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High-Precision Digital-Twin of Qaitbay Fort:
A 3D Model Architecture for the Data-Sensorium

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要旨

モバイル LiDAR の普及により 3D 計測は身近なものとなったが、視覚化と解析的データの峻別は依然として重要な課題である。本研究では「データ・センソリウム」の枠組みを用い、Matterport と iPad 搭載 LiDAR の比較評価を行った。その結果、iPad は効率性に優れるものの、空間読解に不可欠な精度を欠くことが明らかになった。対して Matterport は、知覚と計測を両立させる分析空間として機能する。高精度な 3D データ取得は、静的なモデルを遺産保護のための動的なツールへと昇華させる、研究における最重要の鍵を握っている。

Abstract

While mobile LiDAR has democratized 3D capture, the distinction between mere visualization and analytically rigorous data remains critical. This study evaluates Matterport high-density systems against iPad-based LiDAR within a Data-Sensorium framework. Findings indicate that while iPad scans offer efficiency, they lack the integrated metric and material fidelity required for deep spatial reading. Conversely, Matterport environments function as authentic analytical spaces, supporting simultaneous perception and measurement. Ultimately, high-fidelity 3D acquisition is essential for research-grade documentation, transforming digital models from static representations into dynamic tools for longitudinal spatial assessment and heritage preservation.

Keywords: Qaitbay Fort, Digital-Twin, Data-Sensorium Framework, Spatial Perception

Introduction

Digital heritage has become essential for multiple objectives. Digitization techniques go beyond simply creating an accurate, immersive 3D model for traditional documentation. Qaitbay Fort (1477) in Alexandria is an outstanding coastal cultural heritage site. (G. C., Deepali, *et al.,*2018) The Pharos Lighthouse, one of the seven wonders of the ancient world, is the predecessor of Qaitbay Fort and was completely demolished as a result of consecutive earthquakes and tsunamis that caused severe damage. Chronological reports indicate that Qaitbay Fort has been exposed to similar threats. Contemporary studies and investigations emphasize that the fort is vulnerable to natural disasters and the impacts of climate change. Condition assessments highlight that the fort requires regular conservation and maintenance to sustain its value as a celebrated tourist destination.

From a sustainability perspective, the digital representation of the tangible and intangible culture heritage of Qaitbay Fort contributes to multiple SDGs. In the case of Qaitbay Fort, Digital-Twin technology addresses Goals 11.4, 11.3, and 11.b – Sustainable Cities and Communities –by directly supporting the safeguarding cultural heritage, the preservation of identity, and the promotion of inclusive cultural engagement.

The Data-Sensorium system represents Qaitbay Fort Digital-Twin in an ideal cyber-physical environment through real-time visualization. iPad

LiDAR and Matterport Pro3 are two popular LiDAR-based techniques used to model the fort. Although both techniques generate 3D models, their outcomes differ significantly in technical precision, resolution, and texture quality. This research serves as a digital heritage case study that utilizes a technical comparison to propose an integrated Data-Sensorium workflow. Specifically, it examines the compatibility of both 3D modeling techniques for the multiple objectives of digitizing Qaitbay Fort, with a specific focus on integration into the Data-Sensorium system. The atmospheric conditions surrounding Qaitbay Fort, alongside accessibility, availability, and reliability, guide the discussion and inform the usability of each technique.

1. Conceptual Framework: Cultural heritage into a 3D Cyber-Physical Environment

This research adopts the concept of the Data-Sensorium as a theoretical and operational foundation for integrating immersive spatial interaction with Digital-Twin in cultural heritage of Qaitbay Fort in Alexandria (Figure 1).

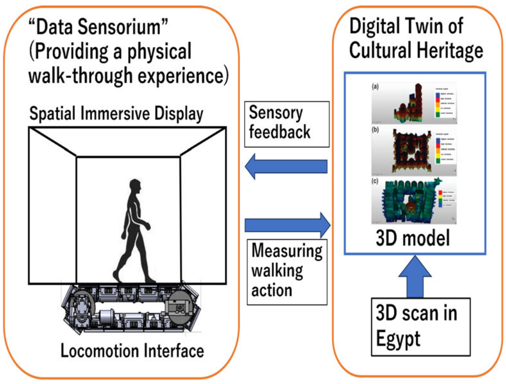


Figure 1: Conceptual framework of Qaitbay Fort cyber-physical environment

Traditional data presentation methods typically position data as an object to be visually read and cognitively analyzed from an external viewpoint. In contrast, an immersive spatial environment transforms this relationship. Users do not merely observe data; they physically enter and traverse it through walking and physical action. In such environments, data is no longer external information but becomes embedded within the cyber-physical experience itself, gradually understood through movement, perception, and interaction over time (Iwata et al., 2023).

Within this framework, the Digital-Twin is generated from high-resolution 3D scans conducted in Qaitbay Fort, Alexandria, serving as a spatially precise, data-rich representation of the tangible and intangible heritage of the fort. The utilized immersive 3D model technique captures precise dimensions, material characteristics, and spatial configurations, enabling the Digital-Twin to function as more than a static visualization (Piumatti P., et al., 2017). Instead, it operates as an interactive environment in which cultural heritage data is spatialized and made perceptible through physical exploration.

The Digital-Twin, together with the Data-Sensorium, is operationalized as an immersive spatial display system combined with a locomotion interface that enables a physical walk-through into the cyber model of Qaitbay Fort. According to the Data-Sensorium concept, data is embedded within the spatial structure of the environment, allowing participants to comprehend relationships incrementally as they move through space (Iwata et al., 2023).

To empirically evaluate this setup, user operations were structured around specific navigation and observation test tasks. Participants were required to execute a directed 15-minute locomotion task through the main courtyard and internal vaulted galleries of the virtual fort. The objective of this task was twofold: first, to evaluate the user's ability to orient themselves using spatialized architectural cues, and second, to identify localized structural details—such as masonry degradation patterns—embedded directly within the high-resolution assets of the 3D model.

The locomotion interface senses geometric walking actions—basically direction, speed, and displacement—and transmits this information to the Digital-Twin in real-time. In response, the Digital-Twin updates visual and sensory outputs, providing an immediate sensory reaction that corresponds to human movement. Through this continuous loop, the walking action, spatial structure, and data representation remain synchronized.

Within this framework, technical model quality directly dictates the psychological parameters of immersion, spatial perception, and presence. The optimization of the 3D mesh and texture resolutions derived from the high-density LiDAR and photogrammetry data ensures that visual fidelity is maintained without causing latency. By sustaining a stable rendering frame rate and sub-centimeter tracking alignment, the system prevents visual-vestibular conflict. Visual indications alone are insufficient; accurate spatial comprehension depends on the tight alignment of what users see, how they move, and how distances and scales are perceived through physical action. When these technical and perceptual processes remain consistent, users can naturally grasp the spatial structure through embodied engagement. Conversely, inconsistencies or drops in model quality—such as latency, geometric distortion, or texture popping—disrupt spatial metrics, induce cognitive dissonance, and ultimately weaken the user's sense of presence and immersion within the historical environment (Iwata, H., 1999).

From the perspective of reliability in a 3D environment, this framework emphasizes perceptual confidence. Reliability is achieved when users can trust their own perception and form stable expectations about the outcomes of their actions. Consistency among spatial structure, physical movement, and responsive mechanisms allows users to intuitively engage with the environment, supporting both experiential understanding and analytical interpretation of tangible and intangible cultural heritage spaces in Qaitbay Fort.

