A CAD-based Framework for Interactive Analysis in the Restoration of Bronze Statues

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Abstract. Nowadays, restoration is a multidisciplinary work that gathers knowledge and skills from different areas (technical, artistic, historical, architectural, …). In the field of ancient bronze statues, technical knowledge may also concern with materials behaviour and its preservation, surface quality, non-destructive diagnostics for integrity, a better understanding of the manufacturing technology, and of details, sometimes hidden, in not directly accessible sections of the artefact. This knowledge, got from different domains, can support restorers in their decision-making process. In many cases, they summarise it on pictorial views of the artefacts, or on images derived from the 3D model that is experimentally acquired through reverse engineering, to reference information on the interested areas. The aim of this paper is to explore the advantages related to a CAD-based framework able to gather the technical domains involved in the restoration of historical artifacts. Doing so, CAD functionalities and related benefits may be extended to cultural heritage applications as tools oriented for restoration, according to a life cycle perspective of the restorer's activities and the artefact preservation and fruition. The proposed CAD-based framework has been implemented to manage the investigation for restoration and conservation of bronze statues. The approach has been applied to the Principe Ellenistico, part of the collection of Palazzo Massimo, one of the sites of Museo Nazionale Romano (in Rome). The obtained results show that the CAD-based framework may speed-up the investigation processes without losing accuracy and restorers' good practices.

Keywords: CAD-CAE, Virtual Prototyping, Cultural Heritage, Design for Restoration, Principe Ellenistico.

1 Introduction

In the field of Cultural Heritage, 3D model acquisition is now a common practice that helps archival, dissemination and investigations carried out during restoration, as highlighted by Scopigno et al in [1]. Many recent works demonstrate that different acquiring methodologies can be used to achieve a virtual model (photogrammetry, laser scanner, phase shift methods, etc.). Accuracy of the digitized shape is the most relevant aspect together with the easiness of acquisition and the surface texturing reproduction, especially if virtual reality applications are investigated for divulgation or analysis purposes [2,3]. Photogrammetry and laser scanner are widely applied in many works. 3D acquisition of buildings commonly supports architectural investigations at different levels, including restoration [4,5]. Close-range photogrammetry is an emerging technique also for artefacts [6], and, in [7], a recent application is discussed with specific attention to inaccuracy due to reflection and occlusion-points. In [8], a multi-sensor network is investigated to widespread low-cost acquisition for sharing data, so that, more detailed models may be achieved thanks to collaborative work through data cloud sharing.

Reverse Engineering techniques may also help fragment re-compositions and mechanical design of supports as shown in [9,10]. When the focus of the restoration is the static behaviour of the statue or its integrity, the 3D model can be converted in a model for structural analysis by Finite Element Analysis (FEA), as conveniently demonstrated in applications on marble statues (e.g. David of Michelangelo [11], the marble of Alba Fucens [12]) and bronze statues (such as Marco Aurelio and Minerva di Arezzo [13,14]). FEA is used also to evaluate stress concentration and to map critical areas for material weakness or static stability. In [15] and [16], activities related to the Neptune Fountain in Bologna are presented. In these studies, FEA and experimental measurement are gathered on the 3D model to support restoration decisions. Measurements of different kinds (radiography, ultrasound, acoustic emission, etc.) are often necessary for monitoring, for maintenance purposes and for a better understanding of the artefact [17,18]. They may be punctual data or mapped, related to the multidisciplinary aspects involved in the diagnosis of the problems. From the 70s of the last century, innovative non-destructive diagnostic methods allowed restorers to find new strategies for preventive conservation and monitoring with non-destructive procedures [19,20]. In parallel, technological evolution of materials and mechanical design made possible new reversible assembly techniques of fragments and lacuna reconstruction. Due to this, new support designs were developed, and engineering solutions started to increase their help to restores. For example, in [21] the 3D reconstruction of an ancient statue of Zeus Enthroned is integrated through Digital Design by Additive Manufacturing to achieve the legs of the throne.

In [22,23] the integration of different information in a unique tool to support restorers is discussed. In [22], a demo tool is addressed to demonstrate how a "reality-based" model of the Pietà Rondanini may help data archiving and statue exploration for preservation purposes. To achieve a "reality-based" tool, the main requirements of its development are connected to the accuracy of the acquisition, surface texture acquisition and rendering. Data organization has been divided in metadata (local extraction of model data) and "paradata" (results of analysis and investigation by the "reality-based" model). Technical investigations interlaced in the model are physical analysis on single referenced points and areas, like measurements.

