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Addressing Material Issues through Digital Solutions: *Maque-IT* and the Virtual Reconstruction of the Herculaneum Papyri

1 Overview

In spite of the destruction it caused, the eruption of Mount Vesuvius in 79 CE allowed a unique library to be preserved for seventeen centuries, by carbonizing and burying papyrus scrolls under a blanket of ashes, lapilli, and mud.[1] Nonetheless, the Herculaneum papyri, which were brought to light in the 18th century and are now stored in the *Officina dei Papiri Ercolanesi* (Biblioteca Nazionale di Napoli “Vittorio Emanuele III”, Naples), are extremely fragile and complex. Due to their singular state and history of preservation, making the texts readable and accessible to scholars is only the last step in a long and complex process of material study of the artefacts that transmit them. In the past two decades, remarkable technological advancements have given rise to a “Digital Herculaneum Papyrology”, which has been transforming the study of Herculaneum papyri and holds promise for further progress in the field of papyrology as a whole.[2]

One of the initial driving forces behind the digital approach undoubtedly originated from a crucial aspect for effective study of these ancient books, namely the need to enhance the legibility of the carbonized papyri, as the black ink is hard to distinguish from the black background. After several more or less successful experiments to effectively capture the papyri, starting from the late 19th century, mainly with the aim to accompany critical editions or to offer palaeographical *specimina*,[3] in the last two decades of the 20th century the photographic reproduction of the Herculaneum papyri began to

This paper is the result of close collaboration between the two authors, who take shared responsibility of the work described. As for the individual sections, the “Overview” and the section on “The needs for reconstruction” are by F. Nicolardi, while those on “Maque-IT” and “Future perspectives and *desiderata*” are by M. D’Angelo. We are very grateful to Nicola Reggiani for inviting us to the 2022 Digital Papyrology 3.0 Conference. This paper includes the description of new functionalities added to Maque-IT, presented at the RECREATE Hands on Reconstruction Training Workshop (Università degli Studi di Napoli Federico II, June 11–14, 2024).

1 For a general overview on the *Villa dei papiri* and Herculaneum papyrology see Longo Auricchio – Indelli – Leone – Del Mastro 2020.

2 See Fleischer 2021 and Reggiani 2021. Digital Herculaneum Papyrology is the subject of a specific section in the ENCODE open online course on the DariahTeach platform (D’Angelo, M. – Essler, H. – Nicolardi, F., *Unit 2.4. Digital Herculaneum Papyrology*).

3 Capasso 1983 and 1991, 142–8; Longo Auricchio – Indelli – Leone – Del Mastro 2020, 207–9.

https://doi.org/10.1515/9783111070162-017

respond specifically to the needs of study and to provide precise documentation.[4] The real turning point came when Steven Booras and David Seely of the *Center for the Preservation of Ancient Religious Texts* (Brigham Young University, Provo, Utah) applied multispectral photography technique to the Herculaneum papyri, imaging them in the infrared range and achieving excellent results.[5] The BYU imaging not only provided a valuable working tool with the precise aim of improving legibility and facilitating ink detection, but also inaugurated an era of extensive experimentation in the field of imaging for different purposes. From that moment onward, various techniques have been applied to the Herculaneum papyri, such as Reflectance Transformation Imaging (RTI),[6] shortwave-infrared (SWIR) within the hyperspectral range,[7] reflectography and X-ray fluorescence for ink analysis,[8] up to the ongoing activities aimed at producing 3D compilations of the opened scrolls combining multispectral and photogrammetric data[9] and the use of synchrotron radiation phase-contrast tomography and micro-CT aimed at virtual unwrapping of closed rolls.[10]

The advent of digital images providing millimetric detail also played a fundamental role in another respect, marking a substantial step forward in the development and implementation of methodologies for the virtual restoration of scrolls fragmented into different pieces.

2 The need for reconstruction

The Herculaneum scrolls' extremely precarious state of conservation, carbonized and fragmented into many thousands of pieces as they are, represents a major obstacle to reading them and to the systematic study of their texts. In most cases, reading a Herculaneum papyrus cannot be an immediate activity, but rather turns out to be a 'mediated'

4 The Norwegian team responsible for the unrolling of papyri from the mid-1980s (see Kleve – Angeli – Capasso *et al.* 1991) took two different kinds of photographs. The first consisted in the production of sequences of colour slides, to be viewed under a microscope. These reproductions, allowing letters and even minute traces of letters to be seen clearly, were the first to present themselves as a real working tool for the papyrologist. In addition to these, the Norwegian team also took a very large number of snapshots while working on opening papyri, to leave a record of their previous state and the original position of the various detached layers.