Broadly, this conceptual framework integrates the Digital-Twin and the Data-Sensorium as a unified system in which cultural heritage data, spatial structure, and human physical experience are tightly interwoven. By integrating heritage data within an immersive, cyber-physical environment, the framework shifts heritage interpretation from passive observation to embodied, experiential understanding. The generated walk-through experience provides a foundation for heritage research, education, and interpretation that prioritizes presence, spatial cognition, and the lived experience of cultural heritage, while remaining grounded in a reliable and consistent 3D environment.

2. Qaitbay Fort: values and significances:

Qaitbay Fort is a 15th century defensive fortress that stands as a powerful symbol of Alexandria's maritime resilience and military history. Its value is rooted not only in its defensive engineering but also in its direct physical connection to one of the ancient world's greatest wonders. (M.Abdelaziz, 2019)

2.1. Connection to the Ancient Lighthouse:

Qaitbay Fort holds significant archaeological and historical values as it was built on the exact site of the Pharos Lighthouse, one of the Seven Wonders of the Ancient World. After the lighthouse was destroyed by earthquakes, Sultan Al-Ashraf Qaitbay used its remaining limestone blocks and granite columns as foundational building materials for the fort in 1479. (M.Abdelaziz, 2019) (Figure 2)

Figure 2: Topography of Alexandria and Qaitbay Fort by François Cassas, 1785. (Soliman et.al 2021 and 2025)

2.2. Strategic Defense:

For centuries, Qaitbay Fort served as a primary defensive stronghold for Egypt's northern coast. It was strategically designed to protect Alexandria's harbor from naval invasions, particularly from the Ottoman Empire in the 15th century. (Darwish, 2018)

2.3. Architectural Significance:

Qaitbay Fort is a masterpiece of Mamluk military architecture (Sadeq, 2011). Key features include a massive three-story square tower consolidated with four circular corner towers equipped with arrow slits standalone in an open courtyard. (Figure 3) and (Figure 4) External walls surround inner walls that encloses a courtyard with barracks and storage chambers. Narrow slit windows, arrow loops, crenelations, and cannon emplacements that exemplify the transition from medieval Islamic to early modern European military architecture. An internal water system of cistern network provided infrastructure to supply both soldiers and horses with water. (Soliman, et.al 2025)

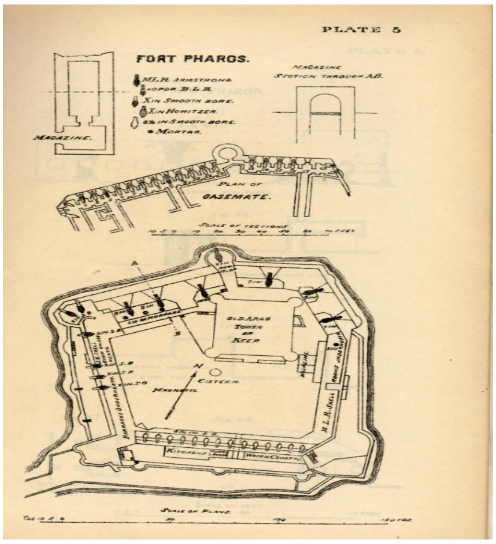


Figure 3: Layout of Qaitbay Fort (Goodrich and Caspar, 1880)


Figure 4: The main standalone tower

2.4. Spiritual and Cultural Significance:

Qaitbay Fort housed a mosque within its walls, reflecting the integration of spiritual and military life in Islamic civilization. (Soliman, et.al 2025) (Figure 5)


Figure 5: The Mamluk mosque in the main tower

2.5. Layered Heritage:

Throughout history, the fort has witnessed the transition of power from the Mamluks, Ottomans, and French (under Napoleon in 1798), and later British forces since 1882. Each era left a remarkable trace, such as the addition of modern cannons by Muhammad Ali Pasha and Khedive Ismail in the 19th century. (Mohammed, 2023)

2.6. Modern Cultural Icon (Tourism and Economic Value):

Today, Qaitbay Fort has transitioned from a military site to a cultural beacon and tourist attraction, drawing international and domestic visitors interested in history, architecture, and heritage. It houses a maritime museum and offers panoramic views of the Mediterranean Sea, serving as a reminder of Alexandria's status as a historic Mediterranean gateway. (Diwdar, S., 2019; Ferrighi, A., 2013)

3. Frameworks and Specifications of 3D Model Acquisition Methods

3D modelling techniques operate within the framework of the Sensing, Processing, and Actuation (SPA) concept. Their increasing innovation and diversity have expanded their adoption in cultural heritage for multiple objectives.

3.1. Low-Cost 3D Sensors and Immersive Methods for Digital-Twin System

A Digital-Twin (DT) creates a high-fidelity and a mapping-measured 3D model that bridges and mirrors a real-world environment within a virtual space. (Ioannides, M. 2025) Importing the Qaitbay Fort 3D model into the Data-Sensorium digital environment demands creation of an immersive 3D model. iPad LiDAR and Matterport are two distinct techniques used to digitize Qaitbay Fort.

Scaniverse, free software installed on iPad (OS Version 16.6.1-3rd Gen.), was used to acquire LiDAR data for the internal spaces of Qaitbay Fort (Figure 6). Leveraging the simplified operation of the iPad LiDAR allows aim and move the iPad toward the targeted surface. The gradual fading of the infrared dot curtain indicates a successful scan. Despite the operational advantage of iPad LiDAR technique, the high-power consumption of the device limits time efficiency. (Soliman et.al 2025) In addition, the maximum ranging beam of <5 meters length, with an effective range of <4 meters, prevented the capture of high-density on external and internal faces exceeding 5 meters height (Soliman et.al 2025). Consequently, data acquisition was strictly restricted to the fort's enclosed internal spaces, specifically the main tower and the coastal passage. This interior campaign required three consecutive days of fieldwork, operating 10 hours per day during October to take advantage of Alexandria's temperate autumn climate, which ensured stable sensor performance.

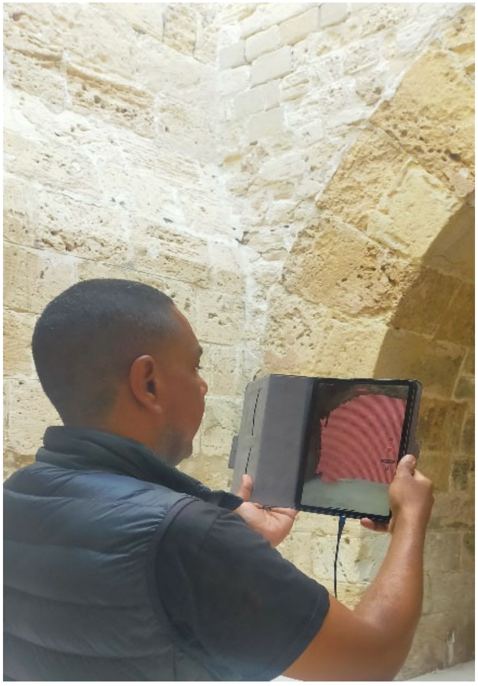


Figure 6: iPad LiDAR mobile scanning with scaniverse interface

Generating an immersive 3D model of Qaitbay Fort required more advanced and precise LiDAR data compatible with the Data-Sensorium. Consequently, Qaitbay Fort was captured using Matterport Pro3 system. Matterport is a compact LiDAR-based 3D acquisition platform designed for efficient and spatial documentation that transforms 360° images and depth information into fully navigable, immersive 3D Digital-Twins of real-world spaces. (Matterport, 2022) (Figure 7). Matterport Pro3 device features a portable profile with dimensions of 181 × 161.4 × 76 mm, weights 2.2 kg, and supports tripod mounting via a quick-release mechanism with a 3/8-16 thread. Integrated GPS enables georeferenced capture. The device supports more than 220 consecutive scans per charge, with a charging time of approximately 2.5 hours to 80% capacity and 3.5 hours to full charge. The Matterport Pro 3 operates within a temperature range of 0–40 °C (storage: −20–60 °C) and is rated IP43 for environmental protection (Matterport, 2025). Comprehensive digitization of the entire Qaitbay Fort was achieved through five consecutive days of fieldwork, totaling 50 operational hours (08:00 to 18:00 daily) and 575 of scanning stations using the Matterport Pro3 scanner. The fieldwork timeline was intentionally scheduled during early November to leverage Alexandria's moderate autumn climate. This timing ensured ambient operational temperatures well within the scanner's thermal thresholds (0–40 °C), thereby mitigating the risk of hardware overheating, protecting battery longevity, and ensuring long-term device stability during intensive data acquisition.

