European
Commission

Study on quality in 3D digitisation of tangible cultural heritage: mapping parameters, formats, standards, benchmarks, methodologies, and guidelines

VIGIE 2020/654

Final Study Report

Cyprus
University of
Technology

STUDY ON QUALITY IN 3D
DIGITISATION OF TANGIBLE
CULTURAL HERITAGE

“...Πεπαιδευμένου γάρ ἐστιν ἐπὶ τοσοῦτον τἀκριβὲς
ἐπιζητεῖν καθ’ ἕκαστον γένος, ἐφ’ ὅσον ἡ τοῦ πράγματος
φύσις ἐπιδέχεται· παραπλήσιον γὰρ φαίνεται
μαθηματικοῦ τε πιθανολογοῦντος ἀποδέχεσθαι καὶ
ῥητορικὸν ἀποδείξεις ἀπαιτεῖν...”

Αριστοτέλης (384-322 π.χ), Ηθικά Νικομάχεια 1094b 25-27

“...It is the mark of an educated mind to rest satisfied with the degree
of precision which the nature of the subject admits and not to seek
exactness where only an approximation is possible...”

Aristoteles (384-322 B.C), Nikomachian Ethics 1094b 25-27

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1. Preface

This document presents the results of the Study on Quality in 3D Digitisation of Tangible Cultural Heritage – VIGIE 2020/654. This work was based on the combined efforts of the in-house study team in Digital Heritage Research Lab at Cyprus University of Technology and a group of sub-contracted collaborators, together with individual external experts. The results include research inputs from the following institutions and organisations:

CUT	Cyprus University of Technology (main contractor), Cyprus
AUTH	Aristotle University of Thessaloniki, Greece
ARC3D	ArchTron 3D - Vermessungstechnic & Softwareentwicklung, Germany
BC	Bene Construere d.o.o (Ltd), Croatia
HES	Historic Environment Scotland, UK
ICOMOS	International Committee on Monuments and Sites, France
NTUA	National Technical University of Athens, Greece
POLIMI	Politecnico di Milano, Italy
TMO	Time Machine Organisation, Austria
Z+F	Zoller + Fröhlich GmbH, Germany

1.1. Project Tasks

The study was organised according to the following tasks:

Task 1	Addressed the definition and exemplification of different degrees of complexity of tangible CH from the perspective of 3D digitisation processes for movable and immovable CH.
Task 2	Addressed identifying and analysing the parameters that determine quality in 3D digitisation of tangible CH for movable and immovable CH.
Task 3	Identified and analysed existing formats, standards, benchmarks, methodologies, and guidelines relevant to the 3D digitisation of tangible CH.
Task 4	Identified and analysed past or ongoing 3D digitisation projects or existing 3D objects that could serve as benchmarks for 3D digitisation of tangible CH.
Task 5	Linked and mapped the elements identified under Tasks 2-4 to the different potential purposes of tangible CH digitised in 3D.

Further tasks covered project management of the study (**Task 6**) and the dissemination of its work (**Task 7**). A mid-term workshop took place to provide expert validation of the interim findings and a final event was organised to present the results of the study.

2. The Process of Digitising Movable and Immovable Tangible Cultural Heritage

2.1. The state of play

Over the last 20 years, the European Union (EU) has invested more than €1 billion in supporting cultural heritage (CH) institutions and stakeholders (museums, sites, monuments, archives and libraries) to digitise their assets, archive, protect, preserve and make them available for use and re-use in research, innovation and education. The instruments used for this purpose comprised Limited liability company (d.o.o.) the Research Framework Programmes (FP) including FP6[1] (2002-2006), FP7[1] (2007-2013) and H2020[2] (2014-2020), eContent[3] and ContentPlus, the European regional development fund[4] (ERDF), European social fund[5] (ESF) and other programmes.

This investment has driven a unique period for research, innovation, education and intersectorial development across the European CH area, in which organisations of all scales have developed models and methodologies for digitisation. In the global education sector[6], more than 97% of the BA, BSc, MSc and MA courses in digital humanities, digital social sciences and cultural informatics have been developed during the last 20 years, a large number of them offered by tetriary education institutions in the EU. Europeana, Europe’s digital library for CH has become a successful reality, promoting the creation of a strong network of EU national and thematic aggregators and bringing together a multidisciplinary professional and technical CH community to increase innovation, collaboration and the creation of new digital multimedia content.

Alongside this public investment in digitisation, the past fifteen years have seen the emergence of medium to large-scale programmes of 2D and 3D Digitisation led by commercial enterprises, such as Google, or NGOs, such as CyArk and Global Heritage, as well as initiatives, such by Smithsonian institute, the Zamani project in Africa and many others. ICT, in dramatically easing the creation and distribution of content, has generated exponential growth in the production of digital information and data. The digital universe is doubling in size every two years and will grow tenfold in the next years.

