, to the personal user gallery, user account information, help and contact details. The "Calculation of the capacity of a vessel from its profile" button gives access to the upload page (fig. 4). The procedure requires only two steps: "Choose" a drawing file from your computer (supported formats are .jpg, .png and .gif) and then "Calculate" its capacity. This page also has instructions for an optimal result and a series of cases where the characteristics of the drawing could present a problem with the calculation. In practice, the application is quite robust and the user should encounter few problems with most usual, not-too-asymmetric shapes.

Once the calculation is complete, the drawing appears with the symmetry axis marked in red and the section half filled in blue from the bottom to the top as shown in fig. 5. If the drawing is not at scale 1:1, the scale has to be indicated manually (red arrow on fig. 5, in our example the cup is drawn at 1:4, so the value of the scale icon needs to be changed from 1,000 to 4,000).

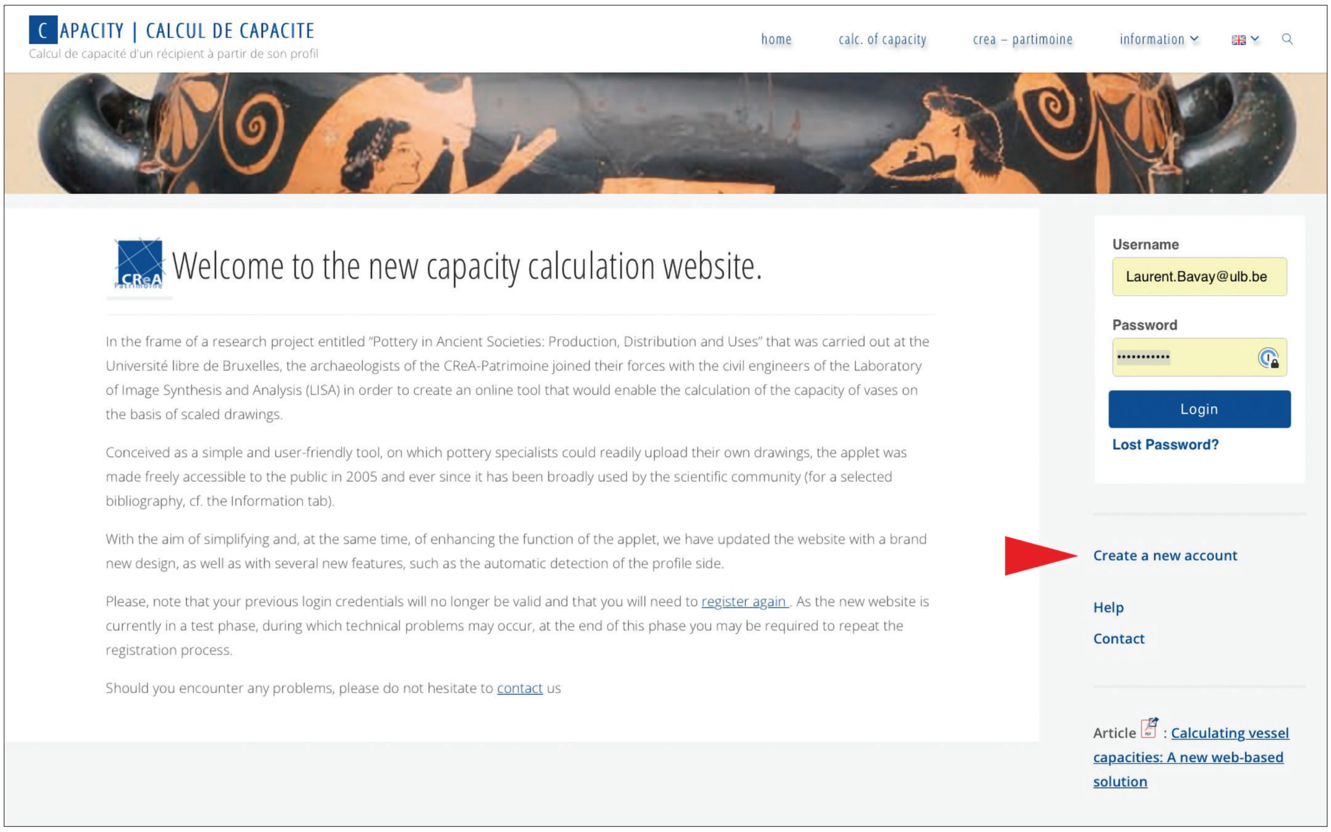

Fig. 3. Welcome page of the new website (2022) at https://capacity.ulb.be (ULB, LISA & CReA-Patrimoine)

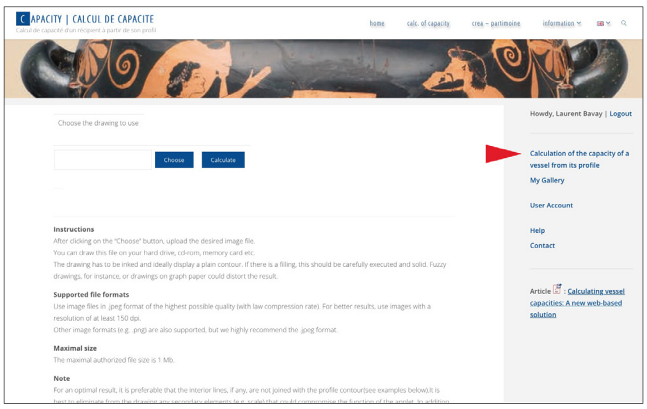

Fig. 4. Drawing upload page of the new website (ULB, LISA & CReA-Patrimoine)

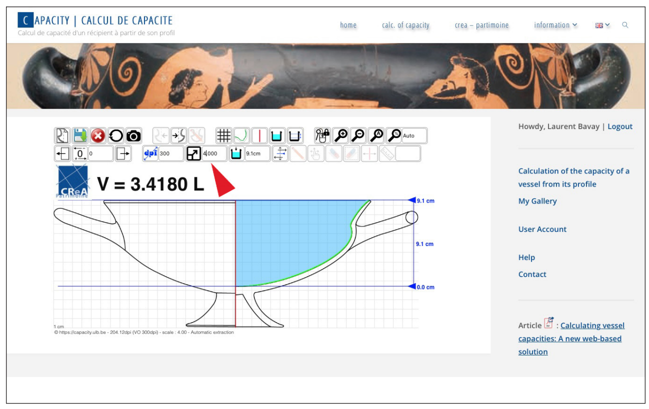

Fig. 5. Viewer of the new website after calculation. The red arrow indicates the scale tool (here, drawing is at scale 1:4) (ULB, LISA & CReA-Patrimoine)

To modify the level of the filling, the user simply slides down the top blue arrow and the capacity measurement adapts in real time (fig. 6). This is especially useful when archaeological evidence provides an indication of the vessel's actual filling level, such as residue marks on the vessel walls.