Figure 7: Matterport terrestrial scanning in qaitbay Fort

Data acquisition is optimized for rapid capture, with a scan time of under 20 seconds and a boot time below 40 seconds. Remote operation is enabled through the Matterport Capture app on Apple and Android devices, using BLE for setup and 5 GHz Wi-Fi for data transmission. The system generates 134.2 MP panoramic imagery using five-exposure HDR frames with automatic white balance. Depth measurements are acquired using a Class 1 LiDAR sensor (IEC 60825-1:2014) operating at 904 nm, providing a 360° horizontal and 295° vertical field of view (FOV). The reported geometric accuracy is ±20 mm at 10 m, with a depth resolution of approximately 100,000 points per second (≈1.5 million points per scan). The effective operating range extends from 0.5 m up to 100 m when exporting in E57 format, with automatic 3D data registration supporting streamlined Digital-Twin generation. (Matterport, 2025)

3.2. Processing pipelines and visualization platforms

Processing Scaniverse raw data through iPad

LiDAR allows basic, limited processing functions. Processing takes <1 minute. Scaniverse exports models to the following formats: FBX, OBJ, GLB, USDZ, STL, PLY, and LAS (Łabędź, P., 2022). However, Filmbox (FBX) and Wavefront Object (OBJ) are the only compatible formats to generate a walk-through experience in the Data-Sensorium via the Unity platform (Unity, 2025). Third-party software is required for advanced and integrated processing to enhance the model (Figure 8). Agisoft Metashape accommodates the alignment and merging of raw data, and further progression, basically meshing and texture building. (Soliman *et.al.*, 2025)

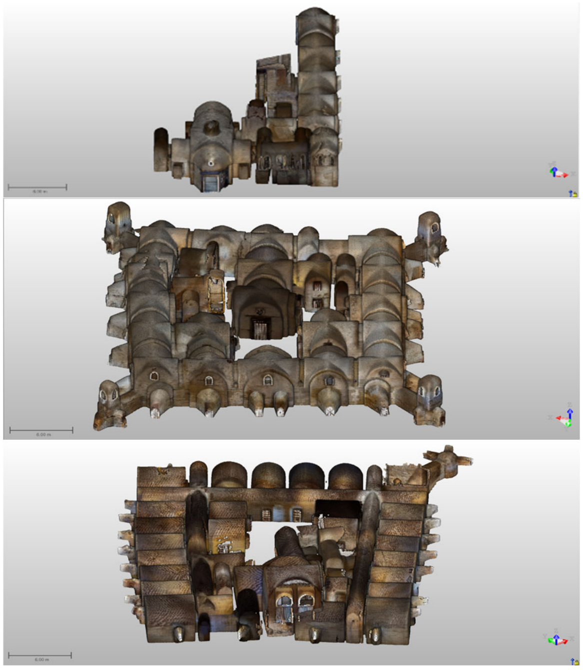


Figure 8: Point Cloud color model of Qaitbay Fort using Agisoft Metashape. (Ground, First, and Second Floors).

The Matterport system supports mobile scanning using smartphones and automates the processing of captured images into 3D models. The platform provides several viewing modes -such as dollhouse views, 2D floor plans, 360° panoramas, and guided walkthroughs- which boots spatial understanding and user involvement. Its intuitive interface and low equipment requirements make it particularly suitable for non-experts and projects with limited resources (Kocaturk et al., 2023; Liu et al., 2023).

Data Processing should be run on the Matterport platform, which requires a paid charge subscription. Despite the scanned models are stored on the utilized control unit (an iPhone 14 Pro Max), they should be uploaded on the Matterport professional platform to enable seamless processing. The platform provides an advanced processing, basically automated and manual alignment, and the merging of model segments (Matterport, 2025) (Figure 9). Model processing time is influenced by a combination of network, system, and dataset characteristics. Upload speeds dictate the initial data transfer to the cloud, while processing queues vary depending on platform demand throughout the day. Model size is the dominant factor; larger datasets with numerous scan positions or complex geometry require substantially longer computation times. Small models with only a few scans may complete within minutes, whereas large models with hundreds of scans may require one to two days. Optional post-processing tasks, such as automated face blurring, introduce additional computation, typically adding several minutes per scan position. In practice, most models are processed within approximately eight hours, while processing times exceeding 24 hours are uncommon and generally associated with unusually large or complex datasets (Matterport, 2025). The MatterPak produces several 3D model formats, including DWG, FBX and OBJ (Unity, 2025).

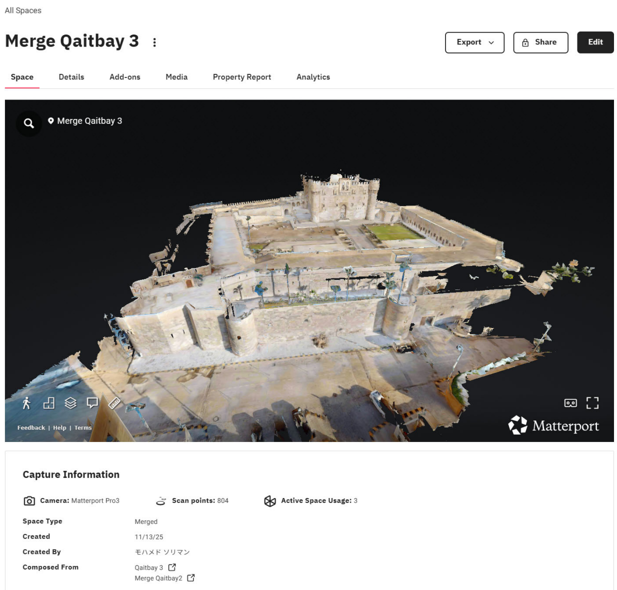


Figure 9: Processing and actuation on Matterport platform

4. Simplicity and Precision: Comparative Evaluation

The typical conflict between simplicity and precision is highly evident in the modelling of Qaitbay Fort. The chosen 3D method is determined by the specific objective. Mobile LiDAR provides seamless scanning small spaces or objects at post-disaster response. However, building a walk-through journey in the Data-Sensorium requires an immersive 3D model with high-density/ precise LiDAR data.

4.1. Limitations of Mobile LiDAR for Data-Sensorium Applications

Distortion of the Mobile LiDAR data appears when displayed within the Data-Sesnorium architectural environment. The reason behind is the insufficient resolution and surface ambiguity. The Mobile LiDAR data of Qaitbay Fort model was acquired by Scaniverse installed on an iPhone 14 Pro Max and an iPad Pro, both equipped with LiDAR sensor. Scaniverse allows visualization of scanned models both in 3D and directly in augmented reality (Łabędź, P., 2022). The application offers three resolution options: Small (2k texture and 12-mm grid), Medium (4k texture and 8-mm grid), and Large (8k texture and 6-mm grid) (Table 1).

