CONSERVAR PATRIMÓNIO

ARTICLE / ARTIGO

Photogrammetry in the conservation of vernacular heritage focusing on the digital preservation of the memory of Algerian ancient ksour: case study of the Kenadsa Ksar

A fotogrametria na conservação do património vernacular com foco na preservação digital da memória dos antigos ksour argelinos: estudo de caso do Kenadsa Ksar

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Abstract

This paper presents the results of our research project KSOUR3D and GIS4D, which aim to explore the use of photogrammetry as an innovative method for the survey, preservation and promotion of the heritage of Algerian Sahara. The adopted approach is based on a methodological strategy and a process model within a global vision of three-dimensional and spatiotemporal modelling (3D/3D+1). Through a case study applied to the Kenadsa ksar, this study underscores the pertinence of establishing a multimodal digital database, which allows the generation of exploitable models for interactive visualisation and scenario planning of heritage interventions. The process is based on data acquisition, processing, and modelling to generate point clouds faithfully representing the buildings studied. The enrichment of models by the incorporation of temporal metadata allows the creation of various 3D model instances usable through augmented and virtual reality visualisation tools, offering immersive animations.

KEYWORDS
Photogrammetry
3D/4D modelling
Digital conservation
Saharan heritage
Restitution

Resumo

Este artigo apresenta os resultados dos nossos projetos de investigação KSOUR3D e GIS4D, que visam explorar a utilização da fotogrametria como um método inovador para o levantamento, preservação e promoção do património do Saara Argelino. A abordagem adoptada baseia-se numa estratégia metodológica e num modelo de processo dentro de uma visão global de modelação tridimensional e espaço-temporal (3D/3D+1). Através de um estudo de caso aplicado ao ksar Kenadsa, este estudo destaca a pertinência de estabelecer uma base de dados digital multimodal, que permita a geração de modelos exploráveis para visualização interativa e planeamento de cenários de intervenções patrimoniais. O processo baseia-se na aquisição, processamento e modelação de dados para gerar nuvens de pontos que representem fielmente os edifícios estudados. O enriquecimento de modelos através da incorporação de metadados temporais permite a criação de várias instâncias de modelos 3D utilizáveis através de ferramentas de visualização de realidade aumentada e virtual, oferecendo animações imersivas.

PALAVRAS-CHAVE
Fotogrametria
Modelação 3D/4D
Conservação digital
Património saariano
Restituição

Introduction

Heritage sites, steeped in history and culture, embody a collective memory and reinforce a sense of belonging [1]. The ksour, real icons of the Sahara, are distinguished by their unique signatures, witnesses of an ancestral heritage [2-3]. They have been recognized as precious territories and historical heritage known for their heritage dimension, namely their identity and cultural value [4]. Some of them have been classified as world heritage sites by UNESCO. Their preservation is crucial to protect the marks of societal identity, in accordance with the provisions of the various international agreements relating to this field.

The rise of digital technologies in cultural heritage has necessitated the establishment of reference frameworks that guarantee a rigorous and ethical use of these tools. In this context that the *London Charter* (2009), with its predominantly methodological and ethical focus, and the *Seville Charter* (2011), which is more practical and normative, were developed. The first defines the principles governing the production and interpretation of digital visualizations, while the second specifies their terms of use, dissemination and evaluation. Both charters highlight the advantages and limitations of digital heritage restitution. The new guidelines emphasize the respect for fundamental values in the virtual restoration applied to the research and enhancement, including authenticity, integrity, and heritage value in its various dimensions (historical, aesthetic, social, spiritual, scientific, etc.).

The *London Charter* is based on six fundamental principles that go beyond technical rules and emphasize ethical and methodological principles. These principles focus on: the scalability of practices, the reasoned choice of the most appropriate methods, anchoring in reliable scientific sources, clear documentation of approaches, the guarantee of the sustainability of results based on data rather than technical supports, and the enhancement of accessibility to strengthen the dissemination of heritage knowledge [5]. Two years later, the *Seville Charter* came into effect to complete and clarify these principles, emphasizing good practices in the visualization of cultural heritage. It extends by adapting them to virtual archaeology and promoting active pedagogy to raise awareness among researchers and the public about the contributions of digital technology in research. Its main principles focus on interdisciplinarity, the link between visualization and scientific objectives, complementarity with traditional approaches, respect for authenticity and historical rigour, the search for sustainable efficiency, scientific transparency, as well as the need to train and evaluate users in order to ensure the quality and relevance of the tools developed [6].

Conservation is based on traditional methods that remain limited in accuracy, speed and representation of fairly complex traditional structures. Digital technologies have revolutionized the way heritage buildings are documented and conserved [7]. The integration of advanced technologies for data acquisition, processing, archiving and analysis is revolutionizing processing methods and results [8]. Several studies show the limitations of traditional methods in heritage documentation and conservation, while 3D digital archiving currently available shows its significant advantages for the documentation, restoration and monitoring of heritage buildings [9]. Photogrammetry has evolved with technological advances to become digital, offering advantages such as automatic orientation and measurements, vector data generation, dense 3D point clouds and surface models [7]. The combination of 3D modelling and information management allows the introduction of the concept of HBIM (Heritage Building Information Modelling) in the documentation of heritage buildings [10-11]. Thus, "digital twins" offer the possibility of monitoring the state of structures in real time, helping to prevent deterioration risks [12]. The integration of the fourth dimension (time) in digital modelling also allows for immersive and emotional experiences in virtual and augmented reality, allowing users to visualise the evolution of buildings and enrich heritage conservation [13-15].

The study aims to enhance the Ksourian heritage, enriched by innovative technologies by integrating the photogrammetry results into global preservation strategies. The initial results presented are the work of two projects, KSOUR3D and GIS4D, by our research team SimulIA which explores the photogrammetry as approach through a study applied to Kenadsa ksar. The objective is to establish a digital database in order to ensure the digital archiving and interactive online accessibility of this city in perpetual degradation. This process stimulates cultural tourism, restoration/education scenarios and promotes enriched interaction with heritage.

Literature review

Research on the virtualization of cultural heritage in Algeria is being developed to contribute to the development of a methodology for the digital restitution of historical monuments and sites, ranging from digital surveys to interpretative restitution. This approach is also part of long-term perspectives, illustrated by the modelling project of the ancient site of Tipasa, led by the 3D platform Archéovision, which uses 3D and digital survey techniques to study and document the architectural remains of Roman city [16].

From the rediscovery and analysis, using 3D laser scanning and digital modelling, of a marble model of Hadrian's Villa, researchers demonstrate that it is an unfinished amphitheater project. The metrological interpretation reveals a design designed according to rules of proportion, while revealing parallels with the amphitheater of Caesarea of Mauretania (Cherchell in Algeria). This underlines the existence of a coherence between the architecture of spectacles buildings and the urban layout of Roman cities, planned according to modular principles. This study thus illustrates how digital technologies make it possible to reconstruct and decipher ancient constructive logics and to highlight the value of models as supports for communication and experimentation in Roman architecture [17].

In the same vein, the introduction of new digital survey methods has enriched the technical and morphological interpretation of ancient monuments. Indeed, the application of photogrammetry to the documentation of three access doors of the nameless temple of Tipasa has allowed the development of a virtual anastylosis protocol based on the modelling of 2D and 3D models of architectonic fragments, supplemented by the contributions of classical architectural treaties to fill the gaps. This method, which combines metrical survey, hypothetical restitution and digital dissemination, guarantees both the material preservation of the remains and the scientific transparency of reconstructions, while always meeting the ethical principles defined by international charters [18].

As an extension of this approach, the digital reconstruction of the fragmentary statue of Hercules highlights the critical dimension of virtual archaeology. Far from being a static restitution, 3D modelling functions as a laboratory of hypotheses, based on material indices and typological analogies, where the management of uncertainty, the transparency of interpretative choices and the reproducibility of the process ensure both scientific rigour and heritage enhancement. This approach gives 3D an epistemological and heritage role, simultaneously affirming it as a cognitive, critical and mediation tool [19].

Materials and methods

Photogrammetry is the technique adopted to study and document the Ksourian heritage in order to preserve the memory of space. Indeed, several studies show the theoretical bases, procedures and tools of architectural photogrammetry [8]. In fact, the "3×3- Rules" provides a practical directive framework for photogrammetric documentation based on three major criteria: geometric, photographic and organizational, each comprising three distinct directives [20]. Following the work of previous research, we propose a summarised methodological process developed in the form of a mind map grouping five important phases: data acquisition, 3D photogrammetry, 3D model instances, 4D photogrammetry and finally interactive visualisation (AR/VR). Each phase consists of a set of successive steps specifying the tools used and the product obtained (Figure 1b).