It is possible that the application does not recognise the position of the profile correctly, or the limits of the profile contour. Although relatively uncommon (see below), this problem was the major drawback of the original version, since the only solution was then to modify the drawing itself in order to remove lines or features which altered the correct logarithmic extraction. The main improvement of the new version is a series of tools that allow the user to manually correct almost all parameters directly on the website: position of the axis, position of the profile (left or right), (fig. 7).

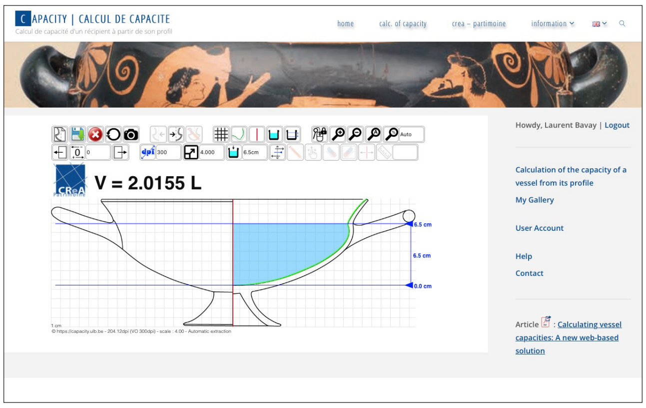

Fig. 6. The water level can be modified by moving the blue arrows on the right side of the vessel and the volume measurement will adapt in real time (ULB, LISA & CReA-Patrimoine)

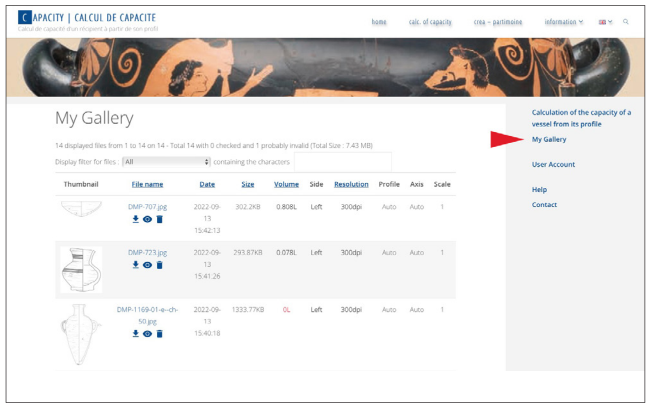

Fig. 8. The user gallery of the new website (ULB, LISA & CReA-Patrimoine)

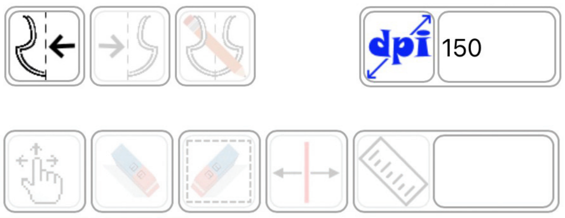

Fig. 7. Tools for correcting extracted parameters in the viewer of the new website (ULB, LISA & CReA-Patrimoine)

The viewer of the website contains other tools allowing the user to show or hide the water level, axis and grid, take a screenshot of the result, adapt the size of the drawing to the screen, etc. These tools are described in detail on the Help page of the website, which also provides links to a series of video tutorials on a dedicated YouTube page. Noteworthy is the floppy disk icon which allows users to save manual corrections to the drawings. The modified version will thus be available for future use in the new personal Gallery accessible from the main menu on the right. This library contains all drawings uploaded by the user, with information such as the calculated volume, upload date, scale of the drawing, etc. The files can be reviewed, downloaded and/or deleted (fig. 8). A search field allows the easy location of files based on specific characters in their file name, and filters can also be used to only display probably valid, invalid, corrected or checked drawings. Some of these terms will be explained in the next section.

Technical description of the solution

The capacity is calculated from an image file, which is a large matrix of color pixels that does not contain any information about the geometry such as lines, curves, etc. Algorithms must therefore be used to group those pixels into known shapes. Most archaeological pottery drawings present the symmetry axis with the profile on one side and the contour line on the other side including some details related to surface treatment, decoration, etc. The application should be able to extract the revolution axis and the inner profile on the correct side as a sequence of segments. Indeed, in order to calculate the volume, the implemented solution uses the “bevelled-walled cylinders” technique[8] where the final volume is obtained by the sum of bevelled cylinders as shown in fig. 9. Each bevelled cylinder is limited by a segment of the inner profile and the revolution axis.

The volume of each bevelled cylinder is obtained by the following formula:

$$V = \pi \, H \, (R1^2+R2^2+R1R2)/3$$

where H is the height of the cylinder, R1 is the top radius, R2 is the bottom radius and V the volume of the considered bevelled cylinder.

A particular but quite frequent feature is a bottle bottom base. In this case, the height H of a bevelled cylinder is taken with a negative sign when the segment of the profile goes up (from bottom to top), i.e. the volume of this bevelled cylinder is subtracted as shown in fig. 10.

8 Senior, Birnie 1995, 322-323.

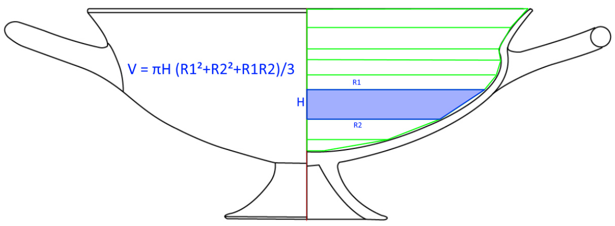

Fig. 9. "Bevelled-walled cylinders" method for volume calculation (ULB, LISA & CReA-Patrimoine)

Fig. 10. Computation of the volume with the bevelled-walled cylinder method for vase with a bottle bottom (ULB, LISA & CReA-Patrimoine)

In order to extract the axis and the profile, a C++ programme was originally implemented using one of the first versions of the widespread image processing library OpenCV.[9] This programme runs on the capacity server each time a user sends a file for capacity calculation.