In the case of Qaitbay Fort- a large real-world object- the maximum scanning range of 5 m is restrictive, so 4 m effective range was deployed. Cropping the Qaitbay Fort model is the only limited editing option available within the application onsite. Another essential feature is the ability to measure the actual size of the scanned model (Łabędź, P., 2022). This measurement option enables on-site investigation of Qaitbay fort, which is a critical requirement for post-disaster response requiring rapid decision-making (Figure 10).

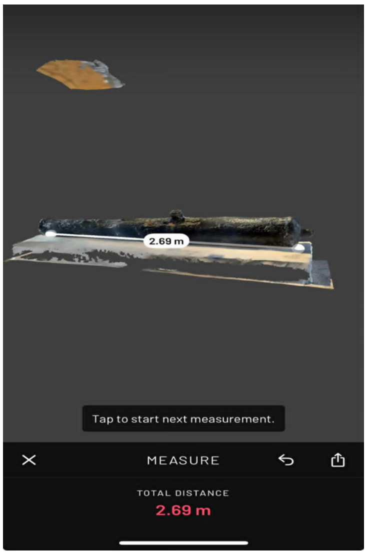


Figure 10: iPad Scaniverse processing and onsite measurement of a cannon in Qaitbay Fort

Despite the practical on-site options of Scaniverse, insufficient resolution and surface ambiguity severely limited its appropriateness for generating walk-through experiences in the Data-Sensorium environment. A risk of false confidence arises from missing scanned faces that cause holes and gaps in the Qaitbay Fort model, effectively resulting in inconsistent point cloud density (Figure 11). The low-fidelity model compromises texture quality, which in turn affect the realization of the true-color model (Figure 12). Its analytical utility beyond visualization is further restricted by misalignment of faces and vertices within Qaitbay Fort single model (Figure 13). This occurs because the point spacing is non-uniform. Moreover, small geometric deviations are averaged out, resulting in the loss of fine details of Qaitbay Fort such as geometric wood patterns of the windows and marble floor design (Figure 14). Fragmented illumination environment negatively affects the True-color reliability.

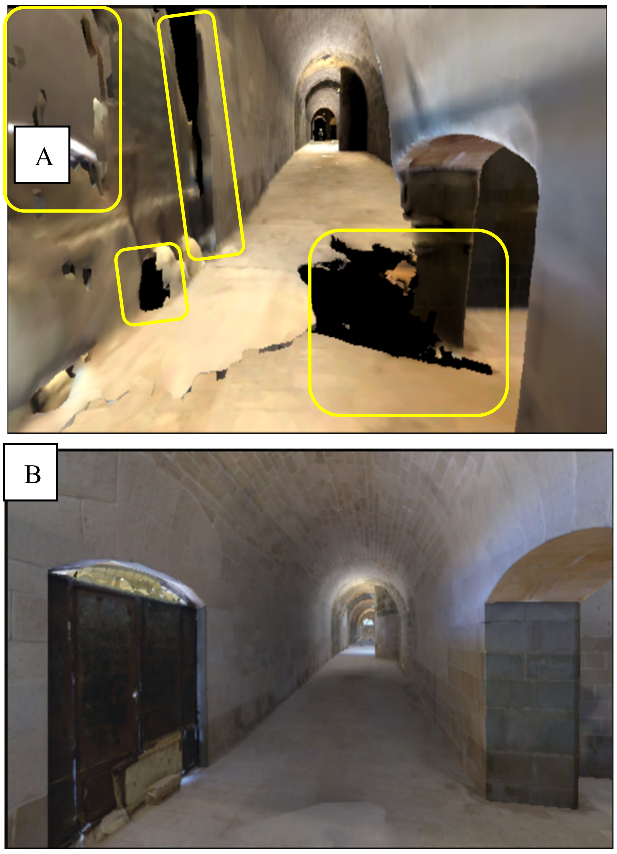


Figure 11: Distortion and misalignment visibility of Scaniverse texture (A) model of the coastal passage comparing with Matterport (B) on Unity Platform interface.

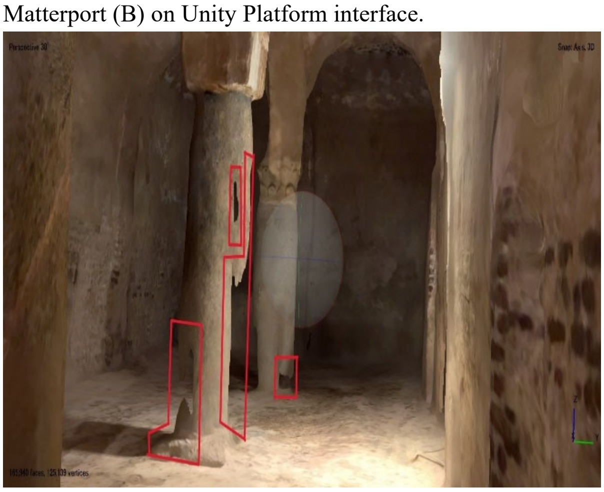


Figure 12: Gaping in the True-color model of the cistern of Qaitbay Fort on Scaniverse interface.

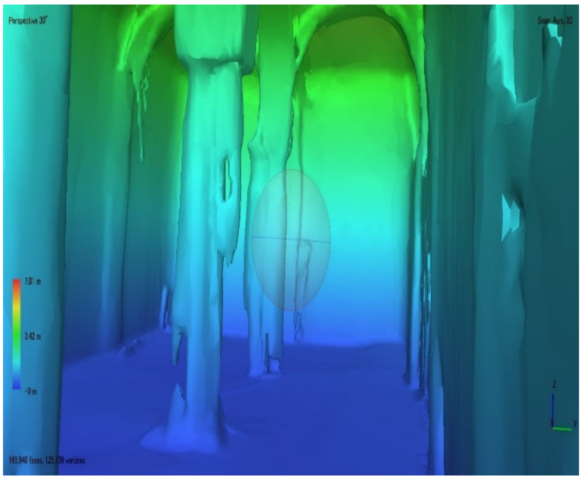


Figure 13: Misalignment in DEM occurred to the faces and vertices the cistern model.

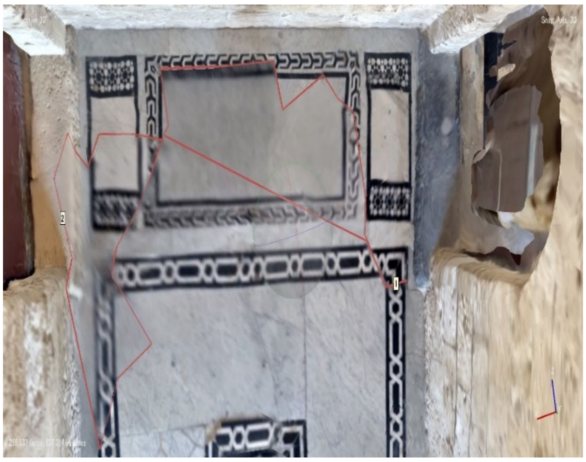


Figure 14: Ambiguity in the texture model of the marble on Unity Platform interface.

Table 1: Scaniverse Object Scale, Resolution, and Density

Mode	Grid Resolution (Point Distance)	Texture Resolution	Distance Range	Use Case
Small Object	~12 mm	2K	0.2<0.8 m	Quick reconstructions of small flowers
Medium Object	~8 mm	4K	0.5<2.5 m	High LiDAR quality for rooms, buildings, and outdoor spaces
Large Object/ Area	~6 mm	8K	2<5 m	Objects, people, and smaller scenes with lots of texture

4.2. Advantage s of Immersive 3D Models

LiDAR scanner specifications provide fundamental information for end-users to optimize the scanner best suited for a case study. These specifications can be classified into four hierarchal categories. (Raj, T. et.al, 2020) According to this hierarchy, the technical characteristics of the Matterport Pro3 can be systematically can be systematically classified into physical parameters, sensor performance parameters, laser-related safety specifications, and scanning LiDAR characteristics (Raj, T. et.al, 2020). This classification enables an objective assessment of the system's suitability for large-scale spatial documentation and Digital-Twin generation.