It should be noted that the penultimate and final step aims to explore other limits of the context, around which the central problem focuses. In this context, the collection of data relating to the past physical state of the ksar's buildings will increase the added value of our knowledge and our appreciation of the tangible (possibly intangible) heritage of the region. The technical question, in this sense, is based on the adoption of methodological strategies capable of taking charge, under the terms of a global vision (3D/3D+1) of the heritage of our ROI (Region Of Interest).

The interest sought is characterized by three facets (Figure 1a), the first concerning the present state (reported with current photogrammetric data on site subsequently processed), the second facet concerns the past of the heritage in ROI (Work by survey, poll and collection of sensitive data in relation, step followed by adequate processing – Photogrammetric assembly and processing of incompleteness such as Gaussian Splatting (advanced 3D processing technique). The third facet touches on in-depth study, using predictive photogrammetric methods by assembling trend models.

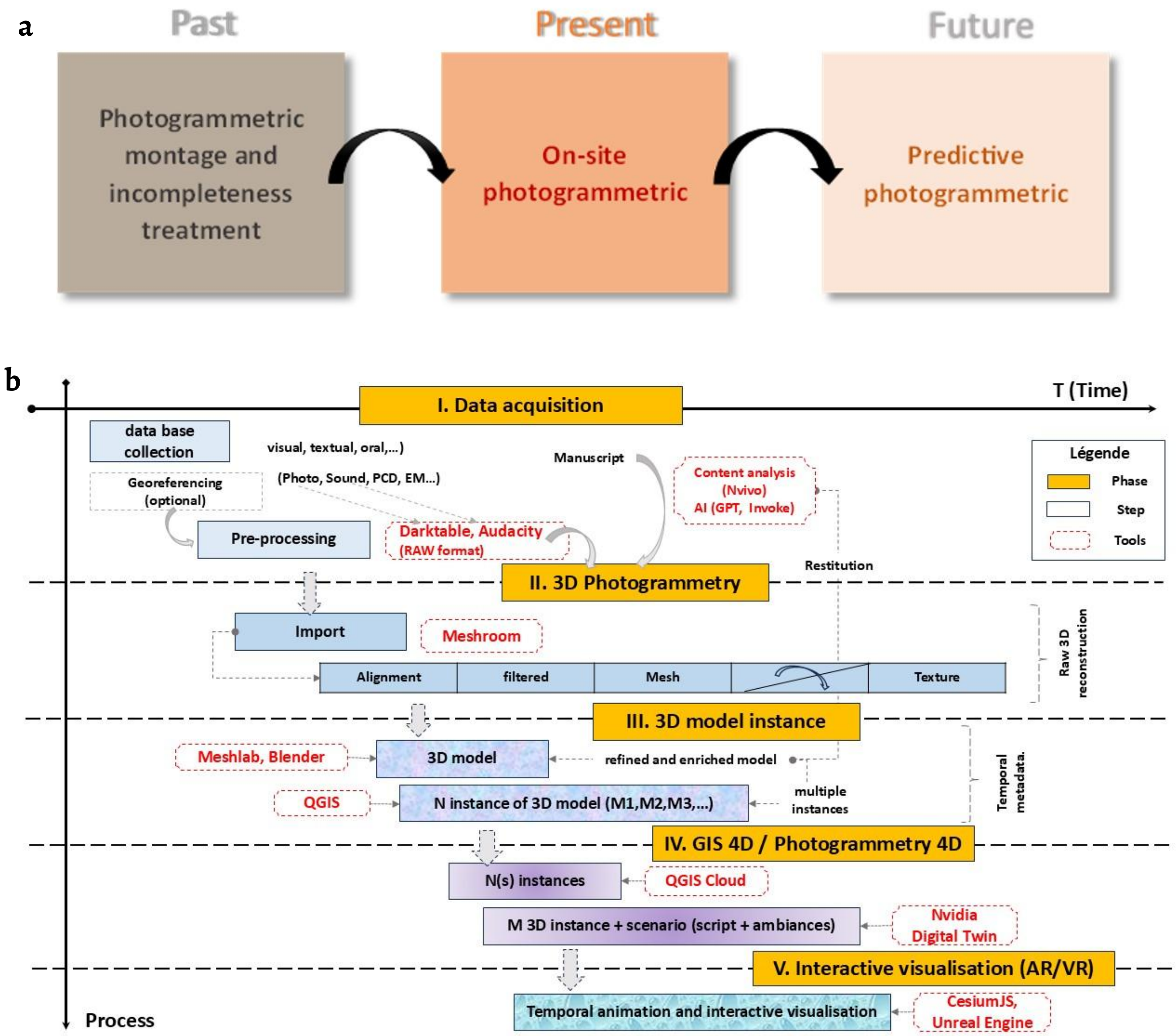

Figure 1. Research methodology and process: *a)* steps of study strategy; *b)* methodology process.

Steps of the overall study strategy:

- On-site photogrammetric (present)
- Photogrammetric montage and treatment of Multimodal incompleteness (past): a reconstruction process combining various data sources to fill in gaps and to obtain the most faithful digital representation possible of a former state of building.
- Predictive photogrammetric (future)

Presentation of the case study "Kenadsa ksar": heritage values and advanced degradations

Over the past three centuries, Kenadsa has exerted a spiritual, cultural, and economic influence in the region. The city is organized around two cores: the ksar, a religious and cultural center and the colonial city. The discovery of coal at the beginning of the twentieth century profoundly transformed the spatial and social structure, transforming Kenadsa from a religious oasis to a cosmopolitan mining city. The ksar has an undeniable heritage value, loaded with cultural, symbolic and architectural wealth. With its specific historical features and buildings with a very special connotation, the ksar is recognised as a common heritage and has been classified as a "historical monument" and national heritage to be preserved since 1999. The ksar's image refers to a structure that is at once complex, labyrinthine and hierarchical, while being perfectly homogeneous and coherent (Figure 2c). The fabric covers a variety of architectural forms and spatial arrangements [17].

The Kenadsa ksar stands out from the other ksour in the region by its type of dwelling commonly called *dwiriyâ* which is characterised by its high-quality architecture, endowed with an undeniable symbolic and cultural value [23]. They have been described as "veritable palaces" [24]. The Riad, seat of the *zawiya*, is described as "..., a beautiful Arab residence in the middle of gardens" [25]. In fact, "the residential complex is formed of small, precious palaces faced with the ambient Saharan bareness" [26]. These residences, of particular symbolic value, are distinguished by the richness of their decoration, the refinement of the doors, courtyards, columns and arches, and are part of the Andalo-Maghreb architectural tradition (Figure 2a-g).

The ksar, a reflection of society and culture, is in a state of alarming decline due to advanced degradation, abandonment, and past inadequate restoration attempts that have compromised their authenticity (Figure 2h-k). This deterioration threatens their identity and cultural memory, highlighting an urgent need for preservation in line with international standards. To address this, the KSOUR3D Project was initiated to use innovative digital technologies, such as photogrammetry and AI sketching/modelling, as a new approach to survey and preserve the Algerian Sahara's ksour. The project's central hypothesis is that these digital tools are effective for documenting, preserving, and promoting this vulnerable heritage for future generations.