5 Booras – Seely 1999.

6 Piquette 2017.

7 Tournié – Fleischer – Bukreeva *et al.* 2019.

8 On ink analysis conducted on Herculaneum papyri see at least Seales 2009; Rabin – Schütz – Kohl *et al.* 2012; Rabin 2021; Brun – Cotte – Wright *et al.* 2016; Bonnerot – Del Mastro – Hammerstaedt *et al.* 2022.

9 Seales – Chapman – Nicolardi – Parker 2023.

10 Seales – Delattre 2013; Del Mastro – Delattre – Mocella 2015; Bukreeva – Mittone – Bravin *et al.* 2016; Stabile – Palermo – Bukreeva *et al.* 2021. On the successful use of virtual unwrapping on P.Herc.Paris. 4, see now Nicolardi – Parsons – Delattre *et al.* 2024 and https://scrollprize.org.

task. Far from being an end in itself, the technical task of virtually joining fragments and reconstructing a given scroll's format is a crucial preliminary step to recovering texts and contexts. Reconstructing a Herculaneum roll requires addressing a wide range of material issues, from those related to the eruption of 79 and the carbonization (alteration of the original cylindrical shape of the roll, the presence of fractures and other damages, reading difficulties due to charred surface, *etc.*) to those raised by the history of the opening and preservation of the scrolls.[11]

Significant material difficulties were caused by the two most widely used methods for opening and unrolling the papyri since the eighteenth century: (1) *scorzatura* ('peeling') and (2) *svolgimento* ('unrolling') by mechanical traction.

The first, particularly invasive technique consisted either in cutting the roll down the middle into two hemicylinders or in making two longitudinal cuts on each side of the papyrus, in order to separate the interior of the roll (*midollo*, i.e. marrow) from the outermost portions (*scorze*, i.e. barks). The stacks of *scorze* thus obtained were then put aside, obscuring the relationship between the *midollo* and the corresponding *scorze*, which were inventoried separately and later opened by scraping their layers away one at a time: once a layer had been transcribed, it was removed (destroyed) in order to reveal the layer below, until the last layer (*ultimo foglio*) was reached. The connection between *scorze* and *midolli* can only be determined through a scrupulous inspection of the whole collection, considering all the available data (script, bibliological data, content, and archive documentation). *Scorzatura* also resulted in the impossibility of obtaining consecutive columns from fragments of the same stack of *scorze* and the loss of information about the original position of the *scorza* in the roll. Thanks to geometrical calculations[12] and the use of virtual models (*maquette*s), papyrologists are now able to determine at least the relative position of the *scorze* and specify their distance in the virtual reconstruction of a scroll.

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11 If one were to retrace some of the early milestones in the development of a methodology for reconstructing the Herculaneum scrolls, its embryonic phase could already be glimpsed in the productive period between the last quarter of the nineteenth century and the second half of the twentieth century, when numerous editions of Herculaneum papyri were published. Some of these editions, although impressive for their time, show a tendency to collect 'fragments' of dubious or completely unknown position, separating them from the better-preserved 'columns' with no particular concern to place them coherently within as complete a text as possible (e.g. Sudhaus 1892, 1895, 1896). In several cases, however, a precocious movement toward repositioning fragments can be discerned (e.g. Scotti 1839; Crönert 1900; Schober 1923). Awareness of the need for reconstruction has been gaining ground for several decades now, especially thanks to pioneering editions published by Obbink 1996, Janko 2000, 2010, 2020, Delattre 2007, Leone 2012. A revolutionary contribution was made by Essler 2008, who devised a highly effective geometric method making use of material and archival data. For an overview on recent developments in Herculaneum papyrology see D'Angelo – Essler – Nicolardi 2021.

12 Essler 2008. He also designed an easy-to-use spreadsheet collecting all the formulas needed for reconstruction (http://www.epikur-wuerzburg.de/downloads/MathRek.xls).