Physical parameters: The flexible physical parameters of the Matterport facilitated the intensive scanning of Qaitbay Fort. The Matterport Pro3 is a portable, tripod-mounted system with compact dimensions of 181 × 161.4 × 76 mm and a total weight of approximately 2.2 kg. It is powered by an internal battery supporting over 220 consecutive scans per charge, with charging life of approximately 2.5 hours to reach 80% capacity and 3.5 hours for a full charge. These physical characteristics making it ideal for stable deployment, mobility, and extended operation during indoor and semi-outdoor documentation campaigns, where autonomy is critical (Matterport, 2023).

Sensor performance parameters: The Pro3 LiDAR provides a minimum operating range of approximately 0.5 m and a maximum detection range of up to 100 m when data is exported in E57 format. It achieves a geometric accuracy of ±20 mm at a distance of 10 m. Depth acquisition operates at a rate of roughly 100,000 points per second, generating about 1.5 million points per scan. These parameters support metrically consistent documentation of large-scale environments and Digital-Twin workflows (Raj et al., 2020; Matterport, 2023). Scanning a vast multifunctional space like Qaitbay Fort presented significant fieldwork challenge. A major difficulty was establishing linkage scan stations between narrow indoor spaces, such as barracks, and openair areas, such as the courtyard and atop the walls. Variation in the lighting affected the surface's true color; balancing daylight with weak indoor artificial illumination frequently caused distortion or misalignment in scans. To mitigate this, LED lights equipped with suction cups were attached horizontally behind the Matterport the LiDAR MEMS mirror (Micro-Electro-Mechanical Systems). Ultimately, this high-fidelity successfully conveys the real-world reliability of Qaitbay Fort.

Laser and safety specifications: The Matterport Pro3 operates using a Class 1 laser in compliance with IEC 60825-1:2014 safety standards. The laser emits at a wavelength of 904 nm, ensuring eye-safe operation under normal usage conditions, thereby satisfying regulatory and safety requirements for professional systems (IEC, 2014).

Scanning LiDAR and beam motion characteristics: The Matterport Pro3 provides a full 360° horizontal and 295° FOV, enabling near-complete spherical coverage from each scan position. Each static scan is completed in under 20 seconds. (Raj et al., 2020; Wang et al., 2025). The spatiotemporal characteristics of the Matterport, combined with its physical portability, allowed for necessary field maneuverability when scanning a highly active tourist destination like Qaitbay Fort, as fieldwork had to be conducted during peak daytime visiting hours.

Immersive 3D data provides a continuous, spatially coherent representation of the environment, supporting real-time model generation within Data-Sensorium platforms. By integrating dense geometric information with visual context, this data enables dynamic navigation, immediate spatial feedback, and responsive interaction.

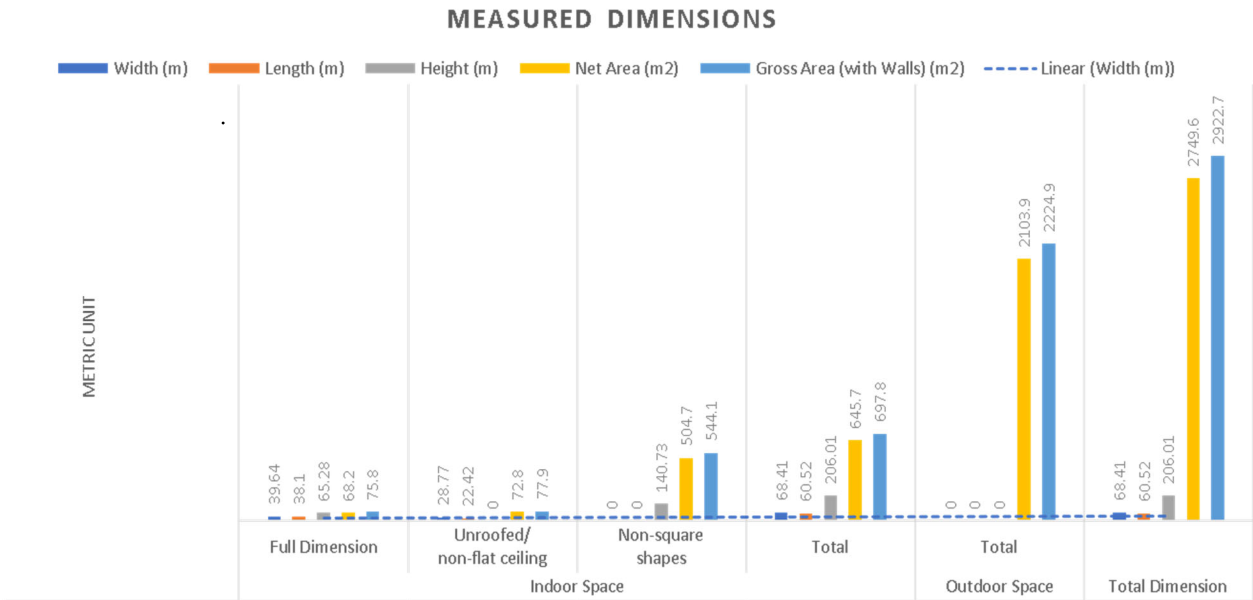
4.3. Technical Suitability and Research Intent:

The advantages of immersive 3D modelling extend beyond creating an architectural environment; it also allows for the structural condition assessment of buildings using immersive data. Post-conservation evaluation based on authenticity criteria are now viable, and large-scale sites like Qaitbay Fort can be scanned seamlessly. (Figure 15)

Figure 15: Dismantle of the limestone in Qaitbay Fort: Matterport model displayed on Unity Platform

Immersive 3D tools provide accurate measurements. The Matterport platform generates report detailing the side (S) dimensions (D) -Width (W), Length (L), Hights (H)- as well as the locations of model segments. Although the report categorizes both indoor and outdoor spaces as "Indoor", true outdoor spaces can be identified when all (W/L/H) dimensions are listed as "N/A" (not available) (**{} S={} D**). Fully detailed 2D dimensions (W/L) are only provided for true indoor spaces featuring standard straight, square sides. However, it does not appear in other indoor spaces with 1>4 sides (S) or curved line **(1>4 S={} W/L)**. Height (H) values are unavailable for unroofed areas or uneven ceilings (C) (**{} C={} D**). However, total area measurements (in square meters) are calculated and classified into Net Area (the interior face of walls excluding wall thickness and inaccessible areas) and Gross Area (the exterior face of walls excluding wall thickness and inaccessible areas). Technically, the reason behind "N/A" measurements are that Matterport does not automatically generate dimensions for spaces with non-square shapes or non-flat ceilings (Matterport, 2022) (Figure 16).

The standard Matterport web viewer does not display point clouds by default; instead, it textured 3D meshes optimized for navigation. Using third-party integration software such as Agisoft Metashape on a H-Spec PC is an effective method in both the VFX and BIM pipelines to reconstruct and visualize the point cloud externally.



	Full Dimension	Unroofed/ non-flat ceiling	Non-square shapes	Total	Total	Total Dimension
	Indoor Space				Outdoor Space	
Width (m)	39.64	28.77	0	68.41	0	68.41
Length (m)	38.1	22.42	0	60.52	0	60.52
Height (m)	65.28	0	140.73	206.01	0	206.01
Net Area (m2)	68.2	72.8	504.7	645.7	2103.9	2749.6
Gross Area (with Walls) (m2)	75.8	77.9	544.1	697.8	2224.9	2922.7

DATA TABLE

Figure 16: Statistical analysis of Matterport property report showing dimensional measurements and net and gross area calculations for indoor and outdoor spaces of Qaitbay Fort.