For the axis extraction, a Canny edge detector[10] is first applied in order to have the axis border with one pixel width. Then a Hough Transform[11] is used to detect lines in the image. Note that even dashed lines can be detected by the Hough Transform. Finally, the most vertical line in the middle area of the images is considered as the axis. If no line is found, the middle of the image is taken as axis position. This algorithm proves to be robust enough to find the revolution axis. Nevertheless, the axis position given by this algorithm is on the axis edge and not its center. This systematic error (in pixels) of the axis position can be easily evaluated by using the formula (n+1)/2 where n is the axis thickness in pixels. As the axis is normally vertical, the 2022 version accumulates pixels vertically around the detected axis position (i.e. the axis edge) to determine the axis width and recenter it. Thus, this light offset error generally either no longer exists or it is at least mitigated in the current version.

The profile extraction was the most challenging part because there are some variations in drawing traditions, such as the profile filled in black or left blank. Therefore, the algorithm analyses external contours instead of whole regions on the profile side, i.e. the left or right side of image. First, the image is flipped if the profile is on the left and the left side, including the axis, is erased from the image. The image is then binarised by the Otsu algorithm.[12] After that, contours for all regions are computed and only the contour with the largest bounding box that corresponds to the profile is kept. In order to find the inner part of the profile, the contour is travelled counterclockwise from the top. By using the proximity of the axis and other points of interest, the inner profile starting from the top is found.

In previous versions of the solution, the side of the image with the profile had to be manually selected by the user. In the current version, this manual selection is no longer necessary since the profile extraction algorithm is always applied on both sides. The side with the highest number of extracted profile segments is selected by default. However, if the automatically detected side proves to be incorrect, a tool in the viewer allows the other (correct) side to be selected manually. Moreover, the latest version of the website tries to assess if the side selection, the profile and axis extraction are correct, i.e. probably valid. To do this, a test is executed based on the observation of profiles uploaded to the server over the years, which shows that the height of the internal profile is usually at least a quarter of the total height of the image. A final test is done by checking the positive value of the computed volume. If both tests succeed, the computed volume is considered as probably valid. If one of the tests does not pass, both tests are checked on the other side of the drawing and if they pass, the other side is displayed to the user and considered as probably valid. If both sides are considered probably invalid, the profile and axis extraction is carried out on both sides of the drawing image whose resolution has been reduced by half. Indeed, reducing the resolu-

9 Bradksi 2000.
10 Canny 1986.
11 Duda, Hart 1972.
12 Otsu 1979.

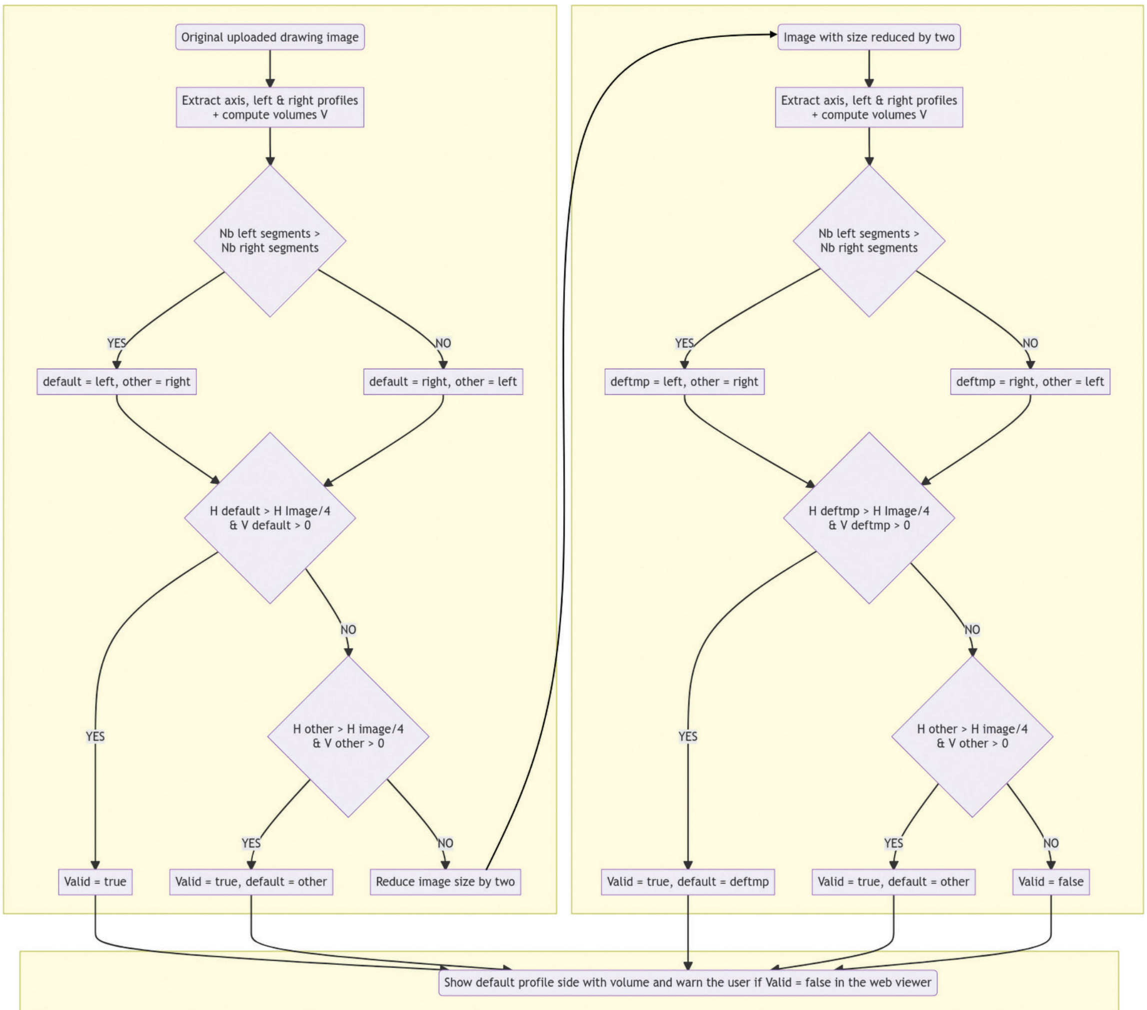

Fig. 11. Flowchart of the automatic side selection and the validation process (R. Ercek, ULB)

tion decreases image noise and may improve the profile extraction since some algorithm parameters are fixed by pixels. User experience has also shown that, when doing so, the programme sometimes manages to correctly extract the profile that was not correctly extracted at the original image size. The same tests are then carried out once again as at the original resolution. If none passes, the computed volume is probably invalid and a message is displayed in the viewer with the (probably erroneous) volume calculated from the default side of the extracted profile at the original resolution. The user may then correct the original image before sending it back for calculation or he can correct the side, extracted profile and/or axis using the new viewer tools in order to directly obtain the good volume. The side selection and validation process are shown in fig. 11.