Progress in 3D digitisation has significantly improved the accessibility of the unique European CH for research, innovation, education and enjoyment. In fact, digitised 3D CH tangible objects can be used in a number of ways:

- High quality 3D scans and records support archaelogists and engineers in conservation, protection and conditional /structural assessment;
- Data of medium quality for 3D printing are extensively used in creative industry such as the games industry, XR applications and education;
- Low and/or high resolution 3D structures are delivered through online platforms, repositories and infrastructures (such as Sketchfab, Smithsonian3D, 3DHOP, Potree, ScanTheWorld, ATON, ARC/K, Clara.io, Stanford-3D, Morphosource, Exhibit, Mozila, Sayduck, Global-Digital-Heritage, Virtual-Interiors, CFIR.science, KOMPAKKT, GB3D, DarkLab, CyARK, NASA3D, PURE3D, etc.) to facilitate the work of scholars, archaeologists, museologists, historians, architects, engineers, multidisciplinary researchers/experts and students;

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[1] EU FWP6 and FWP7
[2] EU H2020 FWP
[3] eContent and eContentPlus (accessed 2. May, 2021)
[4] European regional development fund (accessed 2. May 2021)
[5] European social fund (accessed 2. May 2021)
[6] Higher Education in digital heritage (accesses 30. July 2021)

- More generaly, 3D data may serve as illustrated records in national Collections Management Systems (such as the EU aggregators), potentially for harvesting by Europeana and/or for use by the creative sector in digital marketing and promotion.

At the same time, unresolved issues remain, concerning aspects that may refer to the digital twin, short and long-term preservation, use/re-use, sustainability, return on investment and long-term cost. Such aspects relate to broader questions on the topics of ***accuracy, complexity*** and ***quality***.

At the time of writing, (July 2021) where no generally accepted framework for specifying the ***level of detail and accuracy*** in digital data acquisition of tangible CH [54-121]. Documentation projects are typically determined on a case-by-case basis, using the many available methods, and often require significant multi- and interdisciplinary cooperation [73-121]. It is also important to consider what needs to be scanned, which is related to the 3D features associated with the object's shape and brings into consideration its internal and external geometry, material, colour and texture, as well as its location [54-85]. Therefore, these features influence the methodology and infrastructure to be used for high quality 2D and 3D capture. In addition to the cost of hardware and associated software, there is also a considerable investment in professional staff and in time dedicated to specialised training [69, 80, 81, 96].

The digital representation of CH tangible objects, structures, and environments is essential for analysis, conservation, interpretation and long-term preservation. Selecting the optimum technology and workflow for the 3D digitisation of tangible movable and immovable CH objects is a complicated procedure and one that requires careful consideration:

If the aim is to achieve high-quality results during the 2D and 3D recording process of CH tangible assets, what are the "standards" needed? How much are they going to cost how long will they take, and will they meet multidisciplinary needs? Are the experise and technology available and reliable? Which formats should be used to record the results, enabling long-term preservation is provided? What kinds of knowledge can be embedded in 3D records and how can models be shared interoperably? Can the quality be objectively defined [1-53]?

Museums, sites and monument owners are increasingly investigating the possibility of outputs in more complex formats, such as high-resolution 3D which can be integrated into special effects workflows for the creative industry (such as in films, games, virtual exhibitions, digital cultural tourism and education, etc.) and for rapid prototyping by manufacturers.

Consequently, the recording of movable and immovable CH generally requires the selection of optimal digitisation technology (hardware and software), which usually concerns requirements for the desired technical specifications, size, complexity, material, texture, location, accessibility and accuracy. A first distinction can be made according to the area covered by the site or the size of the object to be scanned. This could range from a very large territory to any kind of archaeological site to a building or group of buildings to large artefacts in museums or available in publicly accessible areas and to small museum artefacts. For large surface areas, such as monument sites or architectural mapping, a combination of regular topographic surveys, laser scanning and photogrammetric techniques is often used. Several alternative vision techniques for digitising small objects include Structure from Motion[7] (SfM) and Image Matching (IM), silhouettes, structured light, motion shading, texture, and focus/defocus. Overall, careful examination is required to define the best available digitisation options, requiring consideration of aspects such as

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[7] SFM (accessed Jun. 16, 2021).

available human resources and expertise, object size, geometric, radiometric and photometric complexity, construction material, texture, IPR and accessibility.

Therefore, this first section of the study summarises the current state of knowledge and practice about technologies, systems and approaches for the digitisation of tangible CH. It provides a baseline for the further findings of our work.

2.2. Terminology – Accuracy and Precision

To explain the digitisation process, especially when dealing with documentation systems and the associated dimensional data, it is necessary to distinguish between data accuracy, precision and resolution and to determine acceptable margins of error. The more accurate the model is, the more analysis of the heritage artefact/scenario is needed. In terms of geometric measurements and visual assessment, at the time of writing this report this can be done virtually, but has an impact on the the costs of 3D acquisition and processing time.

It was noted during this study that important tems, such as accuracy and precision, are not always used consistenly among academic, business / commercial and policy-making stakeholders [26, 69]. Understanding these terms is particularly important when assessing the results from an active recording system, such as laser scanning. For example, precision and accuracy are two ways in which surveyors think about dimensional error. Although the two terms are frequently used interchangeably to indicate the same thing, they have different definitions - which is a critical consideration in a survey-based project. Accuracy refers to how close a measurement is to the ‘true’ or correct value, whereas precision is how close the repeated measurements are to each other. Precision is independent of accuracy. In an ideal world, the more measurements taken, the better the precision, and therefore the smaller the error [25-26].

Measurements can be both accurate and precise, accurate but not precise, precise but not accurate, or neither of the two. A survey instrument can be accurate (recording a value that is near to the actual value for a measured point) but imprecise (recording different values each time a measurement is taken), or precise (returning similar values each time a measurement is conducted) but inaccurate (because the recorded values returned are not close to the actual value).