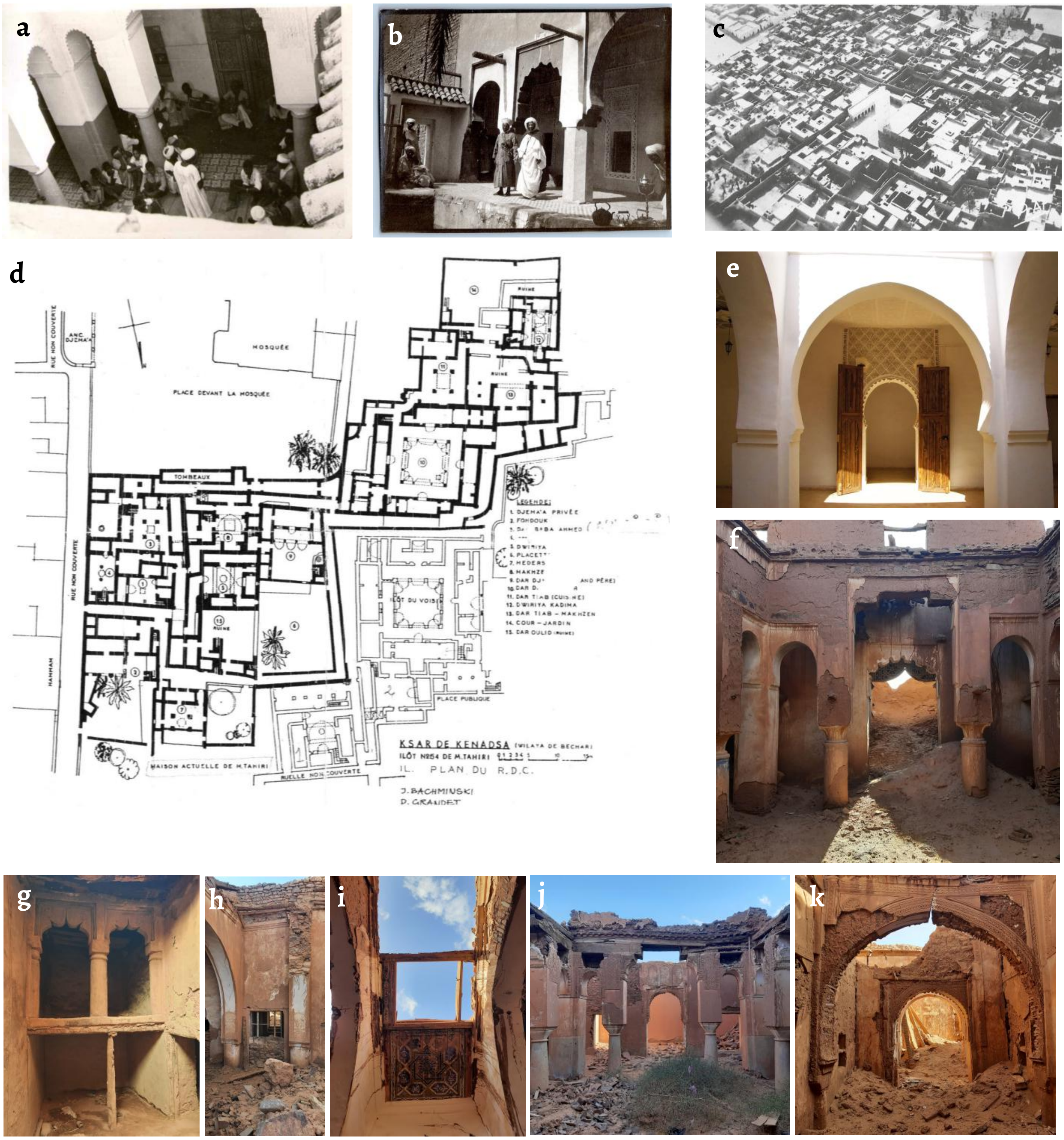

Figure 2. The architectural heritage of Kenadsa Ksar between ancient heritage and current state: old image of: *a)* courtyard house; *b)* portico of the Riad; *c)* aerial view ksar (Houillères Sud-Oranais HSO Archive); *d)* Plan of part of the ksar (Bachminski & Grandet, 1985); *e)* decorated of interior space; *f-g)*-architectural, decorative and technical elements. The current degraded state of: *h)* structural element column; *i)* ceiling; *j)* courtyard and gallery; *k)* keystone and decoration of the arcade.

Analysis and results

From two-dimensional survey to three-dimensional modelling

The digital restitution of the ksar is based on a progressive methodology that gives space to the two-dimensional approach as a preliminary step for three-dimensional modelling. In this work, all the buildings studied were first the subject of precise architectural surveys in two dimensions (more than twenty houses). These include plans, elevations and cross-sections, as well as detailed representations of architectural elements and ornamental components.

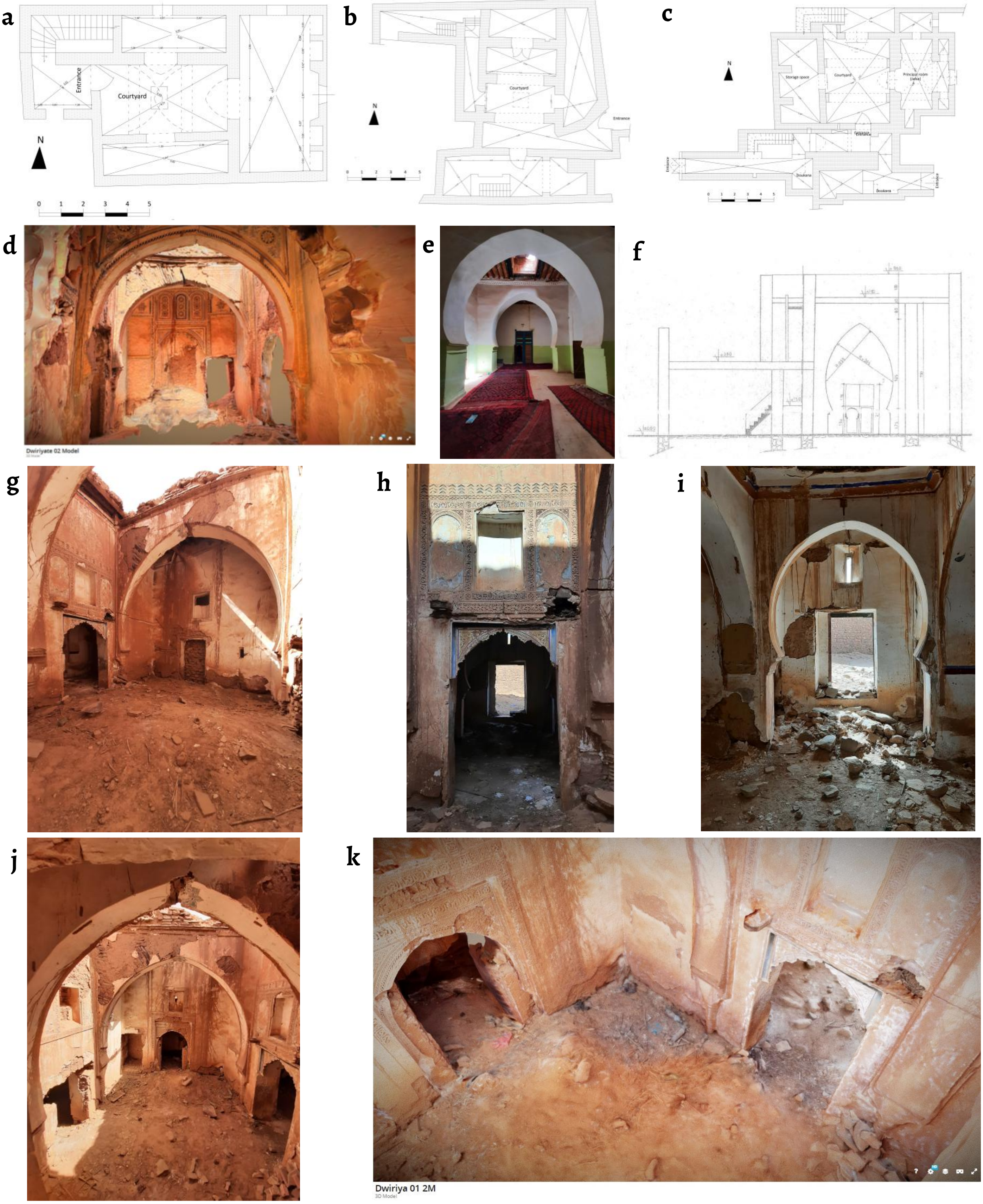

Figure 3. 2D restitution, produced from in situ metric and photographic surveys: *a-c)* various typology houses; *d)* 3D model photogrammetry; *e)* 2D image of courtyard; *f)* section of old house; *g-j)* different 2D views of various interior space; *k)* 3D model in Sketchfab.