It is also important to mention that the volume is computed on the server side and also on the client side when the user changes, for e.g., the water level or the extracted inner profile. This volume is computed in pixels unit (pixels^3) and in order to convert it into litres, the image resolution in dpi (for dot per inch) is extracted from the original image and the volume in litres (Vl) is calculated with $Vl=Vpix*(0.254)^3/dpi^3$. Finally, the user enters the image scale (1:scale) and the final volume value is given by the multiplication of the scale power 3 with the calculated volume. It is also possible to automatically adjust the scale using the vessel depth, or any other known measure on the vase, with the “Measure” tool in the new version of the capacity viewer.

Volume error analysis

The volume computation from vessel drawings is based on the main hypothesis that the vessel is a perfect solid of circular revolution around an axis (as a cylinder). Unfortunately, this hypothesis is rarely met since the majority of archaeological pottery is hand-produced and the contribution of this error is difficult to analyse theoretically. An empirical approach comparing the results obtained by direct and indirect methods will be presented below. We will here discuss some issues which can affect the results of computed calculations and how to minimise their impact.

The "bevelled-walled cylinders" technique is used to compute the volume. In order to use it, the axis position is supposed to be perfectly vertical and the inner profile has to be extracted from the drawing. The extracted inner profile is composed of a multitude of small linked segments that perfectly fit the profile and the rotation axis is generally correctly positioned on its center. Hence, the volume error using this automatic technique for volume calculation should be nearly null with a "good" drawing. If the axis is not perfectly vertical or if the inner profile is manually drawn, the error is more difficult to quantify. In order to theoretically study the link between volume errors and other errors, the volume V of a cylinder is given, as basis, by the formula $V = \pi r^2 h s^3$ where s is the scale factor, h the cylinder height and r its radius. So, the volume relative error $|\Delta V/V|$ of this cylinder can be obtained with

$$\left|\frac{\Delta V}{V}\right| = 3\left|\frac{\Delta s}{s}\right| + 2\left|\frac{\Delta r}{r}\right| + \left|\frac{\Delta h}{h}\right|$$

where $|\Delta s/s|$ is the scale relative error, $|\Delta r/r|$ the radius relative error and $|\Delta h/h|$ the height relative error.
For volume calculations from archaeological drawings, the radius r depends on the height position $r = f(y)$ with y varying from 0 to h but a "mean radius" r_{mean} could be computed with

$$r_{mean} = \sqrt{\frac{V}{\pi h s^3}}$$

This "mean radius" r_{mean} is the radius of a cylinder with the same height (i.e. vase depth) h and that same volume V as the original vase.
Therefore, the volume relative error $|\Delta V/V|$ of a cylinder gives some information about error contribution in general and what the user should pay attention to on vase drawings for volume calculation. The most important one is the scale error which contributes 3 times to the volume error, i.e. a scale of 1 instead of 0.99 or 1.01 produces a 3% volume error. The second is the axis position error (i.e. on r_{mean}) which contributes twice to the volume error, i.e. an axis position error of 1 mm on a vase with an "average" diameter of 20 cm gives a 2% volume error. The last one is the height error which has the same impact on the volume error. Nevertheless, this height error is often linked to the other two errors if the error mitigation explained in the next paragraph is used. Moreover, the height can be manually adjusted by the user and then its error can easily be corrected.

Based on the volume error analysis above, the error can be mitigated by using some vessel information. First, the scale should always be adjusted using a known measure. The best solution is to adjust the water height in the viewer to the measured vase depth or the measured vase height. An alternative is to use the ruler tool of the viewer to adjust a known measure on the vessel to the real one. Secondly, the axis position must be checked and may need to be corrected with at least one or two known radii at specific height. For example, the opening diameter (2r) or its circumference (2πr) at the vessel top should be the best. Any other vase diameter or outer circumference could also be used but the vase thickness should also be known at that height, so it is probably less accurate. Note that using the circumference instead of the diameter to get the radius should somewhat compensate for the error relating to a non-perfect circular vase.

Statistical assessment of the solution

Between November 2020 and November 2022, 7918 drawing files were uploaded on the capacity server by 127 registered users (see fig. 12a). Among these files, 604 drawings (see fig. 12b) were manually checked in order to retrieve information not only about the validity of the automatic axis and profile extraction, but also the automatic side selection and validation process.

Table 2 presents interesting global results. Less than 3% of axes and less than 10% of profiles are not correctly extracted. With more than 90% of valid results, the automatic extraction can be considered as efficient, leaving less than 10% of the extractions to be manually corrected by the user. 85% of the drawings are valid, i.e. with correct profile and axis extraction and side selection. The automatic side selection of only 5% of the drawings did not provide a correct result. It is also important to note that, in the new version of the website, reducing the drawing to half resolution (see above) increases the correct extraction by 7%, from 83% (original size) to 90% (reduced size).

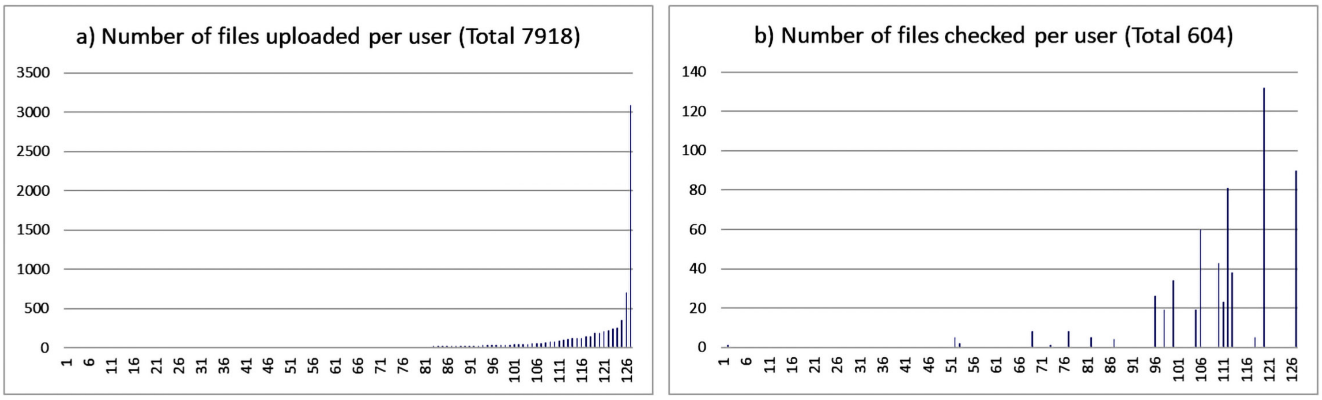

Fig. 12. Number of files uploaded (a) and checked (b) per user.