The present paper further investigates this topic, presenting a CAD-based framework able to integrate data from sensors and other activities usually planned during the investigation of bronze statues. The originality of the work is related to the analysis of the methodological approach usually applied by restorers. So, the CAD-based framework is proposed as a design for restoration tool in the respect of the organization of the knowledge stratification derived from the different fields of expertise applied in Cultural Heritage (historical, artistic, technical, economics, etc.). Doing so, the operational activities may be anchored, to the other relevant aspects of the lifecycle of an artefact (e.g. exposition monitoring and fruition management), thanks to a Product Lifecycle Management approach that is connate in industrial engineering CAD and takes into account all the actors and stakeholders involved in Cultural Heritage sectors [24].

Starting from the requirements related to the workflow adopted for bronze statue restoration, we implemented the tool, analysing its usability on the preservation activities of the Principe Ellenistico of the Museo Nazionale Romano (placed in Rome, at Palazzo Massimo). In section 2, the concept design of the framework is discussed to define the basic requirements and the different domains to be collected; in section 3, the application is presented and then, in section 4, it is discussed. Finally, in section 5, some conclusions and perspectives will be defined.

2 Framework Definition

2.1 Fields of Expertise and Data Collection

Operations connected to restoration and conservation of ancient bronze statues involve many activities both when they are related to a primary intervention after an archaeological finding, and when they concern a planned intervention to preserve the integrity or to change the exhibit status (e.g. change of room, style of the exposition, and so on). Recent examples of these scenarios are the restoration of the Satiro Danzante of Mazara del Vallo, found in 1997 underwater in the Mediterranean Sea [25] and the Vittoria Alata di Brescia, recently restored to be exposed in a new location in Capitolium of Brescia.

Evaluation and decisions are made through an experimental assessment that involves: (a) technical expertise and diagnostic measurements, (b) historical, artistic and archival studies; (c) visual inspection. More in detail:

(a) Technical expertise and diagnostic measurements. Technical expertise can be distinguished in:

- Analyses on the statue integrity which involve fragment analysis (if any) and their assembly condition, on the structural integrity of the cast and related joins, on the structural integrity of the material, on the static support;
- Surface assessment (material composition, corrosion, finishing);
- Architectural aspects for exhibition (position, anti-seismic devices, lighting).

(b) Historical, artistic, and archival studies. They concern with repertory photos, reports (even ancient chronicles or literature), drawings of related studies or previous restorers. They can be organized both by keywords and chronologically, so that research and extraction may be possible in accordance with the criteria selected by the user.

(c) Visual inspection pertains to the professional expertise of the restorer. It merges knowledge and evaluation criteria based on the morphological and surface recognition of the details.

The framework here proposed aims to collect data and knowledge related to (a), (b), and (c) into virtual annotations anchored to the digital mock-up of the statue.

From the visualization point of view, each of these fields is associated to different kinds of data set that involve points or areas of the statue, as reported in Table 1.

Table 1. Fields of expertise and related data types

		3D model	**Surface map /patch**	**Section/photo**	**Point/path**	**Graph/table**	**Docs/images**	**3D annotation**
Technical expertise	**Structural Integrity**							
	Fragment analysis	X		X			X	
	Radiography			X				
	Endoscopy		X		X			
	Acoustic Emission				X	X		
	Inner part 3D acquisition	X	X	X				
	Thickness measurements				X			
	weight, center of mass and inertia characteristics				X	X		
	FEA results		X		X	X		
	Support Design	X						
	Surface assessment							
	Polarization Resistance (corrosion rate)				X	X		
	eddy current				X	X		
	Architectural aspects for the exhibition							
	Assembly model	X						
	FEA results		X		X	X		
	Rendering	X	X					
Historical, artistic, and archival studies				X			X	X
Visual inspection		X	X	X				X

2.2 Bronze Statue Restoration Workflow

Fig. 1 presents a classic design workflow to support the restoration of bronze statues as from in-field experience. Central activities are **ACTION PLANNING** and

STATUE RESTORATION that are the results of investigations related to the blue blocks. The initial input of the process derives from historical, artistic, and archival studies collected in reports, photos, analysis, etc., as described in 2.1. This phase is here called **EARLY ANALYSIS**.