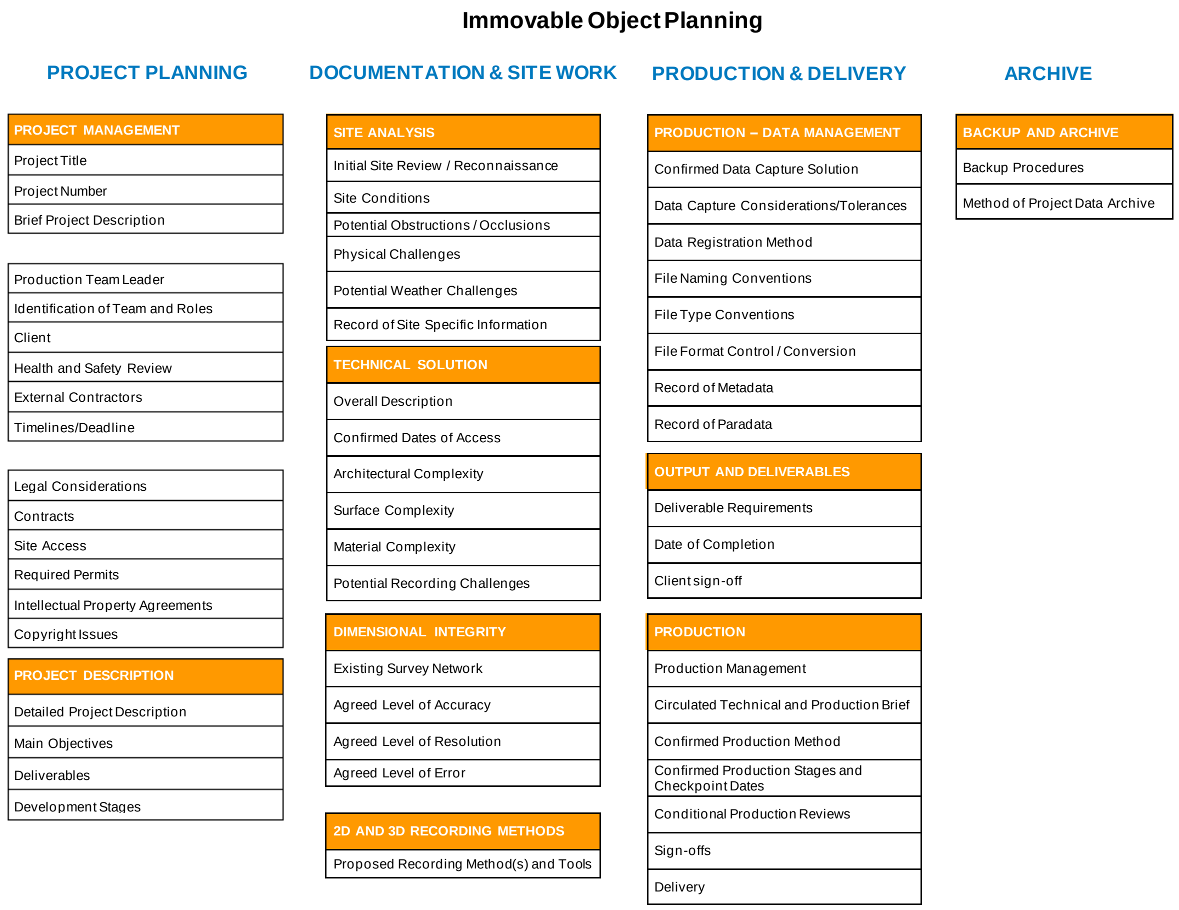
Dimensional survey techniques are required to deliver data that can be verifiably repeated [6-12]. A survey instrument should, in theory, be calibrated, accurate and exact, providing results and measures that are close to the actual value of the measurement and can be repeated with comparable results if the conditions do not change in a significant way. Achieving high precision does not always imply great accuracy because different forms of bias may have been introduced.

In a traditional survey, further refinements to these concepts are also to be made. For example, ‘absolute accuracy’ refers to the accuracy of measurement concerning a particular coordinate system, and ‘relative accuracy’ refers to how well measured points are placed close to one another. A reliable survey instrument is consistent; a valid one is accurate [12, 25, 26, 80, 81].

2.3. Planning the Process of Digitisation

The 3D digitisation of movable and immovable CH is an inherently complex multi-stage process. Not only are there unique documentation challenges for the various movable objects or immovable structures within each organisational category, but the capabilities of the recording hardware, associated processing software, production methods and visualisation systems are continously evolving [6,12, 25, 26, 49, 80, 81].

Project planning should attempt to address the development of a documentation dataset with accuracy and coherence, while keeping in mind project constraints, including, but not limited to, available equipment, budget, and timescale. Before commissioning or undertaking any survey work, it is imperative to understand the expected results, intended outcomes and applications. This informs the survey's specification, methodology, and the quality of deliverables to be generated. A first attempt at detailing the various project planning considerations is shown in Figure 1 (for immovable CH) and Figure 2 (movable CH) below.