Drawings with	Value	on (total)	%
Profile not correctly extracted	49	604	8,11%
Axis not correctly extracted/positioned	18	604	2,98%
Profile or axis not correctly extracted	55	604	9,11%
Profile and axis correctly extracted	**549**	**604**	**90,89%**
Profile and axis correctly extracted at original size	506	604	83,77%
Profile and axis correctly extracted at half size	43	604	7,12%
Profile and axis correctly extracted and correct side selection (valid)	**515**	**604**	**85,26%**
Incorrect side for profile and axis correctly extracted	34	549	6,19%
Incorrect side selection for all	49	604	8,11%

Table 2. Statistics for profile and axis extraction and side selection

	Predicted valid	Predicted invalid
True valid	470 (True positive)	45 (False negative)
True invalid	52 (False positive)	37 (True negative)

Table 3. Confusion matrix for the validation process

Table 3 shows the confusion matrix for the validation process in which the algorithm tries to predict whether the profile and axis extraction and side selection are correct, i.e. valid. From this confusion matrix, it can be deduced that the sensitivity and precision are very good, respectively ~91% and 90%, but the specificity is poor (~42%). Good sensitivity means that the prediction of a valid case will be correct most of the time (i.e. a probably valid case will really be valid) and good precision implies that very few predicted valid cases are invalid. But, with poor specificity, the prediction of an invalid case (i.e. bad extraction or side selection, probably invalid) often fails and needs to be checked. Nevertheless, a good specificity for the validation process is not important because an invalid drawing (true or false invalid) must always be checked in order to correct the side, profile or axis and obtain a correct volume. Note that the accuracy is ~84% and the F1 score (a metric which takes into account both precision and sensitivity) is 0.9 which is really good.

In conclusion, these statistical numbers show that the implemented solution is efficient and can automatically, quickly and correctly calculate the volume/capacity of most uploaded drawings.

Comparative study of indirect and direct measurement methods

It has been postulated that indirect methods based on scale drawings represent the most convenient way to measure the capacity of pottery vessels, since they don't require direct access to the material and they allow the measurement of fragmented vases (provided their complete profile can be reconstructed). However, the use of mathematical calculations raises legitimate questions about the accuracy of the results. These methods indeed assume that the calculated shape is perfectly symmetrical, while it is well known that archaeological vessels, as products of craftsmanship, never reach such a high level of consistency. Therefore, a certain margin of error is inherent in the drawing itself and this will inevitably reflect in the measurements calculated from the drawing.[13]

An empirical experiment was conducted in order to better assess the differences between direct and indirect measurements, and to compare the accuracy of the Capacity solution with other calculation methods. This comparative study consisted of applying different methods to the same body of material. The group of pottery containers selected for the experiment consisted of ten intact amphorae from the shipwreck known as the 'Grand Ribaud F', an Etruscan ship loaded with hundreds of Caeretan amphorae which sunk off the shore of Hyères (Southern France) in the late 6th – early 5th century BCE.[14] The cargo of this shipwreck proved an ideal case study since it contained a large number of perfectly intact vessels, with no cracks that would inevitably affect the capacity measurement. In addition, the use of large vessels seemed more suitable, as the measurement of their volume could result in larger discrepancies between direct and indirect methods than with small vases. This study is based on personal handling and drawing of the vessels and was made possible thanks to the permission of the French Department of Underwater Archaeology (DRASSM).[15]

Firstly, the capacity of each amphora was measured manually by filling it with water. Prior to this stage, the amphorae were immersed in a pool to ensure that their walls were fully saturated and prevent water from penetrating the ceramic during the measurement process. This precaution was necessary to avoid an overestimation of their actual capacity, since old ceramic material tends to be porous and permeable. To determine the potential error, all amphorae were filled once when dry, and again inside the pool with the body soaked in water. This comparison revealed that there can be a difference of almost half a litre. Another experiment measured the water level 15 minutes after the vessel was filled to the rim. The variation ranged from 100 to 300 ml. Despite these possible biases, the measurement with water appears to be the most accurate and serves as the benchmark for other methods in this comparative study.

Another direct approach consisted in manually measuring the capacity using a flowing solid. Tiny styrofoam beads, with an average diameter of 1.2 mm, were chosen for this second step. This material offers a number of advantages compared to sand, rice or any other semi-fluid solid that could be used during this process. It is perfectly homogeneous with a spherical shape and uniform size, as well as being virtually weightless. These microbeads act like a liquid substance and can evenly fill the interior of any vessel without endangering the integrity of the vessel. However, this method encounters some limitations, such as the space between the beads, which will never be the same once poured into the vessel, and the compaction or static electricity that can also cause slight bias. By reproducing the same gestures over again, it is possible to minimise bead compaction while increasing the repeatability, which improves the accuracy of the measurement. Each direct measurement of water and polystyrene beads was repeated three times for all amphorae, with a tolerance of no more than 1% deviation between each measure to ensure consistency and repeatability. In a few cases, an additional measurement was taken to meet the 1% deviation policy. The capacity indicated in Table 4 represents the mean value of these three measurements. Despite their apparent regularity, the capacity of the Etruscan amphorae from the 'Grand Ribaud F' cargo shows considerable variations, with values ranging from 26 to 33 litres.

13 The technical accuracy of the drawing is of course another potential factor of error. We assume here that the drawings used have been produced by an experienced, trained specialist in archaeological illustration.

14 Long, Gantès, Drap 2002; Long, Gantès, Rival 2006.

15 Special thanks are due to Nathalie Huet and to the DRASSM for granting access and authorisation to study this material in the archaeological storeroom ("dépôt des Milles") at Aix-en-Provence (France). My gratitude also goes to Marie-Pierre Jézégou and Luc Long. The comparative study was initially undertaken as part of a PhD research project (Cateloy 2022).