No less problematic is the reconstruction of papyri unrolled using the so-called *macchina di Piaggio*, the revolutionary machine invented by Father Antonio Piaggio in 1753. This machine worked by slowly detaching the outer layer from the underlying one, before it was reinforced with goldbeater's skin and then cut and fixed on a paper sheet. Nevertheless, the use of this ingenious technique often entailed irreparable damage to the papyrus surface and hindered reading of the text. Success in detaching the individual sheets was not always attained. On the contrary, it happened very often during this process that, due to the extreme cohesion of the scroll's circumferences (volutes), multiple layers of papyrus remained attached to one another. Borrowing a term from geology, scholars refer to this phenomenon as the scroll's 'stratigraphy'. A displaced fragment from a deeper circumference that has remained attached over the surface of an unrolled layer is called a *sovrapposto*; a displaced fragment torn off from an earlier circumference, remaining attached under the base layer, is called a *sottoposto* (Fig. 1).

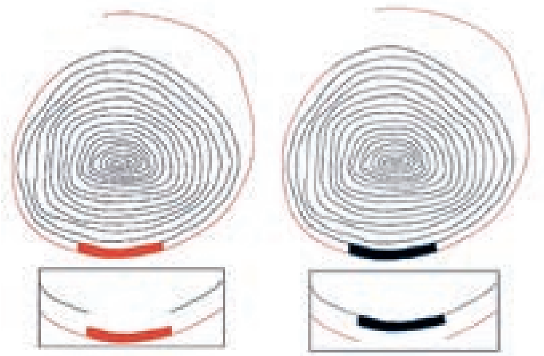


Fig. 1: Origin of a *sovrapposto* (on the left) and a *sottoposto* (on the right), from Nicolardi 2019.

Stratigraphy presents one of the most significant problems in the study of the Herculaneum papyri.[13] The presence of numerous displaced pieces can seriously compromise the reading and the understanding of a scroll's content, since the '*mise en colonne*' of the text appears totally out of order. Restoring the correct order of the layers in a virtual reconstruction is the only way to read the text. The necessary first step is to identify the displaced pieces by analyzing the papyrus under a microscope. Then, the *sovrapposti* have to be virtually placed in the later circumferences and the *sottoposti* in the earlier ones (Fig. 2).

13 The resulting displaced fragments were already occasionally identified and repositioned in the nineteenth century and at the beginning of the twentieth century, but we owe the first systematic approach to this problem to Nardelli 1973. Scholars have since started to reposition fragments more systematically, but papyri with more complex stratigraphy have generally been left aside.

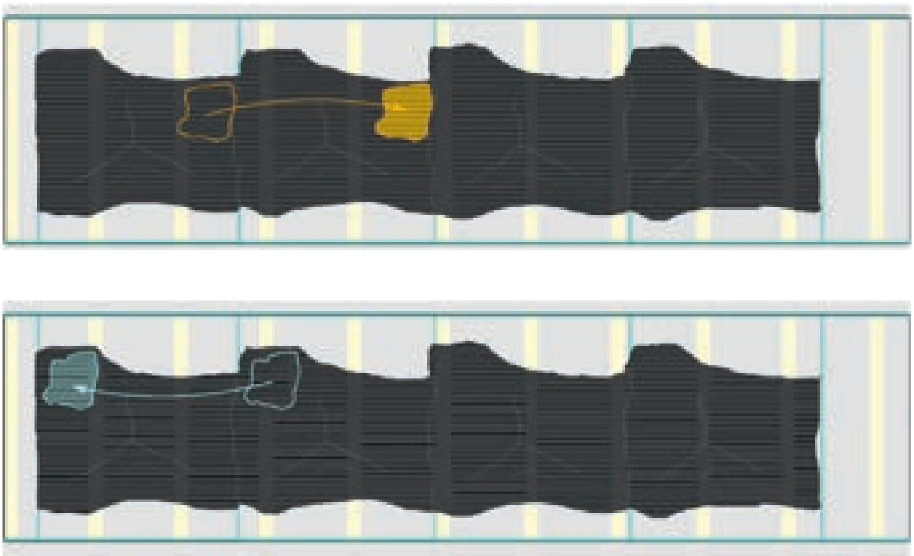


Fig. 2: Placement of a *sovrapposto* (top) and a *sottoposto* (bottom).