In **DEFECT RECOGNITION**, restorers correlate technical data from additional 3D shape acquisitions (e.g., inner surfaces), visual inspection, and experimental data related to discontinuities. **STRUCTURAL EVALUATION** represents the following step that is also interlaced to data from the support design that develops and investigates the interaction effects in the assembly statue-inner supports, to understand loads and static. At this step, shells characteristics, as thickness distribution and joining, are evaluated together with experimental data concerning the position of centre of mass. In parallel, **SURFACES EVALUATION** investigates the external defects related to the skin of the statue, chemical analysis, and corrosion effects. Visual inspection also occurs at this stage. Another input related to surface evaluation includes the architectural aspects derived from the exhibition design. Aspects such as lights and environmental parameters may affect the final aspect of the surfaces during exhibition.

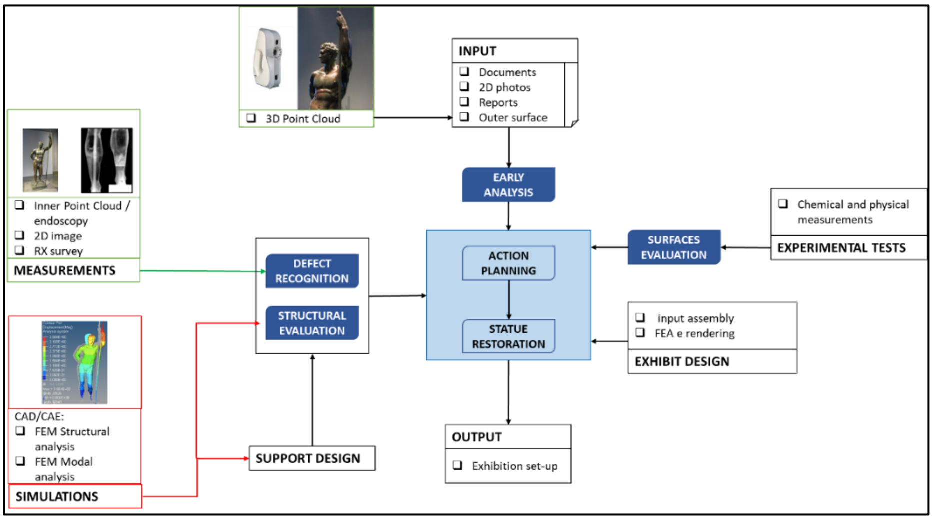


Fig. 1. Traditional restoration design framework

The lateral disposition of the blue blocks has been selected to point out that from the time scheduling point of view, also restoration has the necessity of speed up the process adopting parallel investigations. Unfortunately, this may increase the efforts made in the action of planning and restoration, since it may produce high volume of information to be organized and compared.

2.3 CAD-based Framework

To aid the data analysis, we propose a CAD-based framework as a data hub to support action planning (Fig. 2). The **3D MODELING** phase, via CAD tool, processes a 3D representation of the statue converting a point cloud into an STL file for the CAD elaboration. The **3D MODELING** allows the digital representation of defects and other relevant information that can be tagged into the CAD tool, through the **3D ANNOTATIONS** step. Through them, the Early Analysis of Fig. 1 is collapsed within the input step in which 3D models and documentation are processed. Documentation is uploaded and classified through keywords and tagged through 3D-Annotation where necessary. 3D Annotations are also applied during defects and surfaces evaluation to gather visual inspections. **DATA and RESULTS** phase regards point paths, surface map, and the reference sections used for structural and surface evaluation. They include RX, computed tomography, thickness measure, surface chemical, and physical investigations, etc. A knowledge-based engine is also proposed in the workflow to support the definition of DATA and RESULTS through a collection of rules and best practices to be formalized in an application tool. This knowledge base, represented in Fig. 2 by the KBE tool, can propose past experiences about material selections, procedures, logistics, etc.