The reusability of this data is vital for monitoring Qaitbay Fort as vulnerable cultural heritage. Threatens besieging Qaitbay Fort- the topographic forefront of Alexandria- raise alarms regarding unanticipated exposures. Frequent seismic and tectonic movements threaten the fort's structural stability. Meanwhile, Seawater erosion accelerates causing topographic deformations, such as sinkholes and central cavities, directly impacting on the bedrock of Pharos Island, upon which Qaitbay Fort stands on (Fouad, S. S. *et.al.* 2025).

The advanced specifications of the Matterport, such as accuracy (+/- 20mm @ 10m) and panoramic output (134.2MP), generate immersive 3D data capable of revealing concealed deterioration within the fort (Table 2) (Matterport, 2022). Computed micro-architectural cracks and dismantled stonework, eroded limestone, and damage to the precious marble floors in the main tower became visible and assessable (Figure 17) and (Figure 18). Furthermore, the computational noticeability of surface deformation in wooden tie beams and inaccessible woodturning acts as an early warning for intervention (Figure 19). High-density and resolution precision also allow for assessing the Hydrological impacts; capillarity caused by seawater intrusion -one of the fort's major deteriorations features- became highly visible (Figure 20). Consequently, immersive data represents long-term analytical value, serving as a vital first step toward establishing a periodic monitoring system to support decision-makers in rescuing this outstanding fort.

Figure 17: Visible cracks in the precious marble floor of the Vestibule Matterport model on Unity Platform.

Figure 18: Erosion in the limestone: displaying Matterport model on Unity Platform.

Figure 19: Deterioration in the wooden tie beam in Matterport model on Unity Platform.

Figure 20: Capillarity in the limestone of the coastal passage: Matterport model on Unity Platform.

Table 2 Specifications comparison between Matterport Pro3 and iPad LiDAR (Scaniverse, 2025, Atencio, E. *et.al* 2024, Tondo, G. R. *et.al* 2024, Tee-Ann. T., 2023, Spreafico, A. *et.al* 2021, Apple, 2020, 2022)

Specification Category		**Matterport Pro3**	**Apple iPad Pro LiDAR**
Device Type		Professional Digital-Twin capture (LiDAR focused)	Integrated mobile device LiDAR for AR and depth mapping
Physical Parameters		Portable scanning unit, ~181 × 161.4 × 76 mm, 2.2 kg, external battery (220+ scans)	iPad Pro, 11-inch (249.7 × 177.5 × 5.3 mm), 446 g, built-in sensor
Sensor performance	**Min/Max Range**	~0.5 m to up to 100 m	Scaniverse ~0.2-5 m / effective<4 m
	Depth sensor resolution	~100,000 points/sec ; ~1.5 M pts/scan	2,420 x 1,668 pixel, 264 ppi LiDAR array (~576 points emission)
	Precision	±20 mm @10 m	Approx. ±1 cm
	Frequency	Full scan per ~20 S	Up to 6K/60Hz or up to 4K /120Hz
Laser and Safety Specifications		Class 1 LiDAR, 904 nm wavelength	Solid-state, VCSEL based LiDAR
Scanning LiDAR and beam	**Field of View (FOV)**	360° H / 295° V (full environmental coverage)	Approx. 60° × 48°/ GeoSLAM 360° V/H
	Motion/Scanning Behaviour	Static scan per position (~20 s) with automatic 3D registration	Continuous scanning by handheld motion via ARKit
Output Format		Add-ons order LiDAR in E57 output point cloud: • OBJ (.obj + .mtl + textures), • Point Cloud (.xyz), • Schematic Floor Plan Images (.jpg / .png), • BIM: 3D CAD, 3D Revit • CAD: DWG • Camera Poses (.json), • Metadata (.json)	Depth maps integrated into: • AR meshes formats (FBX, OBJ, GLB, USDZ, and STL). • Point cloud formats such as PLY and LAS. External apps can export meshes/point clouds
Typical Use Context		Large-scale professional scanning and Digital -Twin	AR experiences, preliminary spatial capture, basic room-scale documentati

Specification Category	Matterport Pro3	Apple iPad Pro LiDAR
	creation	on

5. Discussion: Technical Comparison between the Immersive and mobile LiDAR System:

The digitization of Qaitbay Fort discloses several comparative aspects regarding technical suitability of various 3D modelling techniques.

5.1. Technical specification-Pros and cons:

The physical specifications of the Matterport Pro3 (181 × 161.4 × 76 mm, ~2.2 kg) makes it flexible, tripod-based suitable for extended field operation, with a battery capacity (Approx. 2.5 hrs. @ 80% & 3.5 hrs. @ full charge) supporting over 220 consecutive scans per charge (Matterport, 2025). In contrast, the Apple iPad Pro combines a solid-state LiDAR sensor within a lightweight consumer tablet (446 g), emphasizing extreme portability for rapid deployment in risky environments. However, high power consumption makes it more suitable for short duration or opportunistic capture rather than sustained scanning (Apple, 2020).

In terms of sensing performance, the Matterport Pro3 provides a maximum detection range of up to 100 m, with a reported geometric accuracy of ±20 mm at 10 m, and an acquisition rate of ~100,000 points per second, fully supporting large-scale spatial documentation (Matterport, 2025). Conversely, the iPad LiDAR is optimized for near-field depth sensing, with a with an effective range of <4 m and ±1 cm precision only at very close range. Its density, accuracy, and range are significantly lower, reflecting a design focused on augmented reality rather than precise metric surveying (Atencio, E. *et.al,* 2024). On the other hand, depth measurements are generated continuously and integrated in real-time. In addition, density, accuracy, and range are significantly lower and more variable, which specifies the concept of its design focusing on augmented reality and scene comprehension rather than precise metric survey applications (Vacca, 2023 and Spreafico, A. et al., 2021).

Both devices employ Class 1, eye-safe lasers with IEC 60825-1:2014, though the iPad operates via continuous handheld motion (ARKit/SLAM) rather than the Matterport's 360° automated mechanical beam deflection. As a result, the iPad produces a less homogeneous spatial sampling dependent heavily on user movement (Tee-Ann. T. & Chen-Chia Y., 2023; Díaz-Vilariño et al., 2022).

To evaluate the operational readiness of both digitization methods for the Data-Sensorium system, specific computational and perceptual benchmarks must be established. Immersive cyber-physical environments utilizing locomotion interfaces strictly require a rendering speed of ≥ 60 FPS to maintain sensory synchronization and eliminate motion sickness during real-time movement.

When implemented within the Unity-driven Data-Sensorium platform, the raw iPad LiDAR model effortlessly sustained 75–90 FPS due to its heavily simplified, low-density mesh structure. However, this rendering efficiency came at the expense of scale consistency and geometric accuracy, exhibiting a dimensional drift exceeding ±100 mm over extended corridors, which disrupted the physical-to-cyber scaling.

Conversely, the unoptimized Matterport Pro3 mesh initially caused performance drops to 45 FPS due to its massive point density. To satisfy the system's target framework, a polygon decimation pipeline was applied in third-party software, successfully restoring a stable 60 FPS while fully preserving its ± 20 mm metric accuracy and high-fidelity 134.2 MP texture maps. This trade-off confirms that while the iPad offers immediate computational speed and rapid on-site processing, its high missing data ratio (~15–20%) and sparse point density mean only the Matterport data meets the structural, scanning, and visual thresholds required for a true analytical space (Table 3).