This 2D restitution phase, carried out from in situ surveys complemented by photogrammetric processing, constitutes a scientific validation step. It ensures both the metric accuracy and fidelity to the current state of structures, while also verifying the typological and constructive coherence of the built ensembles. The documents produced provide a stable and shareable reference base, ensuring data traceability and scientific reproducibility, while constituting a detailed graphic corpus illustrated by surveys and photographs (Figure 3). Following this two-dimensional restitution, designed as an essential foundation, 3D modelling was undertaken in order to reconstruct the volumes, integrate architectural and decorative details, and simulate various restoration scenarios. The 2D survey provides a cognitive and analytical foundation, while 3D modelling opens the way to a technical, spatial, volumetric and prospective reading of buildings.

The process and steps of 3D photogrammetric modelling

Photogrammetric terrestrial modelling is a methodical process that allows to create three-dimensional models from 2D photographic images. The process includes essential steps, each contributing to the accuracy and quality of the generated models [8, 27].

Acquisition of photos

The first step involves taking 2D photos of the building sequentially [27]. The images were taken from different angles with sufficient overlap (Figure 4e). Additional photos are taken of areas containing important details. The choice of photographic equipment and the acquisition method are crucial to ensure the results quality (Figure 4a-c). A high-quality digital camera (Canon EOS 4000) was used to capture the images, taking care to correctly define the position and the number of shots required to cover all building faces.

Pre-processing and analysis of* "Darktable" *images

Once the images have been taken, pre-processing is performed to optimise their quality. The photos are first processed using Darktable in RAW format, which preserves a wide dynamic range and corrects imperfections in the images (Figure 4f). This software is based on two main features: the "light table", which enables exposure and white balance settings to be viewed, selected and adjusted, and the "dark room", where each image is finely retouched in terms of brightness, contrast, and exposure to ensure optimal quality. Then, the images are georeferenced to associate them with spatial coordinates, ensuring their accurate integration into the 3D reconstruction (Figure 4d).

Importing and generating the 3D model

After this initial processing, the images are then imported into the Meshroom software (open source) / Agisoft Metashape (licensed version), which performs the necessary processing to generate a 3D model (Figure 5a-c). This software analyses the images to identify common points between them and to determine the camera position at the time of each shot. Each point detected is associated with precise spatial coordinates (longitude, latitude, altitude), generating a dense point cloud. By aligning the images and detecting correspondences between the photos, triangulation algorithms can be used to reconstruct the geometry of the building. The perspective dimension is detached from the movement during elementary shots. A point belonging to the scanned space is seen by the moving camera (SFM – Structure From Motion), which allows the depth value to be determined. The triangulation forms the basis of the process, where an initial raw 3D reconstruction is produced, which is then refined by meshing and texturing to produce a complete three-dimensional model. This model generally requires additional processing to improve accuracy and eliminate errors.

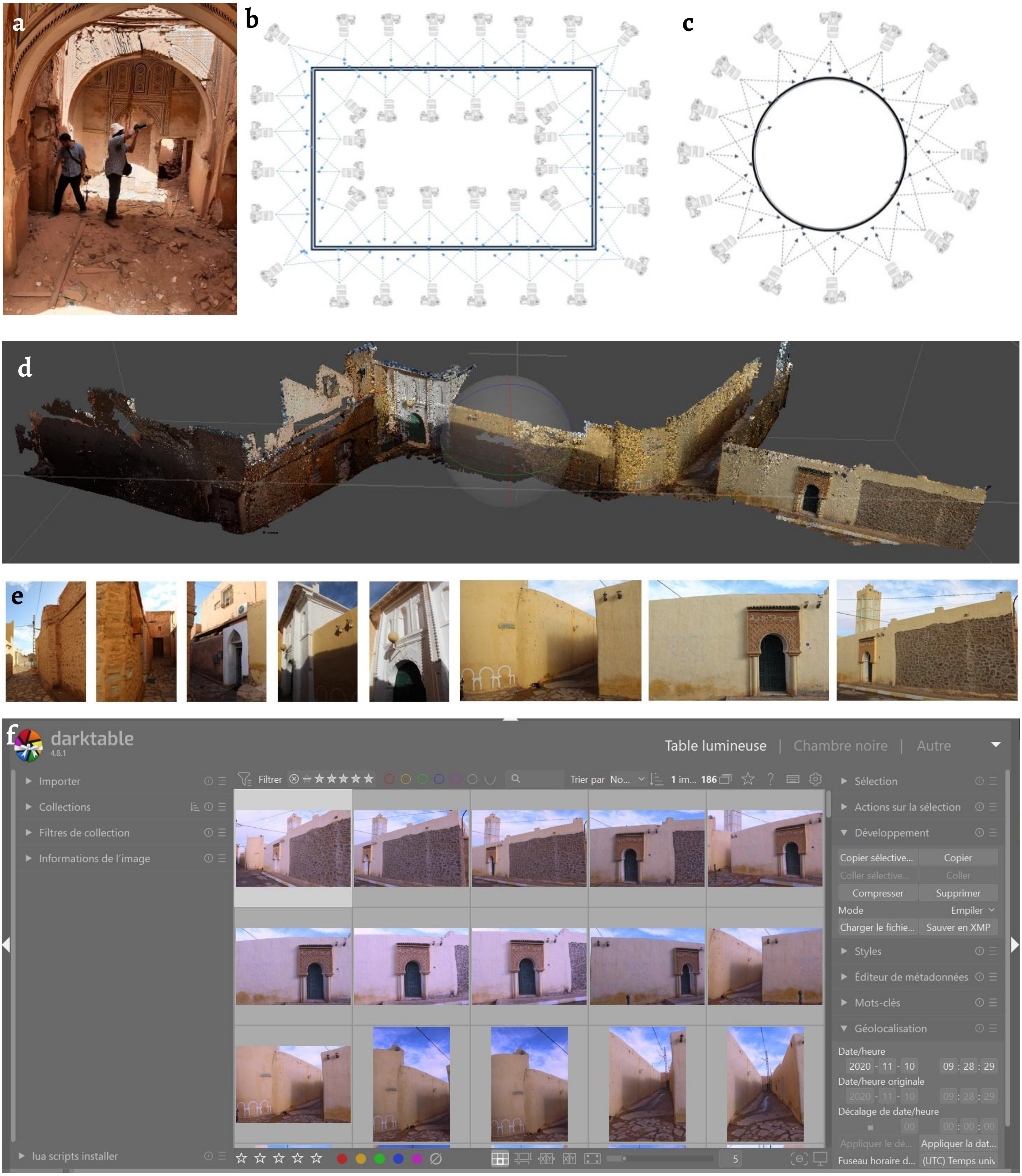

Figure 4. Image acquisition techniques: *a)* Team taking photos; *b)* Map of the captures from different angles; *c)* Photographing key circular architectural elements; *d)* 3D Photogrammetry; *e)* a series of 2D images; *f)* Pre-processing.

Post-processing

After the initial generation of the 3D model, a post-processing phase is essential to improve its quality and accuracy. This step includes cleaning the model to remove unwanted artefacts, correcting irregularities, and adjusting the scale to ensure a faithful match with the real dimensions of the building. Once these adjustments have been made, the model is ready to be used for various applications, such as restoration/education scenarios or realistic visualisations.