Immovable Object Planning

PROJECT PLANNING

PROJECT MANAGEMENT
- Project Title
- Project Number
- Brief Project Description

- Production Team Leader
- Identification of Team and Roles
- Client
- Health and Safety Review
- External Contractors
- Timelines/Deadline

- Legal Considerations
- Contracts
- Site Access
- Required Permits
- Intellectual Property Agreements
- Copyright Issues

PROJECT DESCRIPTION
- Detailed Project Description
- Main Objectives
- Deliverables
- Development Stages

DOCUMENTATION & SITE WORK

SITE ANALYSIS
- Initial Site Review / Reconnaissance
- Site Conditions
- Potential Obstructions / Occlusions
- Physical Challenges
- Potential Weather Challenges
- Record of Site Specific Information

TECHNICAL SOLUTION
- Overall Description
- Confirmed Dates of Access
- Architectural Complexity
- Surface Complexity
- Material Complexity
- Potential Recording Challenges

DIMENSIONAL INTEGRITY
- Existing Survey Network
- Agreed Level of Accuracy
- Agreed Level of Resolution
- Agreed Level of Error

2D AND 3D RECORDING METHODS
- Proposed Recording Method(s) and Tools

PRODUCTION & DELIVERY

PRODUCTION – DATA MANAGEMENT
- Confirmed Data Capture Solution
- Data Capture Considerations/Tolerances
- Data Registration Method
- File Naming Conventions
- File Type Conventions
- File Format Control / Conversion
- Record of Metadata
- Record of Paradata

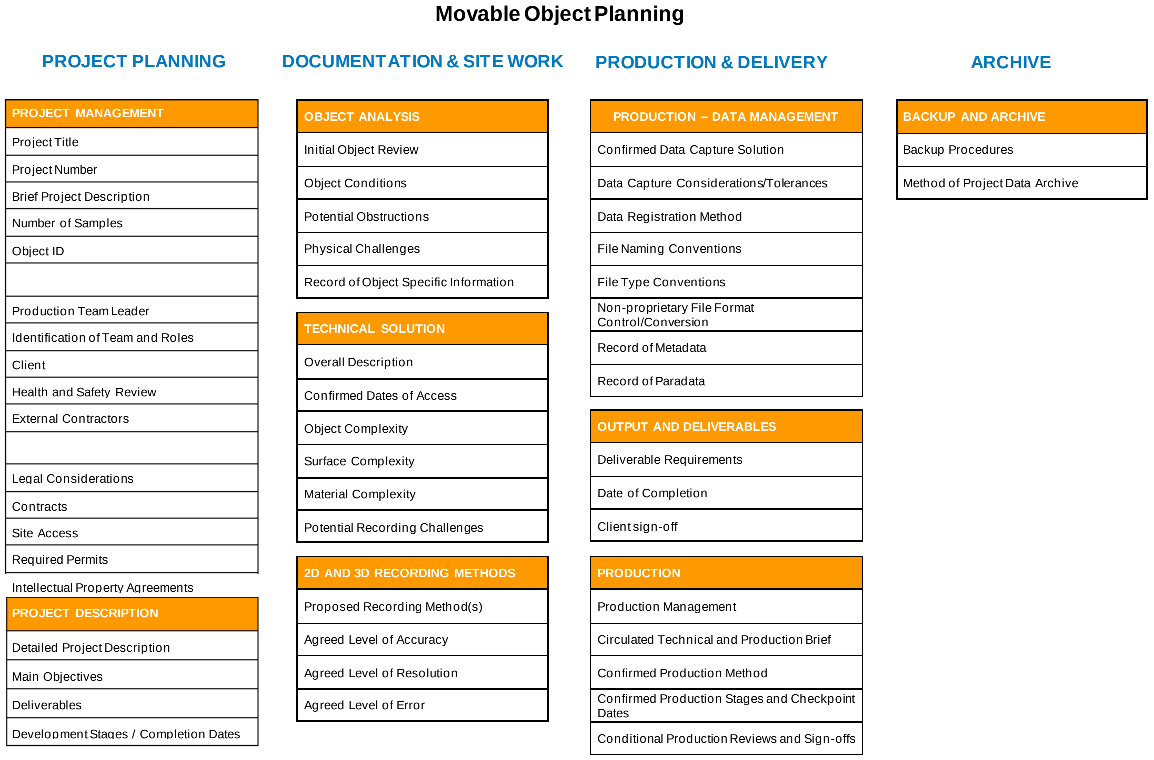
OUTPUT AND DELIVERABLES
- Deliverable Requirements
- Date of Completion
- Client sign-off

PRODUCTION
- Production Management
- Circulated Technical and Production Brief
- Confirmed Production Method
- Confirmed Production Stages and Checkpoint Dates
- Conditional Production Reviews
- Sign-offs
- Delivery

ARCHIVE

BACKUP AND ARCHIVE
- Backup Procedures
- Method of Project Data Archive

Figure 1: Project planning and production stages for immovable digitisation projects as identified at the preliminary approach at the launch of the study.



Movable Object Planning

PROJECT PLANNING

PROJECT MANAGEMENT
- Project Title
- Project Number
- Brief Project Description
- Number of Samples
- Object ID
- Production Team Leader
- Identification of Team and Roles
- Client
- Health and Safety Review
- External Contractors
- Legal Considerations
- Contracts
- Site Access
- Required Permits
- Intellectual Property Agreements

PROJECT DESCRIPTION
- Detailed Project Description
- Main Objectives
- Deliverables
- Development Stages / Completion Dates

DOCUMENTATION & SITE WORK

OBJECT ANALYSIS
- Initial Object Review
- Object Conditions
- Potential Obstructions
- Physical Challenges
- Record of Object Specific Information

TECHNICAL SOLUTION
- Overall Description
- Confirmed Dates of Access
- Object Complexity
- Surface Complexity
- Material Complexity
- Potential Recording Challenges

2D AND 3D RECORDING METHODS
- Proposed Recording Method(s)
- Agreed Level of Accuracy
- Agreed Level of Resolution
- Agreed Level of Error