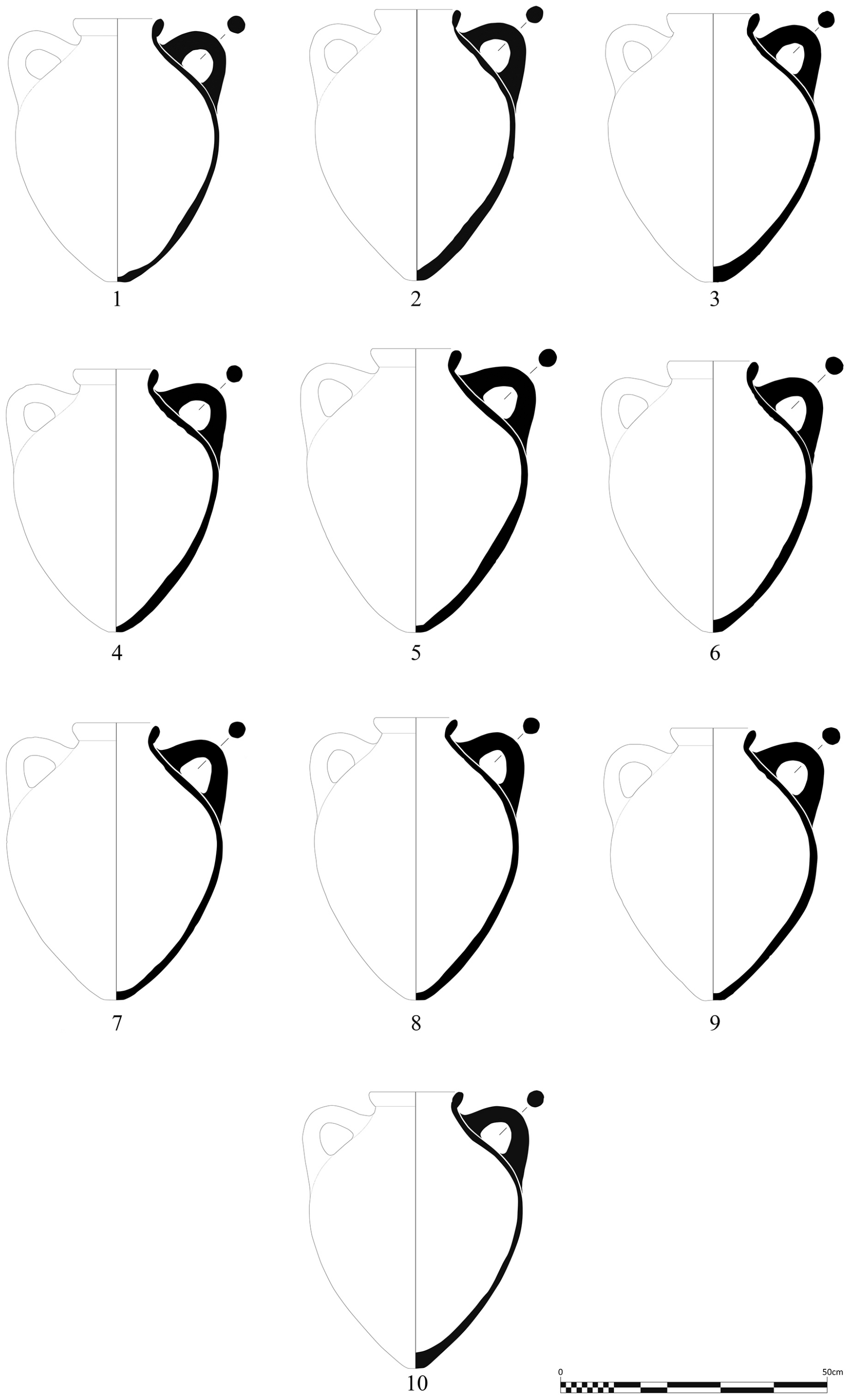

Fig. 13. Drawings of the 10 amphorae from the ‘Grand Ribaud F’ Etruscan shipwreck (DRASMM excavation 2000-2002) used for comparative study of the different methods of capacity calculation (drawings C. Cateloy)

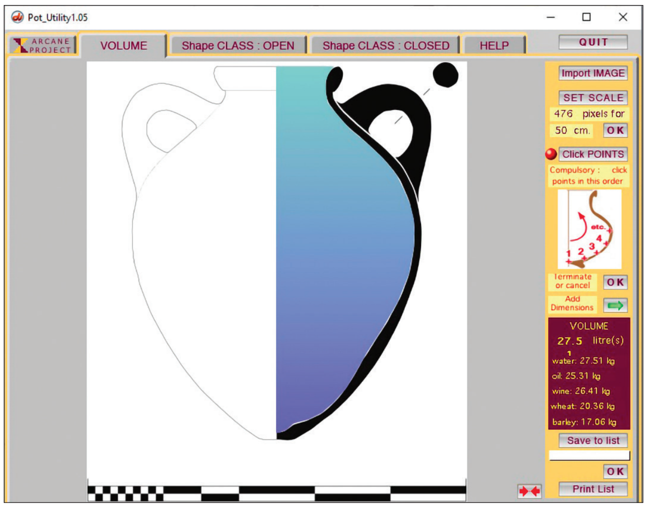

Fig. 14. Pot Utility application for capacity calculation (J.-P. Thalmann, ARCANE)

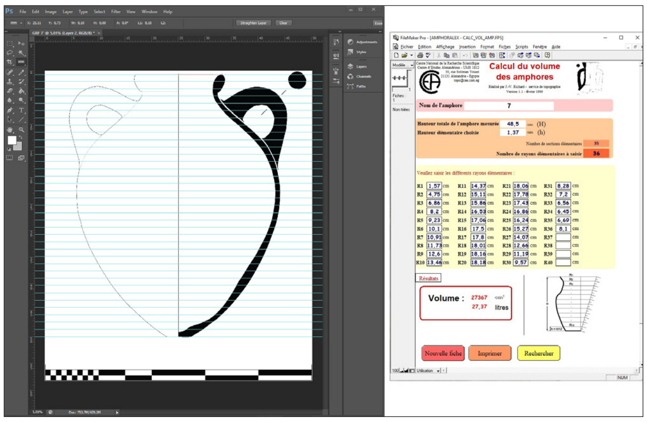

Fig. 15. Amphoralex capacity tool (© Centre d'Études alexandrines/CNRS)