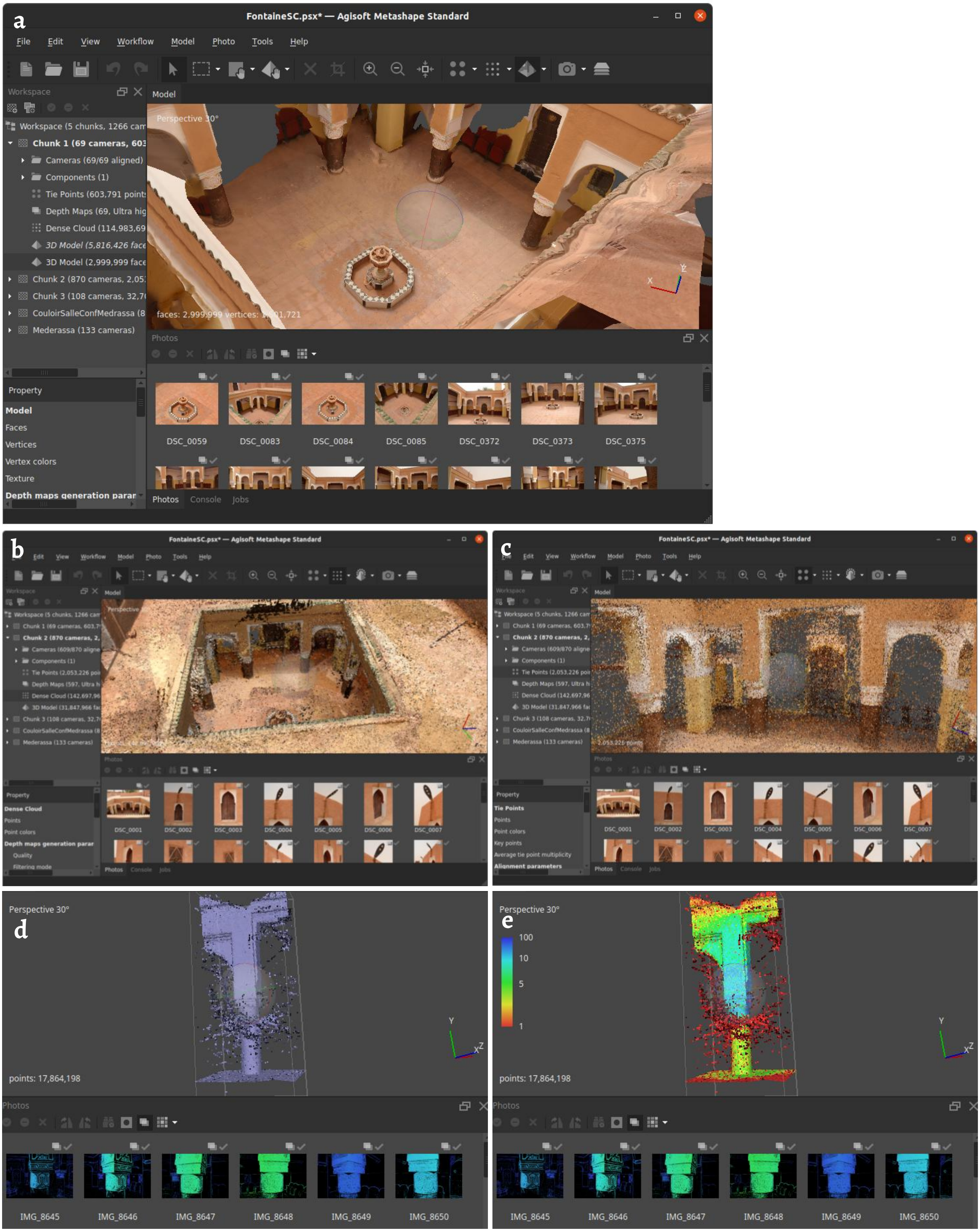

Figure 5. The 3D model of house and column: *a)* 3D model; *b-c)* dense 3D point cloud; *d)* solid model of column; *e)* Point Cloud and structure confidence.

Figure 5d-e show the photogrammetric modelling of the column, a key structural element among the 12 posts of the house, allowing for the accurate restoration of its geometry and architectural characteristics. This column defines the gallery and supports the patio, while integrating capitals and arches that enrich its architectural expression. Different renderings of the 3D model were generated to analyse and validate the reconstruction quality.

The true-colour model represents the most detailed and realistic version, integrating the textures from the captured images. In addition, an untextured model, without colours, was produced to verify the consistency of the overall form of the 3D model. In addition, a rendering based on depth parameters allows a differentiated visualisation according to the depth. Finally, the point cloud offers a raw and precise reading of the acquired spatial data.

From 3D photogrammetry to GIS4D

Beyond 3D modelling, 4D photogrammetry involves the fourth dimension "time", allowing for the analysis of changes in the building and the simulation of dynamic scenarios. The technique involves several steps in which the data acquisition phases are enriched by the incorporation of temporal metadata.

Data collection and pre-processing

This phase combines several types of data (MMD). The visual data (old photographs) is essential to restoring the past state of the building. These images are processed with specialised software to improve their quality. Tools for restoring old items, such as PhotoGlory, are used to remove scratches, creases and stains. The historical textual data (manuscripts, narratives, novels, newspaper articles) are analyzed by software such as NVivo, which can detect which detect manifest and latent content. This analysis involves structuring the corpus, categorising it thematically and defining the variables to be analysed. Then, the sound data, where oral testimonies and sound environments are processed with software such as Audacity to eliminate unwanted noise and improve clarity, ensuring a faithful restitution of past sensitive atmospheres. The specialised data surveys can reveal hidden details or structural features that are not visible (Point Clouds Data PCD) is obtained using LiDAR equipment, measurements with electromagnetic radiation (EM, Echography) (Figure 6). All these different data form a rich and diverse base, essential to trace the temporal evolution of the building and ensure a precise and faithful 4D restitution.

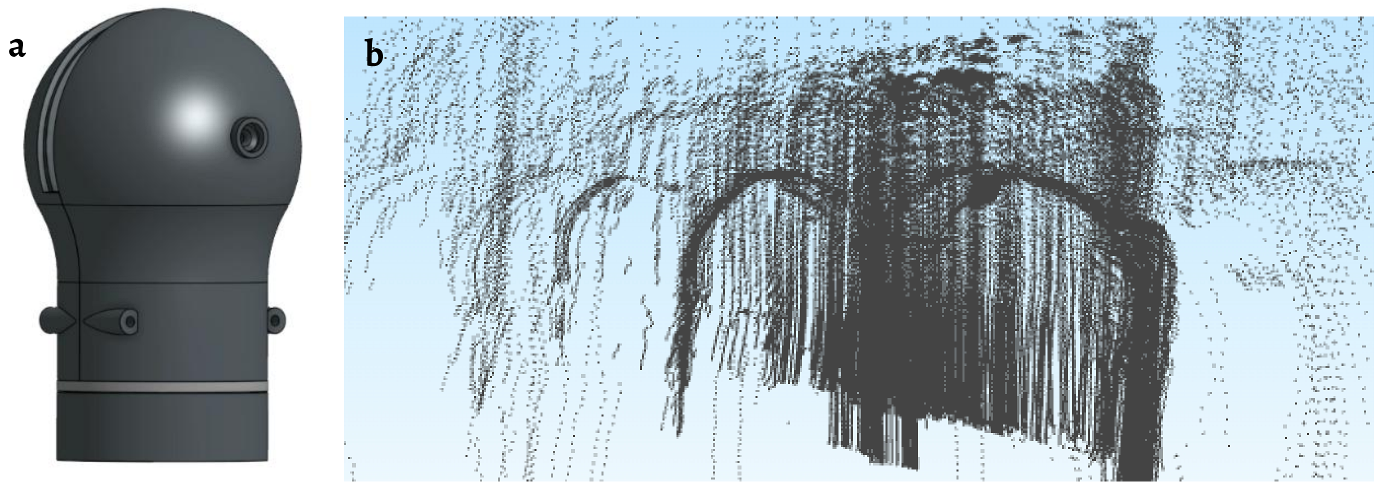

Figure 6. Digitalization of the Mosque Kenadsa Ksar's using laser beam acquisition: *a)* used LiDAR developed by our team; *b)* screenshot of the Point-Cloud, Reduced density.

Integrating the time dimension

This phase aims to enrich the 3D models by generating multiple variants, each corresponds to a particular period or state of the building, modelled in the form of a mathematical equation. This is followed by the constitution of a temporal Metadata where each instance is attributed to specific temporal data in order to trace the chronological mutations of the building.

$$M(t) = \sum mi\ (t)$$

M: model; Σ= some; Mi= ith M instance

These various temporal instances of the models are then structured and examined with QGIS, offering the possibility of integrating temporal data for each model. Thus, the use of QGIS Cloud simplifies the management, analysis and visualization of the building. The steps are as follows:

Firstly, the fields are populated by organizing the temporal and attribute metadata of each 3D model in a structured table where each entry corresponds to a specific instance. This table is then imported into QGIS via a vector layer, ensuring proper georeferencing and recognition of temporal attributes. Then, the temporal parameters are configured to visualize the evolution of the 3D models using the temporal panel. Finally, QGIS allows for realistic 4D visualization, offering the analysis of changes and evolutions of the modelled building.

Interactive visualisation (AR/VR)

To enrich the results of QGIS 4D modelling, interactive visualisation tools in augmented and virtual reality are used, offering immersive temporal animations. Platforms such as Sketchfab [28] (Figure 7a), CesiumJS, Unity and Unreal Engine are used to generate interactive 3D environments in which the user can explore the temporal evolution of the building. These tools cover advanced features to incorporate 3D models with enriched temporal metadata, thus facilitating the development of dynamic and immersive scenarios.