PRODUCTION & DELIVERY

PRODUCTION – DATA MANAGEMENT
- Confirmed Data Capture Solution
- Data Capture Considerations/Tolerances
- Data Registration Method
- File Naming Conventions
- File Type Conventions
- Non-proprietary File Format Control/Conversion
- Record of Metadata
- Record of Paradata

OUTPUT AND DELIVERABLES
- Deliverable Requirements
- Date of Completion
- Client sign-off

PRODUCTION
- Production Management
- Circulated Technical and Production Brief
- Confirmed Production Method
- Confirmed Production Stages and Checkpoint Dates
- Conditional Production Reviews and Sign-offs

ARCHIVE

BACKUP AND ARCHIVE
- Backup Procedures
- Method of Project Data Archive

Figure 2: Project planning and production stages for movable digitisation projects as identified at the preliminary approach at the launch of the study.

2.4. Documentation Methods

Suitable 3D documentation methods [80, 81] should be determined once the stakeholder and project requirements are defined - in particular the level of detail that needs to be captured. While it is always desirable to capture the best possible detail and resolution, this is a matter of the technologies to be used, the duration of the documentation, the data size, and cost. For each object, the parties involved need to agree on the required level of detail to be achieved. For example, with a sculpture, it might be interesting to look at chisel traces, while when documenting the smooth walls of a building, this level of detail might not be of such relevance [81]. Data size increases with the level of detail. Larger numbers of close-up photographic images of a wall will provide more meaningful information. More data is generated than with a single image, requiring more processing and data storage capacities.

It is, therefore, necessary to establish a level of detail at the outset of any documentation project. The level may be consistent for the entire project or relative to specific features of the project. The selection of technology or technologies, duration of the documentation, data size, data processing, and cost will impact the project’s level of detail, resolution, and accuracy. With time and budget allowing, it may be desirable to capture the highest possible detail, resolution, and precision influencing these selections.

Several measurement methods may be applied to 2D/3D geometric recording. They range from conventional simple topometric methods for partially- or un-controlled surveys, to elaborate ones that use contemporary surveying and photogrammetric techniques for completely-controlled surveys. Simple topometric methods are applied only when the small dimensions and simplicity of the monument may allow for it, when an uncontrolled survey is adequate, or when a minor sale completion of the fully controlled methods is required. 3D coordinates of large-scale outdoor scenes can be calculated indirectly using Global Navigation Satellite Systems[8] (GNSS). Such measurements are accurate to the order of a

---

[8] What is GNSS? (accessed Jun. 14, 2021).

few centimetres or even better, usually providing a solid network of Ground Control Points (GCPs) [80, 81].

Surveying and photogrammetric methods are based on direct measurements of lengths and angles, either on the monument or on images. They determine three-dimensional point coordinates in a standard reference system and ensure uniform and specified accuracy (25,26,78,79), also providing adaptability, flexibility, speed, security, and efficiency. Overall, they have undisputed financial merits, in the sense that they are the only methods that reliably meet any requirements with the least possible total cost and the most significant total profit. To this measurement group belong laser scanners such as **laser imaging, detection, and ranging**, both aerial[9] (LiDAR) and terrestrial[10] (TLS). They are able to collect 3D points (a point cloud) in a minimal time frame [25, 26].

However, It should be stressed that since, to date, there is no generally accepted framework for specifying the level of detail and the accuracy requirements for the various kinds of geometric recording of monuments, every single monument is geometrically documented based on the accuracy and cost specifications supplied or agreed to by the owner or stakeholder [1-114].

At the time of writing this report (July 2021), there are many available methods for this purpose, none of which can be considered obsolete. All can contribute something to the final product [25, 26]. This means that disciplines involved in a tangible CH 3D data acquisition project need to cooperate closely, exchange ideas, and formulate common geometric documentation requirements as part of gaining a deep understanding of the movable and/or immovable asset under consideration.

Boehler & Heinz [71] first attempted to illustrate the implementation range of the different methods available, as shown in Figure 3. Today their diagram should be adapted to include newly developed methodologies. In it, the implementation range of each technique in the 3D recording is illustrated in terms of both the number of points per object (y-axis) and object size (x-axis). More traditional methods include hand and tactile measurements, which are helpful for capturing essential details or small objects especially in museums. Geodetic and tachymetric measurements - the ones obtained by using an electronic total station - although accurate, can only record a limited number of points at long range.

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[9] LiDAR (accessed Jun. 14, 2021).

[10] Terrestrial Laser Scanning (accessed Jun. 14, 2021).