It is quite common for more than one layer to remain attached over or under the main surface. As a result, a first level *sovrapposto* must be moved one circumference forward, a second level *sottoposto* two circumferences back and so on. As is clear from Fig. 2, the occurrence of a *sovrapposto* necessarily results in a hole in the following circumference, just as a *sottoposto* results in a hole in the previous circumference. However, it is not always possible to observe this hole in the base layer, as such damages are often repeated in several consecutive circumferences and it is frequent that, after placing a *sovrapposto* or a *sottoposto*, one runs into another similar displaced fragment. This calls for a 'chain repositioning' (*spostamento a catena*).[14] Following some general rules, it is possible to 'predict' the stratigraphical state of a circumference based on the previous or the following ones, making the stratigraphical analysis of a piece more straightforward and certain. Correctly identifying and placing *sovrapposti* and *sottoposti* can revolutionize the study of a papyrus with complex stratigraphy, allowing papyrologists to reassemble lines and columns even from a papyrus that would otherwise only provide sequences of no more than a couple of letters.[15]

All these theoretical conclusions are perfectly suited for practical application leading to a smooth, self-monitored procedure.[16] At a more practical level, the need to repre-

14 Nicolardi 2019.
15 The first complete edition of a papyrus with extremely complex stratigraphy has recently been published by D'Angelo 2022.
16 Due to the special needs and peculiarity of the material, the reconstruction of the Herculaneum scrolls requires high specialization and attention to individual cases and particular features that may

sent the reconstruction in the form of a model was felt very early on by scholars concerned to restore the contents of Herculaneum *volumina*. This type of model, created by printing images, cutting them out, and pasting them on graph paper, was designed to reproduce the material features and layout of the scroll and to allow non-invasive restoration and repositioning of fragments. It is therefore, first and foremost, a tool for the editor of the text, but it can prove invaluable for readers as well. Absolutely pioneering was Delattre's choice to transfer his paper-based reconstruction model (the so-called *maquette*) of Philodemus' *De musica* to a digital medium (CD-ROM). The masterful edition of Epicurus' *De natura* book 2 by Giuliana Leone is also accompanied by a digital version of the paper *maquette*. A purely digital *maquette* was rendered for the first time in 2018[17] and the digital approach is increasingly establishing itself as the standard way of constructing these models.[18]

The structure of a *maquette* must be constructed by reproducing some basic data of the *volumen* relating to its *mise en page* and its material state:

– The model should reproduce the height of the columns (if known) and the average width of column + intercolumn, which represents the basic unit of the scroll as a book (comparable to a 'page');
– The width of the circumferences should be accurately reported in the model, taking into account the average regular decrease observed.

Since papyrologists have been looking for a tool to produce graphical renderings of their reconstructions, they have had to come to terms with the fact that no specialist software application is currently available to deal with the various aspects of reconstruction. It has therefore been necessary to adapt programs designed for completely different purposes, such as raster graphics editors or technical/architectural drawing tools. This renders the procedure for making the virtual *maquette* non-intuitive and time-consuming, and, despite the advantages of using a digital model, some understandably still prefer paper models.[19]

demand special treatment. This is the main reason why technical background information is often given in the introduction to the edition of a scroll, while the effort to collect data and systematically build up a general methodology from practical cases remains rare (e.g. Essler 2008; Janko 2016; D'Angelo – Nicolardi 2021; Nicolardi 2022). To date, the only essential 'guide' illustrating the steps involved in the edition of a Herculaneum roll, from reading and reconstructing on, is by Janko 2016.

17 Nicolardi 2018.

18 D'Angelo 2022.

19 See Janko 2020, 107: "I created a paper life-sized model of the entire roll, based on scaled prints of the digital images and on photocopies of the *disegni* where the originals do not survive; I find this easier to create and use than a digital model".

3 *Maque-IT*

The aforementioned reconstructing needs, with a particular focus on stratigraphical complexity, represented the basis for conceiving *Maque-IT*, the first image import and editing software tool specifically dedicated to the virtual reconstruction of papyri, with a particular focus on Herculaneum scrolls. The aim is to facilitate and speed up the complex work of repositioning the fragments and recomposing the original scroll format, providing the digital reconstructions with a higher degree of reliability. In particular, *Maque-IT* addresses two objectives: on the one hand, to automate the construction of the basic structure of the model of the roll; on the other, to enable papyrologists to check, and even to partially automate, their work with fragmentary texts.

Born in 2019 from an idea of the two authors, the project received over time different funding first to produce a prototype, developed in 2021 with the assistance of the computer scientist Florent Nöel (Curious Company), now to implement the fully functional and comprehensive version of the software, currently under development.[20] The current version of the program is a C++ desktop application using the Qt framework, which can be installed on both Windows and Mac operating systems.