These virtual replicas of buildings are used to simulate, analyse and anticipate their behaviour (Metahuman model) in various scenarios. Their creation allows for the dynamic scenarios simulation by incorporating temporal and contextual data to reproduce historical events based on acquired historical data. Moreover, it also allows for the prediction of the building's state based on extracted profile techniques at a given moment to simulate its dynamic evolution. This enables people to have immersive experiences and to explore the building history in an interactive way, enriching their understanding and engagement. The Figure 7b shows the 3D model results, composed of 3 million triangles and 1.5 million points, with high-resolution textures (8000 × 8000), a specular PBR, an activated UV layer and integrated point coloring.

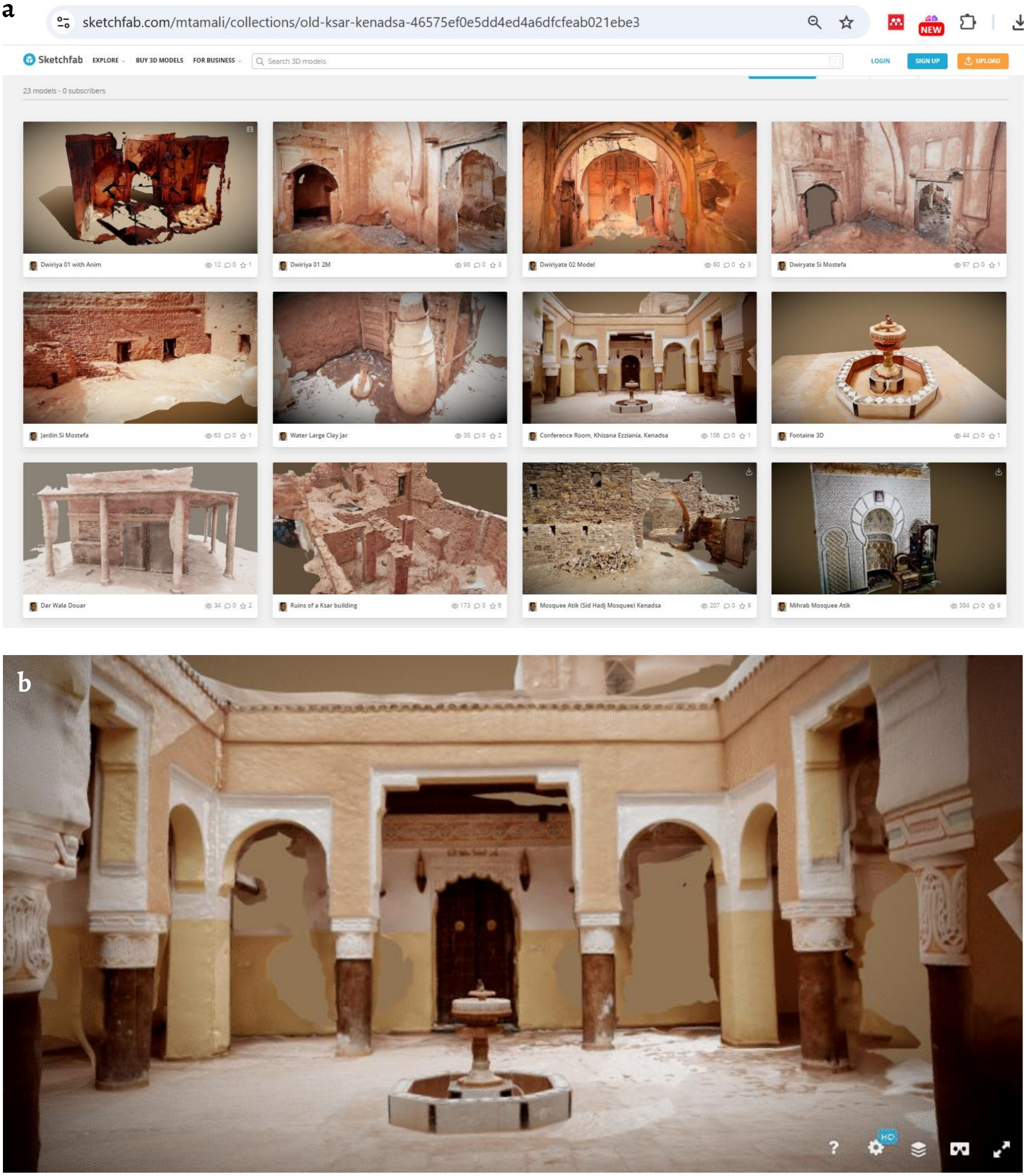

Figure 7. Animated 3D and AR models diffuse on: *a)* the platform which that allows to upload, view, share, and embed 3D models interactively of Kenadsa ksar, Algeria; *b)* courtyard house 3D.

Final product and uses

The definitive 4D model is an exhaustive instrument, designed to be used in scientific research, analysing the structural or aesthetic transformations of the building. In heritage preservation, through the planning of heritage intervention strategies, as well as in cultural mediation offers interactive visualisations intended for the public or educational tools. Using MCP based AI

(Model Context Protocol) tools, along with software such as Blender (Figure 8a-d), Mixamo, and MMD, reduce costs while increasing the efficiency of building a heritage-oriented scene.

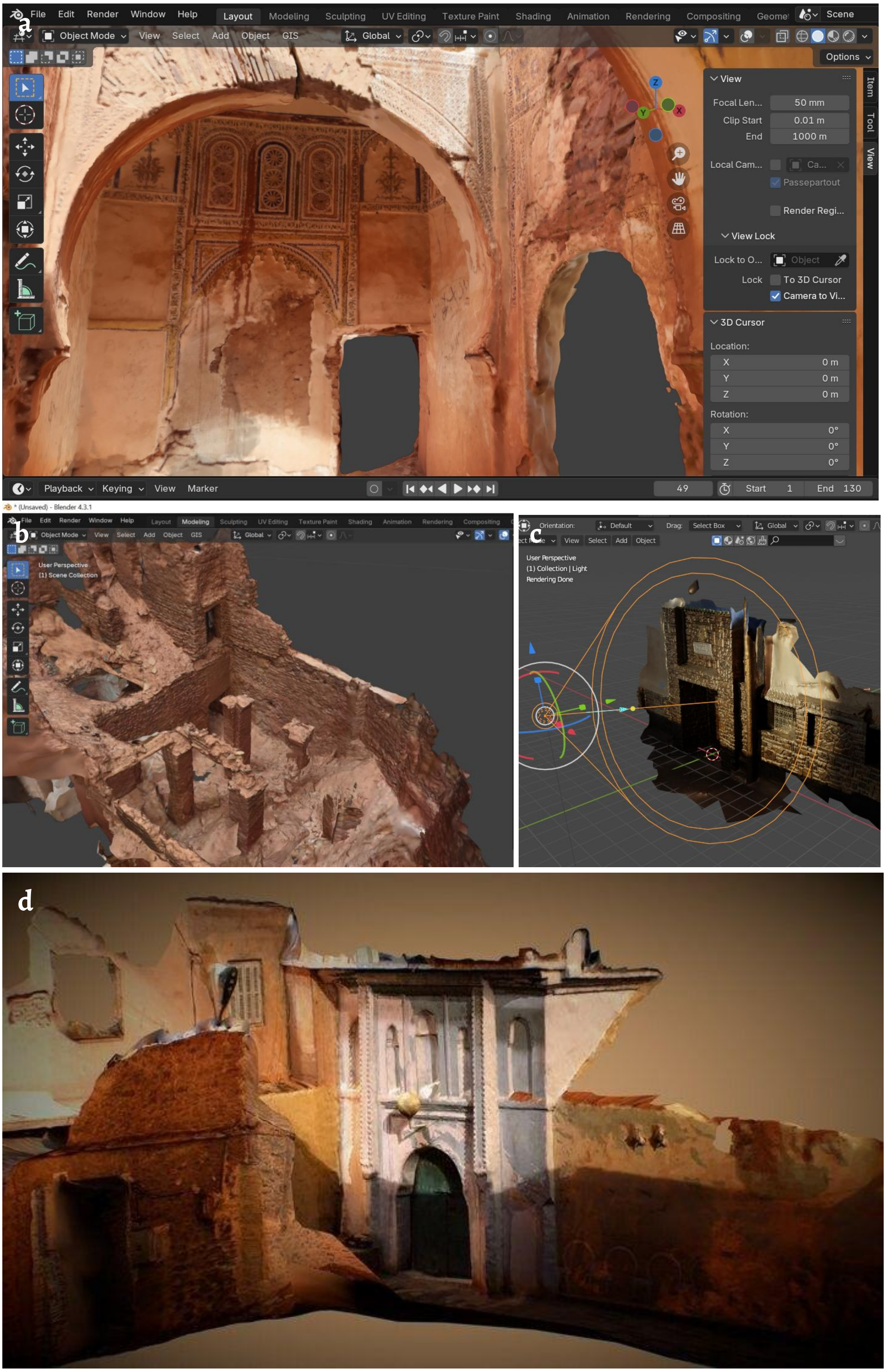

Figure 8. Refined and enriched model by Blender: *a)* house with decorative richness; *b)* old house; *c)* entrance of *Khizana*; *d)* the entrance of the mosque.