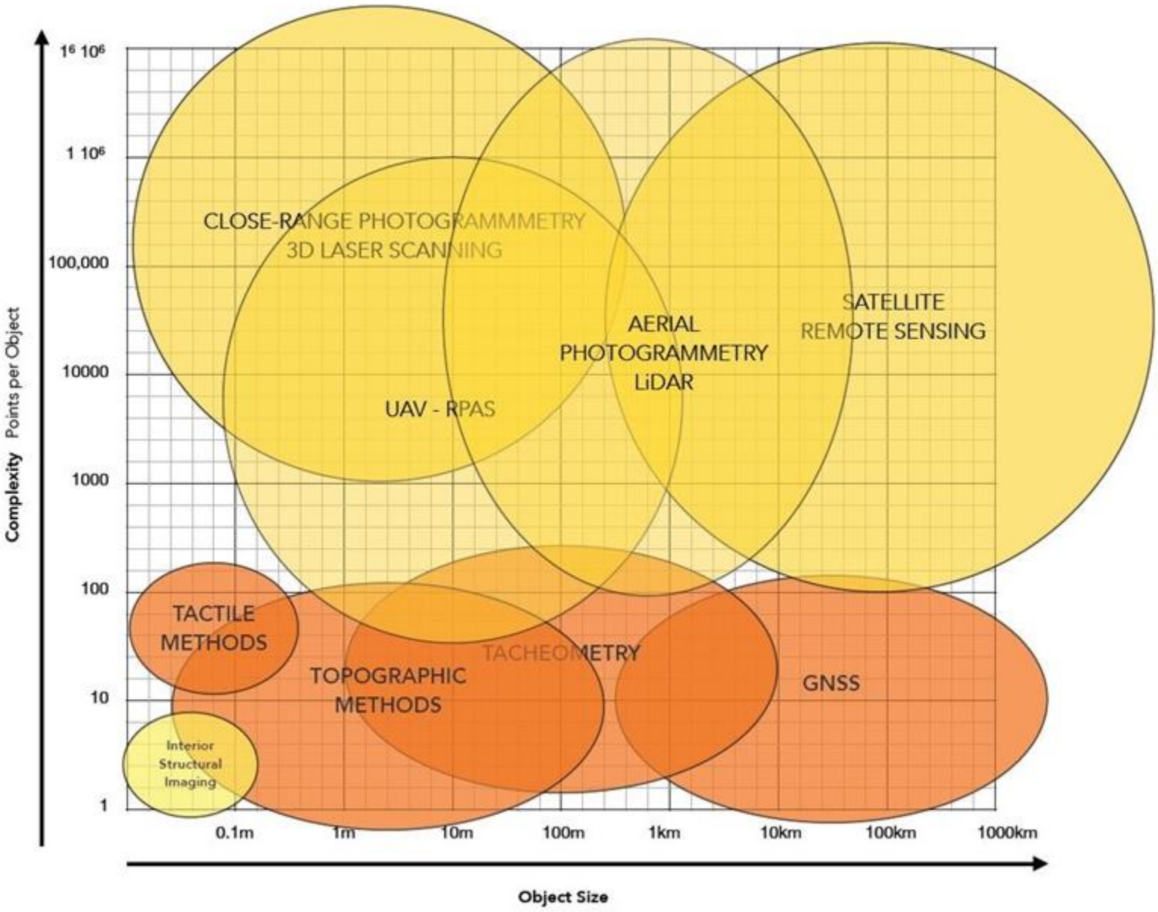

Figure 3: Survey techniques defined by object complexity (points captured) and size. © Adapted from Boehler & Heinz (1999) [71]. © UNESCO Chair on Digital Cultural Heritage at CUT.

For the 3D geometric documentation of movable and immovable assets, the range of object sizes could start from a few mm and go up to a couple of thousand metres, while the number of acquired points and images should practically have no limit. Documentation methods may be grouped in several ways. Firstly, according to those involving light recording (orange areas in Figure 3) and those that do not (yellow areas).

However, the available data acquisition technologies can be classified depending on their principle. Photogrammetry[11], terrestrial or aerial, is an image-based methodology for massive point acquisition at a considerable range. Laser scanning, terrestrial or airborne, allows for enormous point acquisition.

In any case a form of radiating energy is always used for gathering geometrical and visual information, therefore a first distinction can be made between penetrating and non-penetrating radiation systems.

The penetrating category systems are based on similar X-Ray[12] devices used and well known in medical applications, mechanical (aeronautical) engineering, airport security and detailed investigations by police and customs services (Figure 4). They allow the capture of inaccessible internal structures and surfaces of small objects (see also 2.5).

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[11] Photogrammetry (accessed Jul. 28, 2021).

[12] X-Ray (accessed Jun. 11, 2021).