At present, the software has two main functions: (1) it automatically creates the basic structure of the *maquette*; (2) it automatically moves displaced fragments (*sovrapposti* and *sottoposti*) of known provenance and prevents the user from moving a fragment to a position that is not valid according to the over-mentioned stratigraphical 'rules'.

Configuring the fundamental parameters (width of circumferences and decrease interval, width of column and intercolumn), *Maque-IT* is able to automatically build a basic model that can be extended and into which images of the papyrus fragments can be added. Although *Maque-IT* was initially designed to face the specific reconstruction challenges posed by the Herculaneum papyri, its functionality can be applied to any papyrus scroll by adjusting the basic parameters of the *volumen* under investigation. This makes it a versatile tool that can be profitably used by anyone working on the virtual reconstruction of any papyrus roll.

The main purpose behind the idea of *Maque-IT* was to provide scholars working on Herculaneum scrolls with complex stratigraphy with a tool that would facilitate this intricate operation and help them verify their work. Thus, from the very beginning, the software was developed to 'learn' the theoretical 'rules' of stratigraphy and apply them automatically. This tool cannot be a substitute for analysis of the papyrus by autopsy, but it makes the complex work of reordering pieces and layers in the virtual reconstruction easier and faster. This latter function has been tested on some papyri with complex

20 The development of the prototype was funded by the American Friends of Herculaneum and by the Centro Internazionale per lo Studio dei Papiri Ercolanesi 'Marcello Gigante'. The development of the final version is now planned within the project *RECREATE – REConstructing papyrus scrolls and REcovering Ancient TExts with the aid of a new digital tool* funded by the Fritz Thyssen Stiftung in 2023.

stratigraphy specifically selected as case studies. The reconstruction of one of these, *PHerc*. 89/1301/1383 (Philodemus, *[On gods]*),[21] will be used here as an example to illustrate the *Maque-IT* workflow.[22]

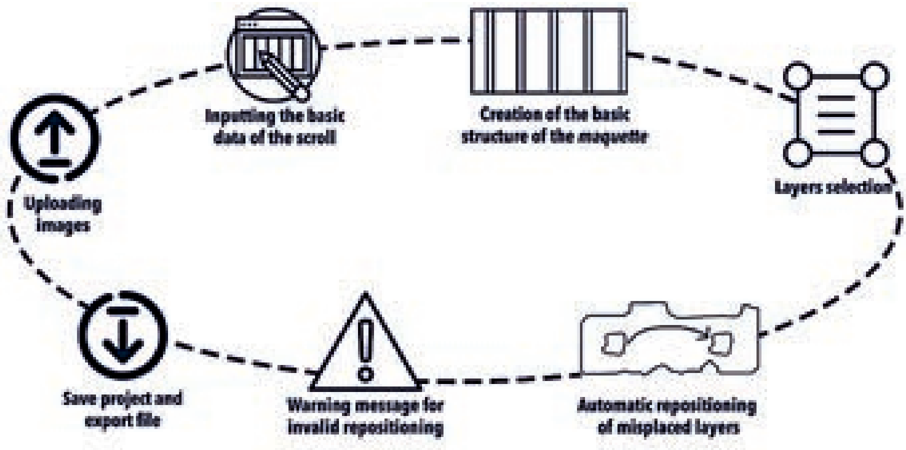


Fig. 3: *Maque-IT* workflow.

Uploading images. The first step is importing the images of the papyrus fragments.[23] In the current version, it is possible to import both images of individual fragments and images containing multiple fragments. A lasso tool allows the user to select and isolate individual fragments within the latter. When importing the first image, the user defines the scale of the papyrus. Further fragments can be scaled or adjusted to match the existing scale. Measurements of the imported fragments can be taken at any time using the ruler tool. To facilitate accurate measurements, all fragments are positioned on a millimeter grid.

Inputting the basic data of the scroll. Maque-IT simplifies the process of building a basic model of the scroll by automatically generating the succession of columns and decreasing circumferences, which has hitherto been done manually and is particularly time-consuming. By inputting the essential data obtained from the material analysis of the papyrus under investigation into the software, users can configure circumferences and columns. Measures in millimeters should be accurately taken on the original papy-

21 D’Angelo 2022.

22 For a general description of the software see also D’Angelo – Nicolardi 2021, 134–7. A demo video of the prototype is accessible on the website of the Centro Internazionale per lo Studio dei Papiri Ercolanesi (https://cispe.org/maque-it-un-software-per-la-ricostruzione-virtuale-dei-rotoli-ercolanesi-con-stratigrafia-complessa).