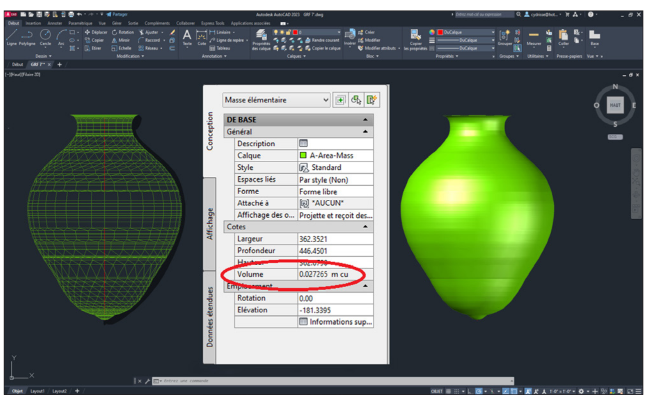

Fig. 16. Autodesk AutoCad® tools for capacity calculation

The ten amphorae were then drawn and digitised to estimate their capacity by means of computer methods (fig. 13). Following the ULB Capacity solution, the first computer-aided mathematical method tested was Pot Utility, a software developed by the late Jean-Paul Thalmann in the scope of the ARCANE project.[16] Its principle is very similar to Capacity, with the difference that it is not web-based but a standalone application for Windows and MacOS (fig. 14). Until recently it was freely distributed on the ARCANE website, but is unfortunately no longer available online and its development is no longer being maintained.

Amphoralex is another capacity calculation solution developed by the Centre d'Études Alexandrines, a permanent CNRS research centre in Egypt.[17] It is based on the commercial software FileMaker Pro. However, unlike Capacity and Pot Utility, it requires the manual input of measurements for the different cylinders that divide the vessel, with a maximum of 40 cylinders, making it a time-consuming process (fig. 15). Finally, the latest capacity measurements were obtained using Autodesk AutoCAD®, a reference computer-aided design software that generates 3D digital shapes. After creating a 3D model of the ceramic vessel based on its scale drawing, the software can provide volumetric data, which is expressed in cubic meters (fig. 16). These measurements can be easily converted to litres (one cubic metre corresponding to 1,000 litres).

For the sake of exhaustivity, we should mention here that the recent Kotyle software application developed in Python programming language[18] has not be included in the present comparative study.

The results are presented in Table 4. It should first be noted that the accuracy of the methods based on a scale drawing, with an average variation of less than 5% compared with direct measurements, were unexpected. Since the degree of standardization of ancient pottery production should not be considered by modern standards, these results demonstrate the validity of the method. Among the different tested methods, the ULB Capacity solution stands out with excellent results, 6 out of 10 capacities in the sample being the closest to the actual

16 Thalmann 2007.
17 http://amphoralex.org/amphores/CalculVolume/CalculVolume.php
18 https://kotyle.readthedocs.io/en/latest/

Method/Amph.	GRF 7	GRF 12	GRF 23	GRF 34	GRF 49	GRF 119	GRF 122	GRF 171	GRF 189	GRF 191	Variation to water
Water	**27,669 L**	**27,856 L**	**28,960 L**	**26,476 L**	**33,444 L**	**26,462 L**	**31,346 L**	**28,886 L**	**27,704 L**	**30,748 L**	
Styrofoam beads	27,453 L -0,89%	27,766 L -0,08%	28,905 L -0,01%	26,287 L -0,31%	33,555 L +0,33%	26,318 L +0,14%	30,844 L -1,26%	28,904 L +0,06%	27,602 L +0,15%	30,634 L -0,10%	**0,33%**
Capacity.ulb.be	27,621 L -0,18%	25,653 L -7,91%	28,855 L -0,36%	25,065 L -5,33%	32,515 L -2,78%	24,663 L -6,80%	30,432 L -2,92%	28,837 L -0,17%	27,835 L +0,47%	30,668 L -0,26%	**2,72%**
Pot Utility	27,580 L -0,32%	25,290 L -9,21%	29,010 L 0,17%	25,140 L -5,05%	31,910 L -4,59%	24,800 L -6,28%	29,790 L -4,96%	28,590 L -1,02%	27,260 L -1,60%	30,980 L -0,75%	**3,40%**
Amphoralex	27,37 L -1,46%	25,11 L -9,97%	28,81 L -0,76%	24,97 L -5,59%	31,48 L -5,39%	24,45 L -7,78%	29,20 L -6,85%	27,47 L -2,86%	27,04 L -2,77%	30,74 L -0,29%	**4,48%**
AutoCad	27,265 L -1,46%	25,078 L -9,97%	28,741 L -0,76%	24,995 L -5,59%	31,642 L -5,39%	24,402 L -7,78%	29,200 L -6,85%	28,060 L -2,86%	26,937 L -2,77%	30,659 L -0,29%	**4,37%**

Table 4. Volumes of the ten amphorae from the 'Grand Ribaud F' (GRF) shipwreck compared according to different methods (C. Cateloy)

volume. While the variation of each calculation method based on drawings are rather similar (less than 2% difference in average between the two most divergent solutions, i.e. Capacity and Amphoralex), the ULB Capacity calculation tool appears to be the easiest and fastest to use[19]. It requires minimal action, and the possibility of adjusting parameters to refine the result offers great flexibility, in addition of being freely accessible online.

Conclusion and perspectives

In conclusion, it should first be stressed that all methods of mathematical calculation from drawings depend above all on the quality and accuracy of the drawing: what is measured is the drawing, not the actual vessel. Despite this reservation however, these methods can be used to calculate the capacity of pottery and containers of other materials whose state of preservation makes direct measurement impossible, thereby greatly increasing the usable corpus and allowing for more relevant statistical approaches of ancient economies.

Since the calculation is based on geometry and symmetry, its precision is directly related to the regularity of the original vessel. Athenian cups or Roman mould-made *terra sigillata* will probably provide a more accurate result than large, coarse jars. Despite these shortcomings, the comparative study demonstrates that the values calculated with the Capacity solution typically present an error of less than 3% (in 7 cases out of 10), with some more problematic cases. Since even “standardised” products in pre-modern societies cannot be expected to result in identical goods[20], the tool can be considered to provide perfectly reliable data for the study of ancient pottery production.

In its revised release, the ‘Capacity’ website provides a powerful and easy-to-use solution for such studies. Using this tool, the volume of over 90% of the uploaded drawings can be quickly obtained with minimal human intervention, simply by adjusting the scale and by changing the default side for 5% of uploaded drawings.

Future developments will focus on technical improvements of the axis and profile extraction of the C++ programme, notably to detect and correct axes that are not perfectly vertical or by correcting inner profile identification. Some features will also be added to enhance user experience, such as a tool based on density standards to convert volume into content weight for the most common goods stored or transported in containers (water, olive oil, wheat, etc.), or the possibility of automatically converting capacity units to ancient measuring units.