Table 3: Quantitative Performance and Evaluation Metrics within the Data-Sensorium Environment

Evaluation Indicator	Data-Sensorium Target Standard	iPad Pro + Scaniverse Performance	Matterport Pro3 Performance	Status / Outcome
Real-time Rendering (FPS)	≥ 60 FPS (Minimum for smooth locomotion)	75 - 90 FPS (Low polygon count, highly optimized mesh)	45 - 60 FPS (Unoptimized high-density mesh; drops below threshold without occlusion culling)	**iPad:** Passes rendering speed but fails fidelity. **Matterport:** Requires mesh optimization/decimation to maintain optimal FPS.
Geometric Accuracy	≤ ± 20 mm deviation for structural analysis	±50 mm to ±120 mm (Significant drift over 5m spans)	±20 mm at 10 m (Stable geometry across vast spaces)	**iPad:** Fails; introduces structural artifacts. **Matterport:** Passes analytical requirements.
Scale Consistency	1:1 Metric alignment (≤ 2% drift error)	High dimensional drift (> 5% accumulation error on long passages)	Strict metric consistency (< 0.5% error across entire fort layout)	**iPad:** Fails; disrupts the locomotion interface scale matching. **Matterport:** Passes.
Texture Quality	Clear mapping at close proximity (≥ 4K texels)	High visual compression, vertex stretching, and texture ambiguity	High-fidelity 134.2 MP HDR panoramic mapping (crisp texturing)	**iPad:** Fails for fine conservation. **Matterport:** Passes for decay detection.
Actual Point Cloud Density	High density for micro-crack extraction (< 10 mm spacing)	Non-uniform; average ~15–25 mm spacing in large halls	Dense and uniform; average ~5–8 mm spacing at 10 m range	**iPad:** Insufficient for micro-architectural analysis. **Matterport:** Passes.
Missing Data / Gaping Ratio	Minimization of gaps (< 5% missing data)	~15–20% missing surface faces (severe gaping in high ceilings/cistern)	< 2% missing data (confined to absolute deep structural shadows)	**iPad:** Fails; high risk of false confidence. **Matterport:** Passes.
Raw Export File Size	Manageable asset pipeline size	Low footprint (~35–50 MB per .OBJ mesh)	Large uncompressed dataset (~4–6 GB total .E57 point cloud)	**iPad:** Ideal for quick web/mobile streaming. **Matterport:** Requires heavy storage/high-spec PC pipelines.
Processing Time	Efficiency vs. Analytical Return trade-off	Near-instant (~3–5 mins automated on-device processing)	Extended pipeline (~20s per static scan station + ~6 hrs PC registration)	**iPad:** Superior for rapid emergency response. **Matterport:** Required for long-term monitoring twins.

5.2. Availability, scientific reliability, and compatibility with the Data-Sensorium:

The selection of digital tools for cultural heritage research should be guided by research intent rather than the mere availability of technologies. Different tools offer distinct levels of accuracy and analytical capacity Tool choice must be compatible with the broader Data-Sensorium environment to ensure ensuring interoperability and long-term usability (Ishibashi, N., *et.al* 2023).

Digitizing cultural heritage at risk requires distinct methodological responses. Climate change significantly intensifies the risks to Qaitbay Fort, with sea-level rise (SLR) threatening inundation, brackish water intrusion, and severe shoreline erosion by 2100 (Figures 21 and 22) (Nadia, K., et al., 2025; Fouad, S. S., et al., 2025; Soliman, M. 2025). In disaster preparedness and post-disaster response scenarios, the iPad Pro (via Scaniverse) offers a highly accessible, quick-response methodology for non-specialists to generate georeferenced, real-time 3D models (Soliman, M. et al., 2025; Teo, T.-A., & Yang, C.-C. 2023) (Figure 23).

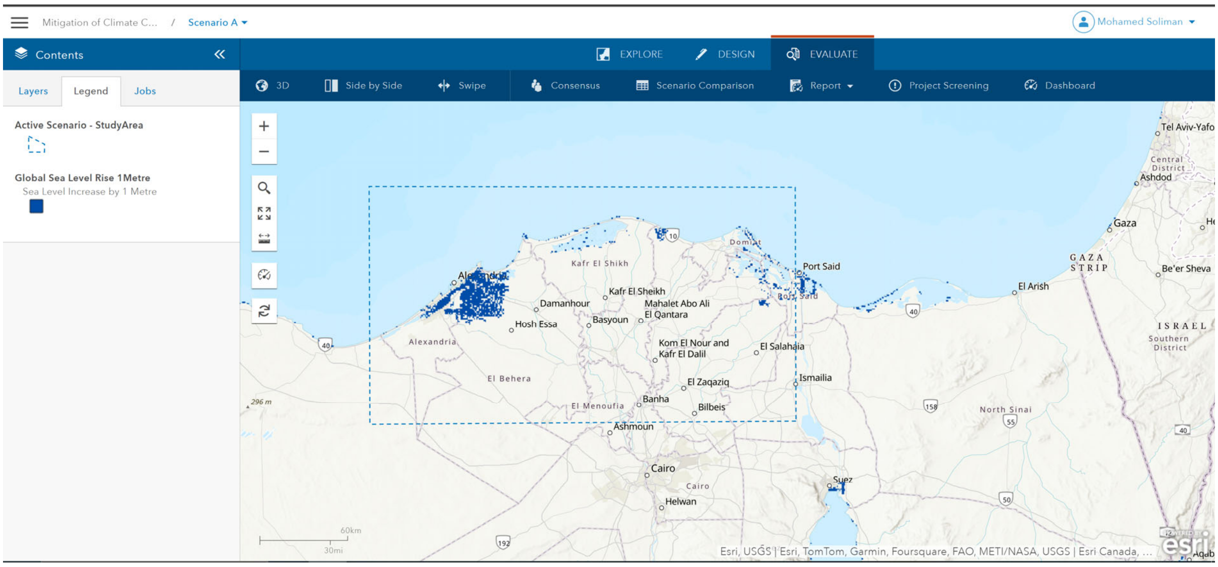


Figure 21: By 2100 Anticipated Sea level rising and water intrusion in Alexandria (Esri, ArcGIS LivingAtlas)