Architectural comparative analysis for predicting photogrammetric restitution

In his study, J.C Echallier highlights a series of formal and decorative clues that allow to specify the architectural stratigraphy and guide the restitutions. He emphasizes that the Kenadsa Ksar "has a completely different appearance [...], a city of old culture and established architecture" [29], and clearly distinguishes between ancient phases, close to Mauritanian traditions, and later influences from the Maghreb and especially Morocco (Figure 9). The oldest cores, built in dressed stone in polychrome shades, have sharp edges, carefully treated frames and sometimes decorations in "fish bone", showing technical affinities with Mauritanian models (Tichite, Akreijit). Conversely, the Moroccan influence is manifested in later layers, notably through the decoration of the facades coated with an ochre coating. Thus, the facade of the mosque, adorned with niches and clumsy polylobate arches, and decorated with rosettes carved in plaster, pilasters and cornices, glazed tile awnings or portals embellished with low-sprung arches. In some of the most prestigious residences, the portal is distinguished by pointed arches, enriched with colonnettes and surmounted by partial canopies covered with glazed tiles.

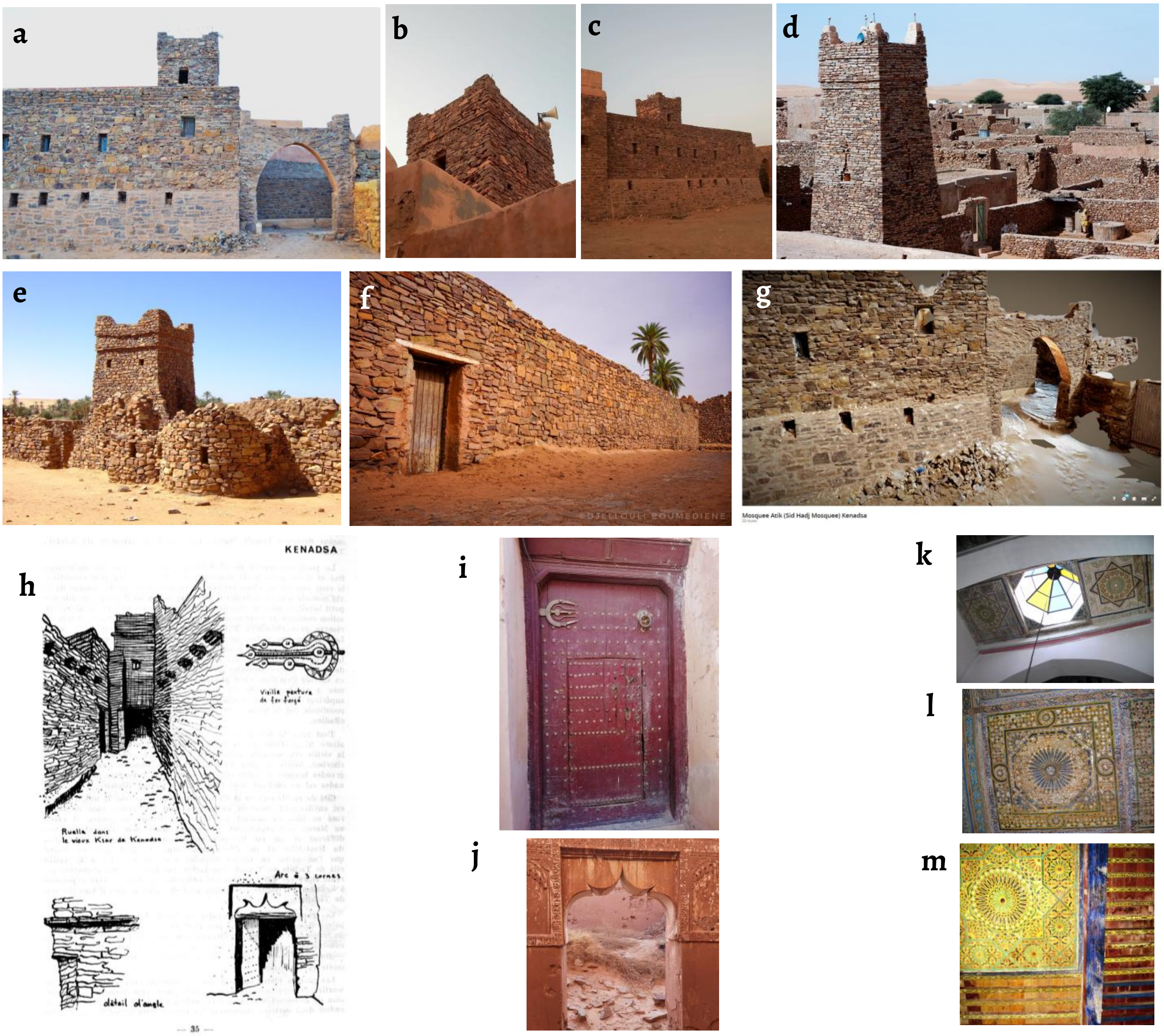

Figure 9. Architectural typology between Mauritanian traditions and Maghreb influences: *a-c)* stone architecture in Kenadsa ksar*; d-e)* stone architecture in Mauritania (Chinguetti)*; f)* stone wall in Kenadsa; *g)* 3D restitution of Kenadsa fortification wall; *h)* Kenadsa details elements by Bachminski and Grandet; *i)* traditional door; *j)* arcade type*; k-l)* decorated ceilings Kenadsa*; m)* ceilings in Fez.

Echallier also pays particular attention to the ornamentation of the doors, some elements of which seem directly imported from the Maghreb. They are indeed framed with wooden mouldings carved in "cable", studded leaves combining large leaf and small wicket, and especially wrought iron hinges with three parallel branches whose birth draws concentric circles. Thus, there are motifs (triangular rafters and internal metal twists) identical to those of hinges in Meknes in the eighteenth century, not only in general form but also in the geometric decoration of the main branches. He also points out singular morphological elements such as the three-horned arch created by a breach of the tympanum coating, also found on the great mosque of Tamelhat near Touggourt, as well as arches in recticurvilinear accolade, which complete the local formal repertoire (Figure 9h-j). The mihrab of the B. Bûziyân mosque bears a strong resemblance to those of the mosques of Fez, particulary in its polylobed arcature pediment [24].

For their part, the work carried out by Bachminski and Grandet highlights the process of gradual assimilation of new architectural forms, linked to interactions with the outside: "frequent contact with foreigners influenced them to assimilation and the use of new, more attractive architectural forms" [30]. Their work and the old photographs collected constitute a valuable reference for the reconstruction of parts that have now been demolished or completely disappeared (Figure 10). This historical database, combined with recent photogrammetric surveys, allows for a faithful reconstruction of the initial state of the building. It also proves to be indispensable in the framework of the adopted methodology, based on architectural analogy and the reconstitution of incompleteness, with a view to proposing scientifically argued hypotheses of restitution consistent with the original constructive logic

As part of our research conducted in 2011, strong similarities were revealed between the great houses of Kenadsa and those of the Maghreb. These similarities are based on both field surveys and data from oral and written archives, as well as on the work of J. Reveault and A. Paccard devoted to the architecture of Fez and decorative craftsmanship, confirming that the architecture of Kenadsa, is fully inscribed in the Andalusian continuum-Moorish and shares many common features. They concern the vegetal and epigraphic ornamentation in sculpted plaster, the coatings in *Zellij* (mosaic), as well as the decorated ceilings, made of sculpted wood and painted with natural pigments, and adorned with finely crafted floral motifs (Figure 9k-m). These elements clearly reflect Andalou-Maghrebin influences. To these decorations are added calligraphic inscriptions such as *al-ʿāfiya; al-bāqiya*, which are also found in Marrakech and even in the Alhambra.