23 At the moment, high-resolution 2D images, but an experimentation with new 3D images is planned.

rus and provided in the software. To configure circumferences, users need to enter the width of a single circumference, the average width of the decreasing interval from the circumferences, and the desired number of circumferences. To configure the columns, users need to enter the average width of column + intercolumn (the basic unit of the scroll as a book), their height, and the desired number of columns.

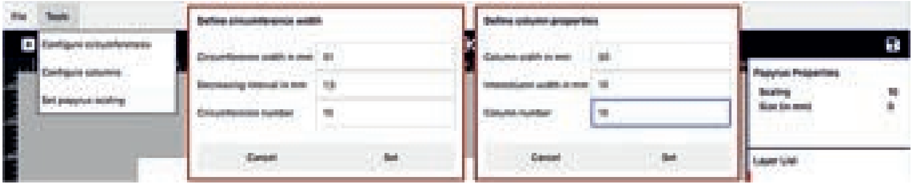


Fig. 4: *Maque-IT* Tools section.

Creation of the basic structure of the maquette. The circumferences are displayed as light blue outlined rectangles, each of them showing its width in mm at the top; the intercolumns are displayed as yellow rectangles. Once automatically created, circumferences and intercolumns can always be refined by manual adjustments. When the width of a circumference is manually modified, the measurement at the top will also be automatically updated. The basic scroll model can be extended at any time by adding more circumferences and columns to the beginning and end.

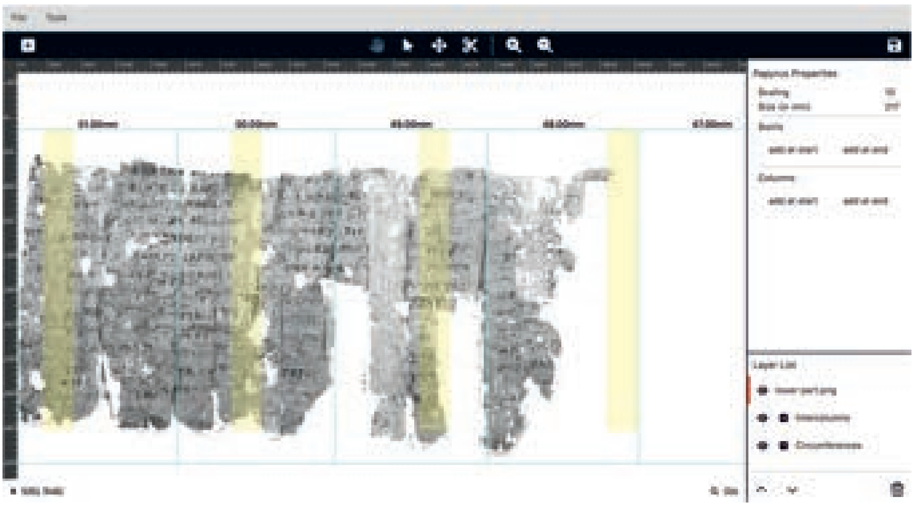
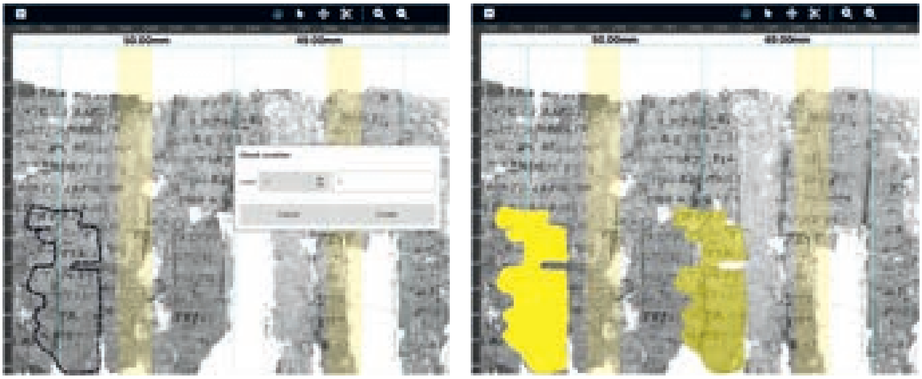


Fig. 5: *Maque-IT* basic model.