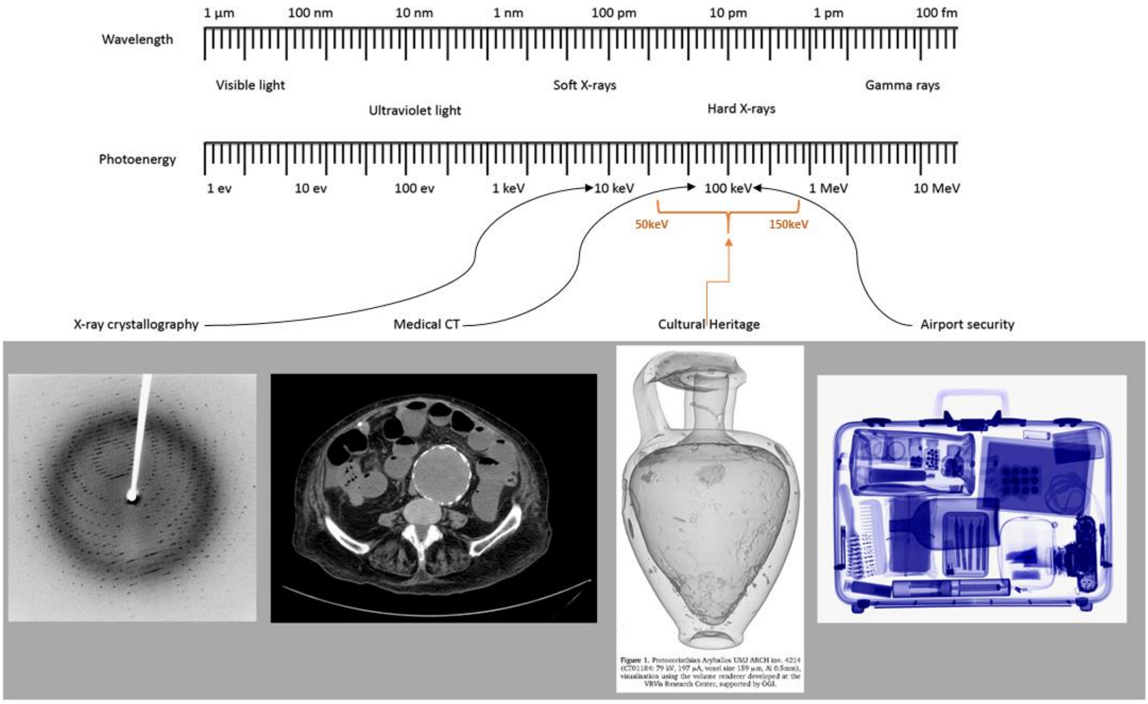

Figure 4: X-Ray analysis in the area of Cultural Heritage

InfraRed[13] thermography for non-destructive testing and evaluation aims at the detection of sub-surface features (i.e. sub-surface defects, anomalies, etc.), owing to temperature differences observed on the investigated surface during the digitisation by an infrared camera. In temperatures of practical interest, all bodies emit electromagnetic radiation that can be readily used for quantitative measurements. Infrared thermography or thermal imaging is a measurement technique based on the detection of radiation in the infrared spectrum (usually in the 2–5.6 μm and 8–14 μm regions). These two spectral bands are commonly used, because of their low atmosphere absorption. The principal problem as far as infrared measurements are concerned is the emissivity of the material(s). An infrared camera detects and records the radiation emitted by a material under investigation and renders this energy to a temperature – thermal image. In this process, the main characteristic that describes the relation between the emitted radiation and the material's temperature, is termed as emissivity. Emissivity is actually a surface property that characterises the ability of the investigated material to emit energy [65].

For non-penetrating 3D digitisation, the electromagnetic energy that is essentially used covers the visible and the InfraRed[13] spectrum. The latter may actually allow for a little penetration under the illuminated surface depending on the actual wavelength used, ranging from fractions of a millimetre for Near InfraRed, to several millimetres for the Far InfraRed, used in so-called TeraHertz imaging[14]. That is also one of the main limitations of the technique.

On the other hand, an advantage of thermography over destructive testing techniques is that large areas can be scanned fast and without being destroyed during testing (Figure 5: Overview of Infrared technologies for different investigations and Data Acquisition This results in major savings in time, people, work and machinery. In addition, infrared thermography has advantages over the other non-destructive techniques. The infrared

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[13] Infrared (accessed Jun. 10, 2021).
[14] Terahertz non-destructive evaluation (accessed Jun. 10, 2021).

thermographic device is risk-free, as it does not emit any radiation and only records the infrared radiation emitted from the material that is under assessment. Moreover, infrared thermography is an area-investigating technique, whereas most of the other non-destructive methods are either point- or line-testing methods. Furthermore, thermographic testing may be performed during the hours of both day and night [65].