This analogy grid plays a decisive role in the interpretation of gaps and in the mitigation of uncertainties inherent to digital restitution. The metric attributes provide objective benchmarks to complete the degraded parts of the building, while the decorative attributes allow to assign with more precision a chronological phase or a cultural area to the reconstructed elements. Thus, the combination of material indices recorded in situ and typological analogies from regional corpora contributes to validate photogrammetric restitution hypotheses, reducing the margin of arbitrariness and ensuring the scientific rigor of the models produced.

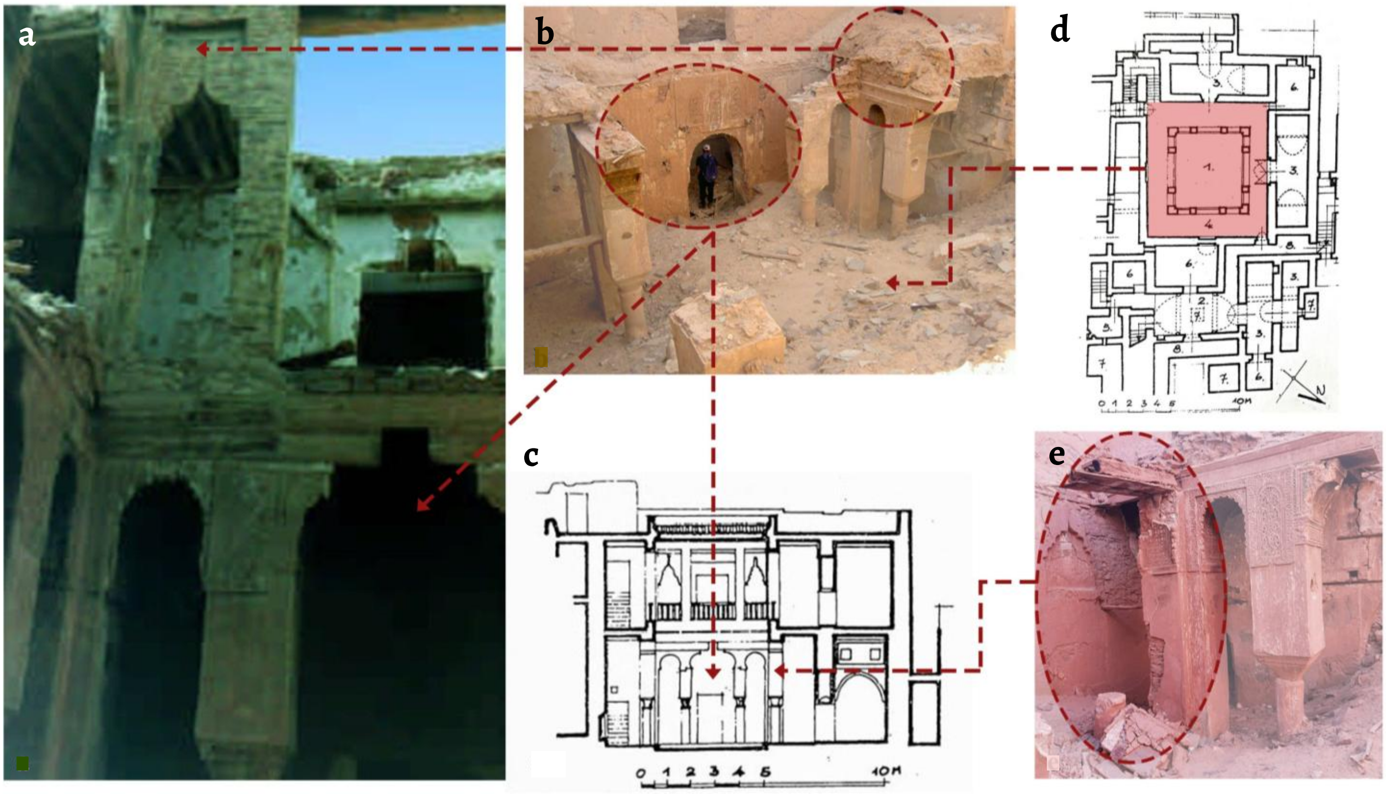

Figure 10. 2D restitution, produced from in situ metric and photographic surveys before 3D modelling: *a)* old photos of parts now disappeared; *b-e)* recent photos show parts completely disappeared; *c-d)* sectional and plan survey.

Discussion and conclusion

This paper addresses methodological approaches used to digitalize the Kenadsa Ksar's damaged building using well-known photogrammetry (for acquiring *Dwiryates*) and Laser beam acquisition for LiDAR (for acquiring *Sidi Mhmed Abi Zyan* Mosque (Figure 6b)). Data acquisition involved processing over 3 000 photographs (all phases combined) taken with EOS professional camera (Electro-Optical System) renowned for its optical performance suitable for photogrammetric surveys. This metadata was processed using ExifTool to determine the general parameters of the acquired images. The resulting point cloud achieved subcentimeter metric accuracy (less than 1 cm), confirmed by control points measured on-site, attesting the reliability of the method and the geometric accuracy of restitution. The retopology in Blender allowed for "texture baking", recentring the model on the reference (0,0,0); and then uploading the final model to Sketchfab (specialized collection). For the RPLIDAR A1M8, the point cloud "density" is best understood through its angular resolution and how the sample frequency is distributed across each scan. With an angular resolution of ≤1°, the LiDAR can theoretically capture one data point at least every degree in its 360° rotation, and up to 8000 points per scan at 10 Hz. This indicates a trade-off, where a higher scan rate (Hz) can lead to more scans per second but potentially fewer points per individual scan if the sample frequency is fixed. This defines the fineness of the environmental outline it can perceive in a single scan. The number of points in one full 360° scan is not fixed. The search results mention different values under various configurations: 1450 points per scan at 5.5 Hz.

Owing to its precision, digital restitution improves stakeholder decision-making for the sustainable management of built heritage and offers an effective way to reduce intervention costs. This study is in line with approaches that consider photogrammetry not only as a documentation tool, but also as a methodological support for restoration operations. This methodology provides a reliable and adaptable framework, using photogrammetry to create 3D digital models that aid in decision-making and ensure the conservation of traditional forms. The process addresses current conditions, past data gaps, and future predictions, with the resulting models supporting heritage popularization, digital archiving, and cultural tourism. The photogrammetry allows for rigorous documentation of the current state of buildings, identification of deformations, as well as anticipation of conservation interventions and simulation restoration scenarios in an experimental setting that respects the material integrity of buildings. Our work has focuses on collecting history of the available data relevant to the studied building (attached to the studied culture) and through architectural analogy in order to propose scientifically reconstruction hypotheses. By reverse-engineering the observed facts, process of restoration can be guided and then achieved.

Several challenges are encountered during the project advancement in order to ensure optimal data acquisition. Some of these have been overcome through the use of appropriate measures using several documentation's type, while others require digitalization techniques and tools that offer high precision of complex architectural structures and areas that are difficult to access. In addition, photogrammetry has more than one method for digitization, but other generalizations such as the use of Max Range LiDAR or aerial scanning, using a UAV, or even acoustics (a method using sound to scan obscure sites). If the data comes from a multitude of sources and methodologies, the result of processing the artifact could yield significant observations and details.

Moreover, the methodology implemented is adaptable to other ksour and similar vernacular settlements, by offering a reproducible framework that respects local architectural and cultural specificities while generalizing good practices of documentation and rehabilitation (Unified framework). The methodology steps vary depending on the details level to reach or observations requested. The experimental application on Kenedsa Ksar concretely illustrates the global approach: photogrammetry allowed to record with a great precision the existing structures, to restore virtually degraded parts and to simulate several restoration situations and scenarios. This experience shows the scientific method's value as well as its ability to constitute an operational basis for developing coherent rehabilitation interventions that respect traditional materials and structural procedures. Our aim is to unify considerations in aspects organization of Tangible and Intangible heritage, this by introducing a unified classification for both types.

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RECEIVED: 2025.4.25
REVISED: 2025.8.6
ACCEPTED: 2025.11.3
ONLINE: 2025.11.21