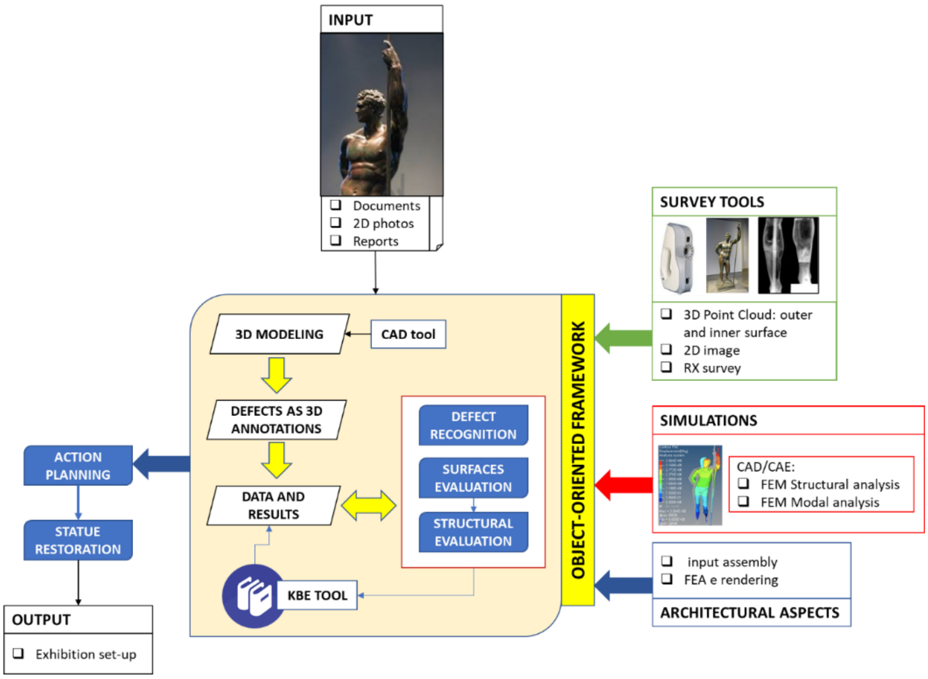


Fig. 2. Restoration workflow with CAD-Based framework

According to this, the CAD-based framework has been developed as an Object-Oriented Framework (OOF). Different digital information has been integrated and managed with a class-diagram organization. Fig. 3 shows the OOF, highlighting the main objects of the analysed structure (STATUE, REPORT, DEFECT, SOLUTION) with the main fields and functions (SET SOLUTIONS). The SET SOLUTIONS function may allow the restorer to analyse the possible solutions for producing the planning of the restoration actions through the KBE tool.

As a CAD platform, Rhinoceros® has been selected for the 3D representation of the bronze statue with the related information. The automatic elaboration of the geometrical and non-geometrical information has been performed using scripts in Python.

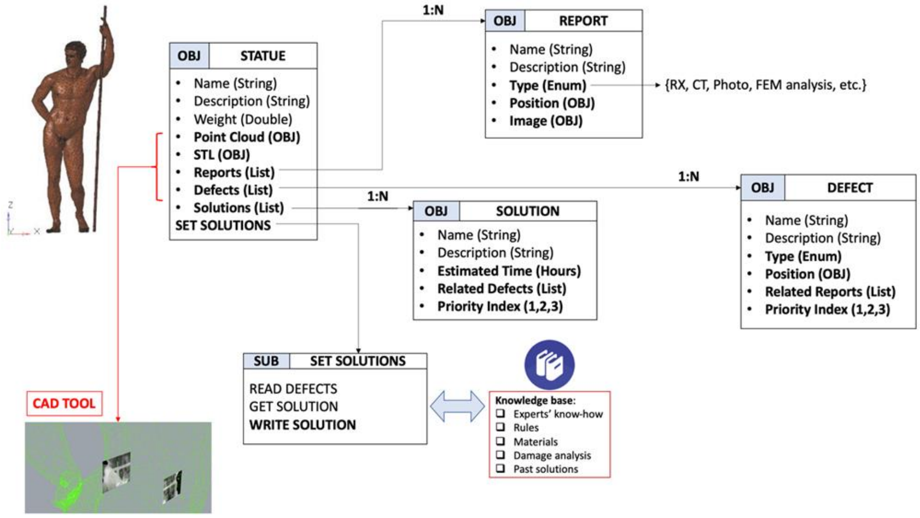


Fig. 3. The description of the OOF related to the proposed framework.