Layers selection. The software provides a selection tool that enables recording on the digital image of a Herculaneum papyrus the stratigraphical analysis carried out under a microscope. Users can select regions corresponding to displaced layers and add a tag (and a related colored outline) indicating whether they are *sovrapposti* or *sottoposti* and of what level (1+, 2+, 3+, 4+ …; 1-, 2-, 3-, 4- …).

Automatic repositioning of misplaced layers. After completing the selection, the software automatically moves the misplaced layers one or more circumferences back or forward, depending on the added tag (e.g., '1+' moves circumference forward, '2-' moves two circumferences back, and so on …), according to the established rules. In the images below, the area corresponding to a first-level *sovrapposto*, after being selected (Fig. 6), has been automatically moved one circumference forward (Fig. 7). In the model, the misplaced portions appear fully colored (with different colors assigned to different levels of *sovrapposti* and *sottoposti*), while the repositioned ones have the same color but with transparency.



Figs. 6–7: On the left, selection of a layer and addition of the related tag (here, first-level *sovrapposto* = 1+); on the right, automatic repositioning of the layer one circumference forward.

Warning message for invalid repositioning. To ensure repositioning accuracy, *Maque-IT* prevents the user, via an error message, from moving a layer to a position that is not valid according to the stratigraphical rules. For instance, one of the fundamental rules of the 'chain repositioning' of *sovrapposti* and *sottoposti* is that a *sovrapposto-sottoposto* sequence cannot occur.[24] If the user identifies a layer that breaks the stratigraphical rules, a warning message appears, informing that the move is invalid and suggesting a level change (Fig. 8).

Save project and export file. Maque-IT allows to save the current project as an editable file and export the reconstruction in .tiff format at any time.

24 See Nicolardi 2019.

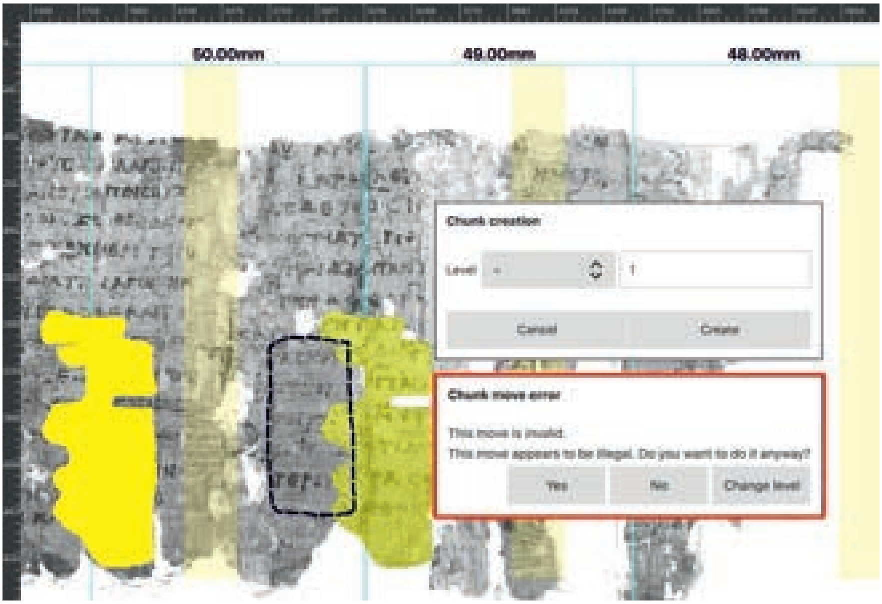


Fig. 8: Warning message for invalid repositioning.

Correctly identifying and placing *sovrapposti* and *sottoposti* can revolutionize the study of papyri with complex stratigraphy, enabling papyrologists to reassemble lines and columns even from a papyrus that would otherwise only provide sequences of no more than just a couple of letters[25]. In such cases, repositioning the misplaced layers allows not only the restoration of the original succession of the identifiable text columns but also the recovery of new text columns, reconstructed for the first time through the association of letter sequences previously scattered across different levels. In such cases, a final confirmation of the correct replacement can be provided by textual data (Fig. 9).