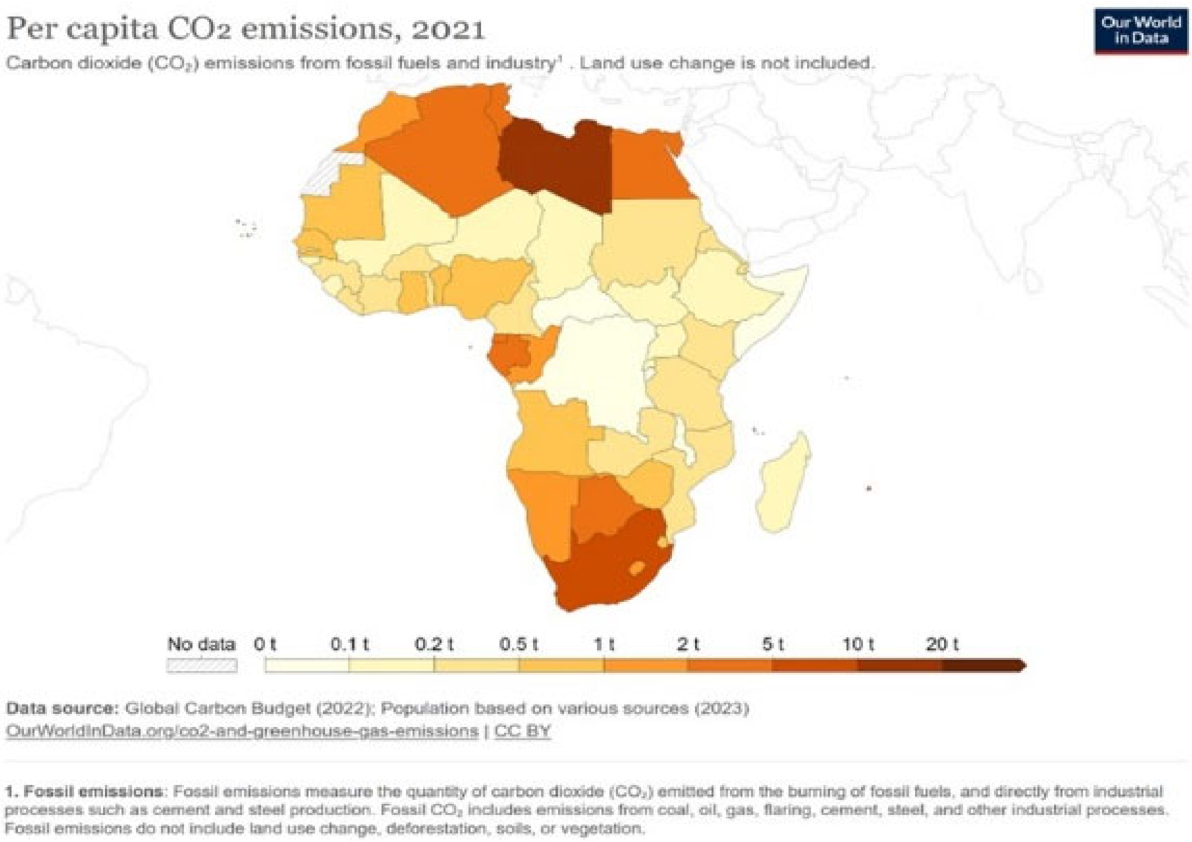


Figure 22: Fossil emissions measures of CO_2 (world bank 2023)

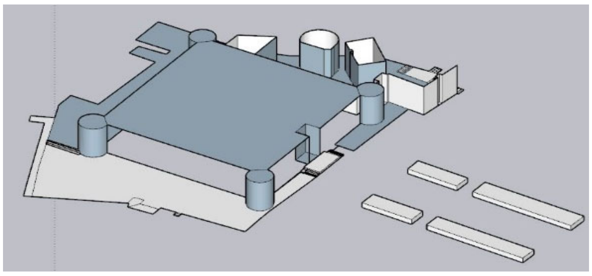


Figure 23: Processing of iPad LiDAR data in SketchUp: 3D perspective of the ground floor of Qaitbay Fort.

Conversely, the advanced accuracy of the Matterport technique is essential for professional conservation projects and comprehensive condition assessments (Tamborrino, R., & Wendrich, W. 2017). It allows for the computational analysis of micro-surface deterioration, such as architectural cracking and capillarity in limestone.

High-quality 3D renderings of tourism promotion enhance effectively the attractiveness of Qaitbay Fort. The Both techniques generate 3D models enhance visitor experiences and virtual offerings can increase tourism revenue, positively affecting local businesses such as hotels, restaurants, and shops, ultimately benefiting the local economy. (Soliman, .M. *et. Al,* 2025)

A Careful balance is required between accessibility and scientific reliability. While widely accessible platforms play a crucial role in public outreach, their scientific value depends on transparent workflows and documented accuracy. Integrating digital tools within a coherent research framework allows heritage professionals to strengthen analytical robustness without compromising scientific standards. (Wang M., 2024)

6. Conclusion

The reliability of 3D modelling techniques has accelerated rapidly. Several techniques can be utilized to digitize cultural heritage for multiple purposes, depending on availability, accessibility, and overarching objectives.

The typical debate between simplicity and precision emerges clearly in the digitization of Qaitbay Fort in Alexandria. As a vulnerable site exposed to seismic hazards and severe climate change impacts (SLR, seawater intrusion), the Digital-Twin of Qaitbay Fort strongly supports SDGs 11.4, 11.3, and 11.b by aiding in risk mitigation and cultural preservation. The digitization of Qaitbay Fort follows the SPA conception (Sensation, Processing, and Actuation). Defining an appropriate 3D modelling technique requires a comprehensive understanding of these three dimensions. A full understanding of the parameters of each technique supports the selection of a 3D modelling tool that is compatible with the project objectives. Availability only is insufficient to define the appropriate 3D modelling technique. Considerations of accessibility to the cultural heritage property, reliability of technical parameters, resolution, precision, and texture quality lead to more effective on-site operation.

Data-Sensorium serves as both a theoretical and operational foundation for integrating immersive spatial interaction with DigitalTtwin technologies to visualize the tangible and intangible cultural heritage of Qaitbay Fort in Alexandria. Data-Sensorium requires highly precise immersive models generated through 3D modelling techniques empowered by Digital-Twin technology. The iPad Pro and Matterport Pro3 are both reliable 3D modelling tools equipped with LiDAR technology. According to the SPA conception, the iPad LiDAR provides a simplified, rapid-response technique suitable for scanning, processing, and acting on Qaitbay Fort as heritage at risk directly on-site. This aligns with disaster preparedness and post-disaster response phases. However, integrating the iPad LiDAR model into the Data-Sensorium system reveals critical limitations regarding resolution, misalignment, and texture ambiguity, making it insufficient for generating a convincing immersive walk-through experience, due to its limited scanning range under5 m. Scaniverse exports models in several formats; OBJ and FBX are the only compatible with the UNITY platform and support integration with the Data-Sensorium system. Third-parties software, such as Agisoft Metashape and Blender, provide precise processing and segmentation. This conception can be extended to the preservation of cultural heritage at risk in countries exposed to armed conflict and vandalism, such as Iraq, Syria, Yemen, and Sudan, alongside regions affected by natural disasters, including earthquakes in Egypt, Japan, Turkey, and Morocco.

In contrast, the Matterport Pro3 produces high-density captures that generate immersive Digital-Twin environments functioning as true analytical spaces, enabling deeper spatial interpretation and informed assessment. Its immersive specifications- including a 360°/295° field of view, expanded point-cloud density up to 100,000 per scan, and an operating range up to 100 m (Table 4)- compensate for limitations related to scale and coverage.

From a conservation perspective, immersive 3D datasets enable monitoring structural stability and fine-conservation analysis of the ongoing conservation project at Qaitbay Fort by facilitating the detection of material surface deterioration.

Overall, the Matterport Pro3 is far more suitable for generating large-scale, metrically reliable Digital-Twin of complex heritage sites like Qaitbay Fort, while iPad LiDAR is best reserved as a quick-response technique for rapid, preliminary depth capture for disaster-response documentation.

Table 4: Quantitative and operational comparison of iPad Pro vs. Matterport Pro3 within the SPA framework for the Qaitbay Fort Digital-Twin.

Feature / Metric	**iPad Pro (LiDAR + Scaniverse)**	**Matterport Pro3**	**Academic/Conservation Implication**
Max Operating Range	< 5 meters (Observed)	Up to 100 meters (Spec)	Limits iPad to localized elements; Matterport handles large-scale structures.
Point Density / Accuracy	Low; visible misalignment on large surfaces	High (up to 100k pts/sec); metrically stable	iPad introduces geometric drift; Matterport ensures structural fidelity.
Texture & Resolution	Moderate; texture ambiguity/stretching	High-resolution 134 MP panoramic imagery	iPad fails for fine-conservation analysis; Matterport allows decay detection.
Workflow Speed	Ultra-rapid, on-site real-time processing	Moderate; requires cloud processing	iPad suits immediate disaster response; Matterport suits analytical archiving.
File Compatibility	OBJ, FBX (Direct to Unity)	Proprietary (Requires export/conversion)	iPad offers faster pipeline integration for Data-Sensorium.

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