3 Application: The Principe Ellenistico

The described framework has been applied using, as case study, an ancient Hellenistic bronze statue, the "Principe Ellenistico", found in the end of 19th Century in Rome. It is datable around the 2nd Century B.C. and probably brought in Rome as spoils of war. This prince, two meters tall, is represented in a typical pose as a sovereign or warlord. Since its finding, it has undergone to several restoration operations firstly in order to recompose and join its fragments and then to improve its exhibition conditions. Currently conserved in Museo Nazionale Romano, at Palazzo Massimo, it is frequently subject to controls, checks and analyses useful to evaluate its conditions and to assess possible interventions, under the "preservation" point of view.

As already detailed, in this kind of application, several aspects and data need to be overlaid, to accomplish a complete and exhaustive evaluation that could drive to the optimal intervention to be planned and made.

Concerning archival data, reports of previous restorations represent the core of the input documentation preliminary investigated, together with works on the finding and the timeline of different exhibition both in the museums of Rome and temporary expositions. They usually involve manoeuvring, thus inspections and possible measurements. Repository includes documents collected as pdf files, photos and archive references.

a) b) c)

Fig. 4. a) The Principe Ellenistico of Museo Nazionale Romano (Rome, Italy); b) 3D tessellated model through laser scanner; c) simplified model for FEA.

A 3D model has been acquired through a portable laser scanner by MCM s.r.l. and assembled as a single object of about 200x10^3 points (Fig. 4.b), another acquisition has been provided more recently in 2019 through close-range photogrammetry [7]. Fig. 4.c shows the reduced model used for structural evaluation made by FEA [20]. Reduction consists of a point filtering that provided about 20x10^3 points tessellated through triangular elements.

From the structural integrity point of view, a wide range of data have been collected. First, the information about fragments and previous actions to guarantee solidity of legs and left arm. Fig. 5 summarizes part of these data related to legs. Fig. 5.a, on the left, shows details of the left leg as from an old report and from the tessellated 3D model obtained through laser scanner. The 3D model can highlight the conjunction plates as depicted in the old document made to map criticalities. On the right, the 3D annotations associated to that detail are shown, as derived from the application of the CAD-based framework. Fig. 5.b shows the sketch related to the inner support and the composition of the RX images related to the same view and to a 3D rotation, to highlight the advantages of RX in the case of inner details reconstruction. Fig.5.c shows an example of data visualization related to measurements useful for structural and surface evaluation. Fig. 5.c, on the left, represents thickness distribution as derived from ultrasonic measurements, they are reported as a path of points associated to spikes. On the right, a detail of stress distribution as derived from FEA. Similar representation may be derived for other measurements like corrosion rate.