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19 Compare, for e.g., the procedure proposed by Moreno, Arévalo, Moreno 2018, which requires the successive use of different softwares (here Autodesk AutoCad® and Wolfram Mathematica®) to process the data.

20 See the many contributions in Kotsonas 2014.

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ABOUT THE CONTRIBUTORS

Laurent BAVAY
Université libre de Bruxelles,
CReA-Patrimoine, C.P. 133/01
50 av. F. D. Roosevelt
1050 Bruxelles
Belgique
laurent.bavay@ulb.be

Martin BENTZ
Universität Bonn
Institut für Archäologie und Anthropologie,
Abteilung für Klassische Archäologie
Am Hoftgarten 21
53113 Bonn
Deutschland
m.bentz@uni-bonn.de

Cydrisse CATELOY
Université Paris 1 Panthéon-Sorbonne,
Archéologies et Sciences de l'Antiquité (ArScAn),
21 allée de l'Université
92023 Nanterre
France
cydrisse@hotmail.fr

Cécile COLONNA
Bibliothèque nationale de France
Département des Monnaies, médailles et antiques
58 rue de Richelieu
75002 Paris
France
cecile.colonna@bnf.fr

Anne COULIÉ
Musée du Louvre
Département des antiquités grecques, étrusques et romaines
75058 Paris cedex 01
France
anne.coulie@louvre.fr

Martine DENOYELLE
Institut national d'Histoire de l'Art
2 rue Vivienne
75002 Paris
France
denoyellemjm@gmail.com

Rudy ERCEK
Université libre de Bruxelles
Ecole polytechnique de Bruxelles, CP 165/57
50 avenue F.D. Roosevelt
1050 Bruxelles
Belgique
rudy.ercek@ulb.be

Norbert ESCHBACH
Justus-Liebig- Universität Giessen
Klassiche Archäologie
Otto-Behaghel-Strasse 10 D
35394 Giessen
Deutschland
norbert.eschbach@archaeologie.uni-giessen.de

Georg Simon GERLEIGNER
Antikensammlung der Friedrich-Alexander-Universität
Erlangen-Nürnberg
Kochstrasse 4,
91054 Erlangen
Deutschland
georg.gerleigner@fau.de

Guy HEDREEN
Williams College,
35 Driscoll Hall Drive
Williamstown, MA 01267
USA
ghedreen@williams.edu

Pieter HEESEN
Independent researcher
(PhD University of Amsterdam)
pieter.heesen@planet.nl

Alan JOHNSTON
University College London,
Institute of Archaeology,
Gower Street
London WC1E 6BT
United Kingdom
alan.johnston@ucl.ac.uk

Cécile JUBIER-GALINIER
Laboratoire CRESEM UR 7397
Université de Perpignan Via Domitia
52 avenue Paul Alduy
66860 Perpignan Cedex 9
France
cecile.galinier@univ-perp.fr

Ursula KÄSTNER
Stubbenkammerstrasse 1,
10437 Berlin
Deutschland
ukaestner@gmx.de

Ronak KOSTI
Friedrich-Alexander-Universität Erlangen-Nürnberg,
Martenstrasse 3
91058 Erlangen
Deutschland
ronak.kosti@fau.de

Hans MOMMSEN
Rheinische Friedrich-Wilhelms-Universität Bonn Helm,
Helmholtz-Institut für Strahlen- und Kernphysik
Nussallee 14-16
53115 Bonn
mommsen@hiskp.uni-bonn.de

C.W. NEEFT
Université Libre de Bruxelles
CReA-Patrimoine, C.P. 133/01
50 av. F.D. Roosevelt
1050 Bruxelles
Belgique
keesneeft8@gmail.com

Corinna REINHARDT
Universität Zürich,
Institut für Archäologie / Fachbereich Klassische Archäologie
Rämistrasse 73
8006 Zurich
Switzerland
corinna.reinhardt@archaeologie.uzh.ch

Christian RUSSENBERGER
Archäologische Sammlung der Universität Rostock
Heinrich Schliemann Institut für Altertumswissenshaften
Schwaansche Strasse 3
18051 Rostock
Deutschland
christian.russenberger@uni-rostock.de

Victoria SABETAI
Academy of Athens
Research Centre for Antiquity
Anagnostopoulou Street, 14
10673 Athens
Greece
vsabetai@Academyofathens.gr

Susanna SARTI
Ministero della Cultura
Direzione regionale Musei della Toscana
Palazzo Mozzi Bardini
Piazza de'Mozzi, 2
50125 Firenze
Italia
susanna.sarti@cultura.gov.it

Udo SCHLOTZHAUER
Deutsches Archäologisches Institut
Eurasien-Abteilung, Im Dol 2
14195 Berlin
udo.schlotzhauer@dainst.de

Stefan SCHMIDT
Bayerische Akademie der Wissenschaften
Corpus Vasorum Antiquorum
Alfons-Goppel-Str. 11
80539 München
Deutschland
schmidt@cva.badw.de

Alain SCHNAPP
Institut national d'Histoire de l'Art,
2 rue Vivienne,
75002 Paris
France
alain.schnapp@inha.fr

Francesca SILVESTRELLI
Università del Salento
Dipartimento di Beni Culturali
Via D. Birago, 64
731000 Lecce
Italia
francesca.silvestrelli@unisalento.it

Tyler Jo SMITH
University of Virginia
McIntire Dept. of Art
Charlottesville, VA 22903
USA
tjs6e@virginia.edu

Mark D. STANSBURY–O'DONNELL
University of St. Thomas
2115 Summit Avenue, #55C
St. Paul, Minnesota 55105
USA
m9stansburyo@stthomas.edu

Anne R. STEINER
Franklin & Marshall College
637 College Ave,
Lancaster, PA 17603
USA
ann.steiner@fandm.edu

Athena TSINGARIDA
Université libre de Bruxelles/Ecole belge d'Athènes
CReA-Patrimoine, C.P.133/01
50, av. F.D. Roosevelt
1050 Brussels
Belgium
athena.tsingarida@ulb.be

Vicky VLACHOU
Aristotle University of Thessaloniki
Department of Archaeology and History
54124 Thessaloniki
Greece
vikyvlachou@hist.auth.gr

Christine WALTER
Musée du Louvre
Département des antiquités grecques, étrusques et romaines
75058 Paris cedex 01
France
christine.walter@louvre.fr

Dyfri WILLIAMS
Université libre de Bruxelles, C.P. 133/01
CReA-Patrimoine
50 avenue F.D. Roosevelt
1050 Bruxelles
Belgique
dyfri@hotmail.com