4 Future perspectives and *desiderata*

The current version of *Maque-IT* is still a prototype that requires improvement and implementation, first of all to ensure stability when dealing with a high number of images, as when rendering the reconstruction of an entire scroll, as well as fluency and smooth user experience. Paying attention to these aspects will entail adding new functionalities that can make the tool helpful for any papyrologist working on the virtual restoration of a scroll with known parameters.

25 D'Angelo 2022, part. 86–90, 108–11.

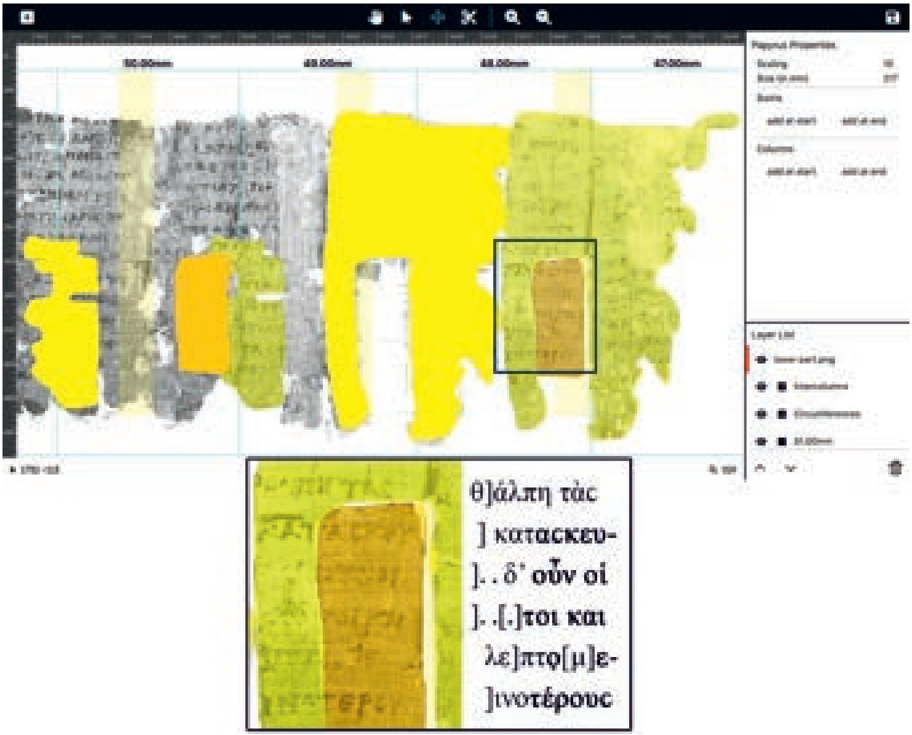


Fig. 9: Reconstruction carried out using *Maque-IT*. At the bottom, detail of the text recovered after repositioning two *sovrapposti* (Philodemus, *[On Gods]*, col. 151, 32-37 D'Angelo 2022).

While remaining open to implementing features that cater to different reconstructing needs, the primary focus of *Maque-IT* is to become a comprehensive tool for the reconstruction of the Herculaneum papyri, promoting remote and non-invasive study of the collection. The final version aims to include everything needed for the recomposition of a carbonized scroll, even new functions allowing for easy and intuitive calculations. In particular, it will be possible to estimate the total length of the original scroll by using the available material, bibliological, and archival data. A dedicated new section is planned for the reconstruction of scrolls subjected to *scorzatura*, aimed at automatically placing the *scorze* in the reconstruction model according to the circumference calculated from input data. This section will support users in applying reconstructing geometric methods currently in use, benefiting greatly from the integration of MathRek, an easy-to-use spreadsheet designed by Holger Essler that collects all the formulas needed for reconstruction.[26] As far as the stratigraphical issues, the software will become smart-

26 See above, nn. 10 and 11.

er and learn how to predict the presence of displaced layers, suggesting their possible placement according to the rules of 'chain repositioning'.

At a later stage of its development, *Maque-IT* will explore some completely novel and hitherto unexplored possibilities. The first step will be to evaluate the potential benefits of using the new 3D images of the Herculaneum papyri.[27] Another *desideratum* is to enable the inclusion of the facsimiles (*disegni*) of the fragments alongside the images of the papyrus. This could prove particularly helpful in cases where they display text no longer preserved on the original papyrus. Finally, a new text-image alignment function will be tested, allowing users to add parallel transcriptions of the texts while they work on the reconstruction. This feature will provide users with the opportunity to work with both the visual representation and the transcribed content simultaneously.

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