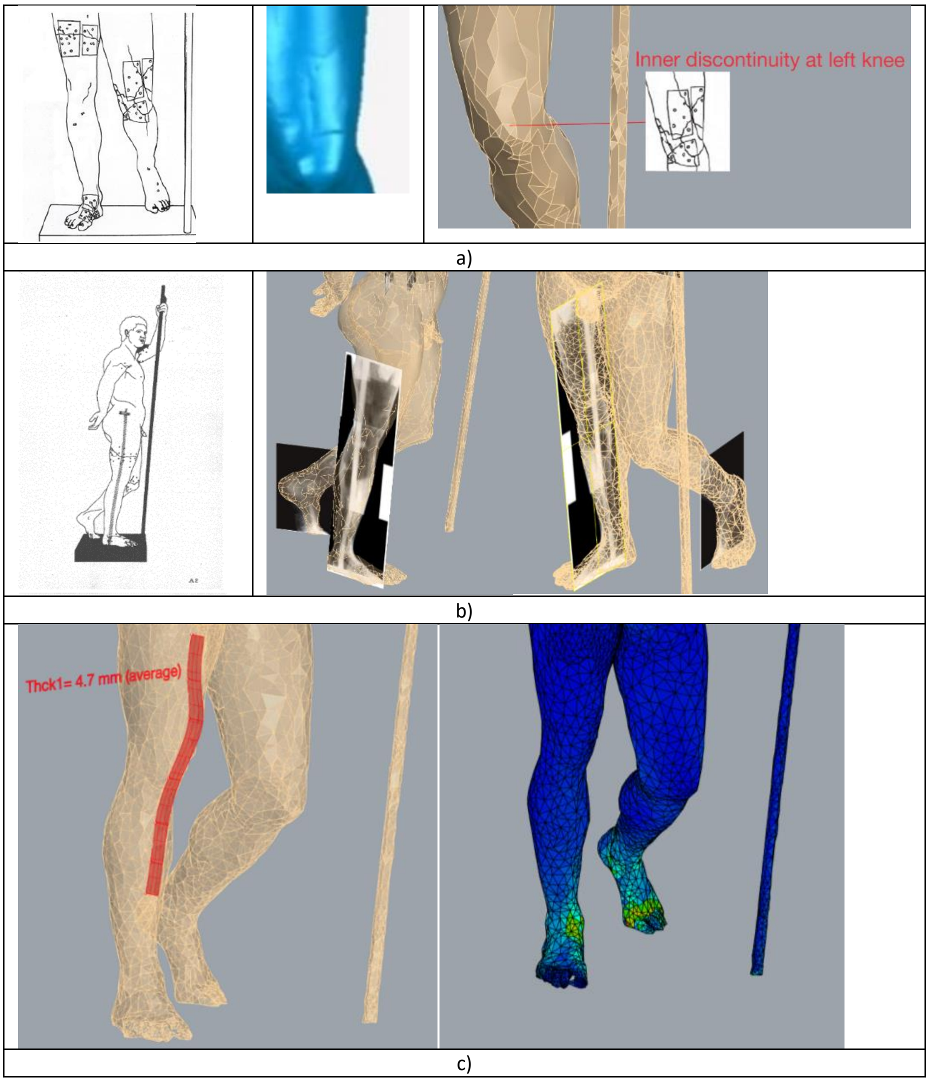
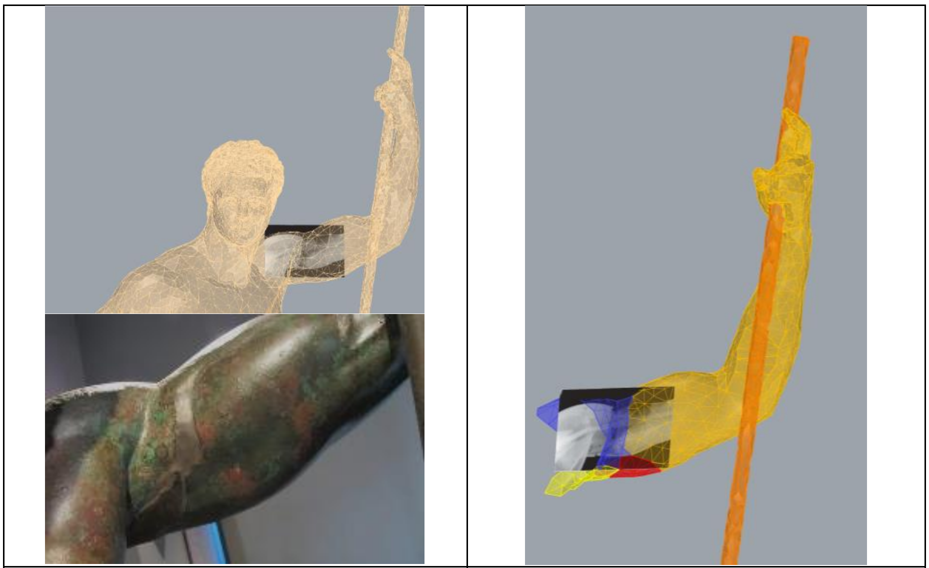


Fig. 5. Legs: a) discontinuities on the 3D model (on the left), 3D annotations (on the right); b) RX image as sections of the 3D model; c) visualization of the measured thickness path (on the left) and stress map evaluated by FEA (on the right).

Fig.6.a investigates the upper part of the statue, showing fragment recognition of the left arm together with a reference image and associated RX. Fig. 6.b shows the superimposition of data in the CAD-based framework, including original fragment subdivision.



a) b)

Fig. 6. Arm's fragment assessment: a) RX section (at the top), visual inspection of fragments (at the bottom); b) data overlapping on the 3D model through the CAD-based framework.

4 Discussion

The application made on the Principe Ellenistico may explain how the CAD-based framework assists the data visualization derived from different fields of knowledge. The 3D model overcomes the adoption of pictorial maps as shown in Figures 5.a and 5.b, adopting an interactive digital mock-up that allows a virtual navigation according to the different layers of expertise. According to [26], polygonal modelling has been selected as visualization strategy, since, as requested from restorers, main requirements for what concerns model visualization are precision, interactivity, and visual consistency.

The relevance of the precision requirement is not only related to the capability of seeing discontinuities, as shown in Fig. 5.a, but also the chance of benefit with image overlapping between RX and 3D model. It may assist reverse modelling of supports, as shown in Fig.7.a, where FEA of the inner support is derived through sketches design from RX images (Fig. 5.b). It assumes importance in the respect of structural integrity assessment and support design. In fact, reverse engineering of the inner parts of statues is not always possible and RX coupled with 3D modelling from sketching are a good approach to rebuild geometries. Doing so, FEA can become the tool for structural assessment of the statue, allowing the correlation among material weakness, stress distribution and fragment statics. An example of this analysis is provided by means of the right part of Fig.5.c and Fig. 7.b. In the first one, the stress distribution on the right foot shows relevant changes that can be correlated to the lines of the edge among fragments, confirming the critical conditions of that part. This imposed to increase stiffness and displacement control on the support arrangement at the basement, but also a corrosion evaluation driven by corrosion rate measurements. In this context, the CAD-based framework assumes an innovative aspect, since it may extend also to bronze statues the concept of design of restoration, already present in the preservation of buildings [27].

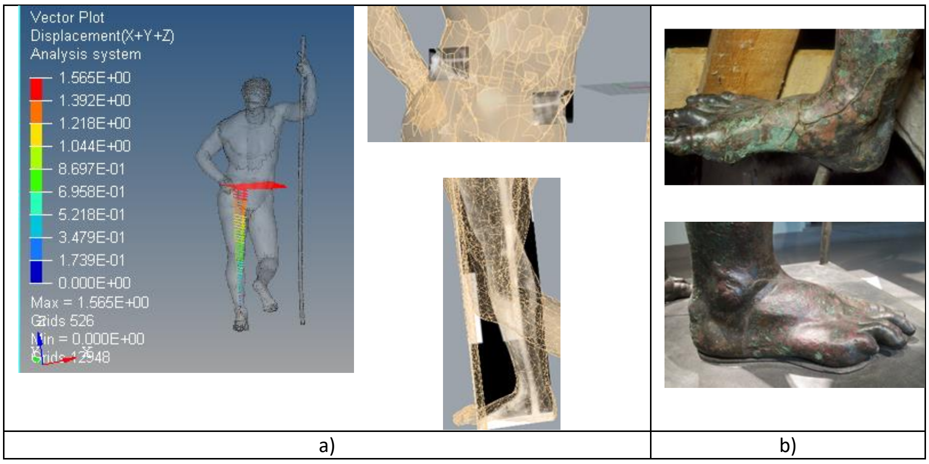


Fig. 7. Leg and support analysis: a) FEA (on the left), RX at their reference positions (on the right); b) Details of the left foot.

5 Conclusions

During bronze statues restoration, researchers plan activities and solutions through an intensive analysis anchored to surfaces and specific parts of the statue. So that, usually, the overall view of the data is stratified on pictorial views of the statue, usually called criticality maps. 3D models in CAD-CAE environments derived from an engineering design approach may increase the capability of the restorers of investigating details from multiple points of view, thanks to multi-layer data visualization, integration of FEA analysis, component design, and rendering of the exhibition set-up and full data management.

This paper presents a CAD-based framework able to fulfill these requirements, as discussed on the application made on the ancient bronze of the Principe Ellenistico, exhibited in Museo Nazionale Romano in Rome (Italy). In particular, the data structure, gathered from practical experience, technical measurements, simulations, and past reports, has been organized and implemented in an Object-Oriented Framework. The proposed design framework has been implemented using Rhinoceros® and scripts in Python. The results show a good level of usability towards data collection, visualization, and interaction towards simulations. Moreover, the proposed approach improves the analysis of the inner characteristics of the bronze statue by mixing the CAD geometry with the 3D annotations. The use of the digital mock-up is an innovative method in the field of restoration. Future applications will concern other important bronze statues such as the Pugilatore and the Vittoria Alata, so that a KBE tool may be developed from the collected experience.

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