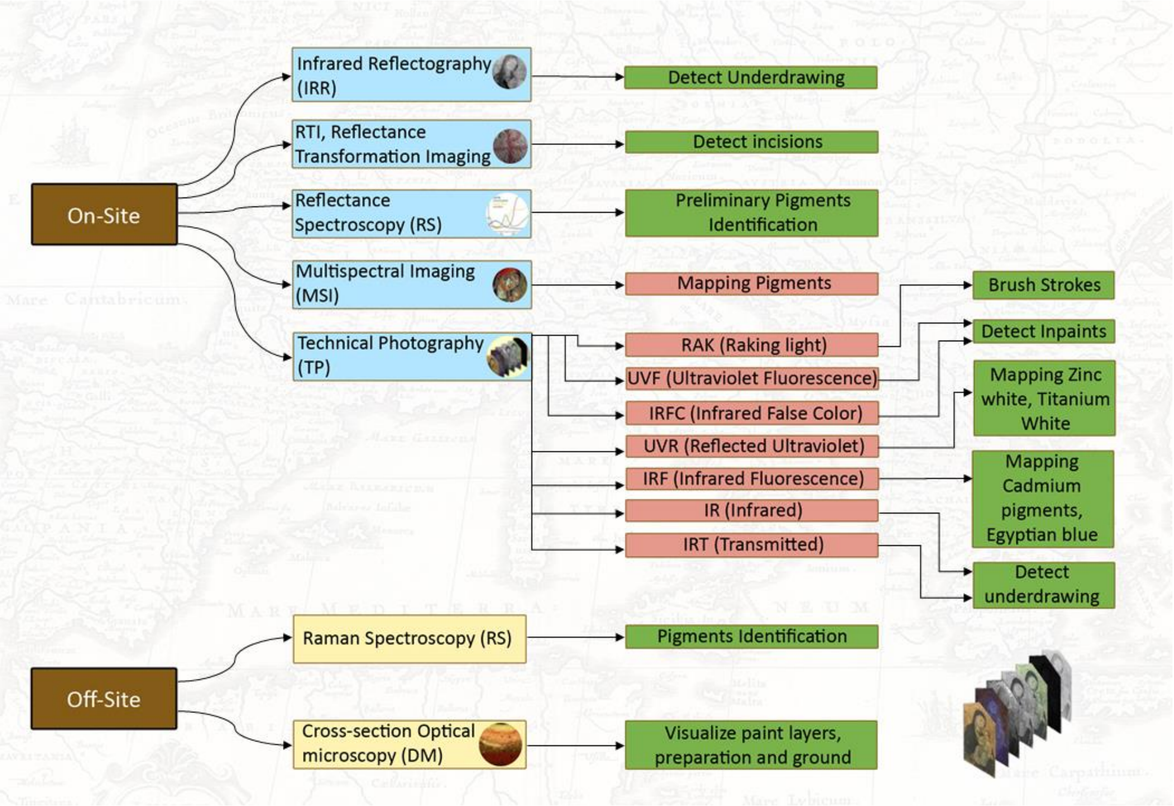

Figure 5: Overview of Infrared technologies for different investigations and Data Acquisition in Cultural Heritage. © Adapted from chsopensource.org

Finally, environmental conditions (e.g. cloud cover, solar radiation, wind speed) also play an important role in outdoor infrared thermographic surveys utilising passive recording approaches, when working on monuments, sites and artefacts exhibited in open areas.

Within non-penetrating devices a further distinction should be made between active and passive 3D data acquisition methods.

2.5. Active and Passive Recording Categories

In general, there are two types of recording methods, **active** and **passive** ones. Active recording methods use directed radiant energy to mark a point in space, whereas passive methods record the reflected radiation from a surface. Active sensors are typically terrestrial laser scanners (TLS), structured light scanning (SLS) systems and range cameras. Passive or image-based documentation systems include (*cameras*) aerial photogrammetry (satellites, aircraft, and UAVs), terrestrial photogrammetry, and close-range photogrammetry. These systems capture the surface geometry of an object as well as the surface texture [67, 107].

A multi-view 3D reconstruction is another process for generating a 3D point cloud (and model) from several overlapping images, using robust automated algorithms. The resulting 3D models are appropriate for metric information extraction for visualisation purposes, for the creative industry and augmented or virtual reality applications. Passive methods include studio image acquisition, uncontrolled environment image acquisition and video frames extraction [25, 26, 80, 81].

2.5.1. Active Recording Systems

Active recording methods use their radiation to record points in space instead of sensing the reflected radiation from another source. These sensors are commonly called range sensors because they can measure the depth, or range of object points. Since they rely on their radiation source, they are independent of scene illumination and can theoretically work in totally dark environments. The most used active sensors in the 3D recording of CH are as follows.

Total Station

The Total Station Theodolite[15] (TST) is a beneficial geodetic survey instrument with near-limitless measuring abilities. Recent advances in Total Station technology such as robotics and GPS integration have increased the efficiency and accuracy of field surveys. A Total Station allows the surveyor to choose individual points to measure, with each shot being made with relatively high precision in angular and distance measurements. Although accurate, this can be tedious and time-consuming if recording numerous individual shots of more complex surface features.

Global Navigation Satellite Systems (GNSS)

3D coordinates of large-scale outdoor scenes can be calculated indirectly using Global Navigation Satellite Systems (GNSS). Such measurements are accurate to the order of a few centimetres or even better, usually providing a solid network of Ground Control Points[16] (GCPs). The performance of GNSS is assessed using four criteria: (1) Accuracy: the difference between a receiver’s measured and real position, speed or time; (2) Integrity: a system’s capacity to provide a threshold of confidence and, in the event of an anomaly in the positioning data, an alarm; (3) Continuity: a system’s ability to function without interruption; (4) Availability: the percentage of time a signal fulfils the above accuracy, integrity and continuity criteria.

Terrestrial Laser Scanning (TLS)

Laser scanners[17] are active range sensors able to produce dense point clouds for an object, recording information for the position (geometrical coordinates: X, Y, Z) of every point along with the intensity of the reflected radiation. TLS is a ground-based version of the airborne LIDAR frequently used for large archaeological sites, terrain and landscape mapping. Terrestrial laser scanners are a relatively recent development for high-resolution mapping, originally developed for as-built modeling of architectural and engineering structures. They can also be used for high-resolution mapping of terrain, vegetation, and other landscape features over limited distances in the range of 50–300 m. Like their airborne counterparts, they are active sensors that emit laser signals to calculate distances based on the time delay of the returned laser pulses [112]. TLS systems range from airborne laser scanning for terrain surface modelling to mid-range terrestrial scanners for data acquisition of facades, entire buildings, ensembles or sites, and to close-range 3D scanners for high-resolution digitisation of movable objects such as archaeological finds, artefacts, and sculptures. ALS (Airborne Laser Scanning) or LiDAR (Light Detection and Ranging), mounted on aircraft or Unmanned Aerial Vehicles[18] (UAVs), have become compact and relatively lightweight [80, 81].

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[15] Total station (accessed Jun. 10, 2021).
[16] Ground Control Points (accessed Jun. 10, 2021).
[17] Laser scanning (accessed Jun. 11, 2021).
[18] Unmanned Aerial Vehicle - UAV (accessed Jun. 11, 2021).

Laser scanners are commonly used in the field of CH digital documentation, as they enable measuring natural or manufactured objects of different sizes, varying from parts of the landscape, buildings and architectural elements down to smaller pieces up to a few decimetres in size. The advantages of using this technology for 3D recording are the very large number of points acquired in each scan in a short time, their high accuracy and density. A large variety of TLS systems are commercially available: time-of-flight, phase-shift, or triangulation scanners. These devices differ in their measurement principle, maximum measuring range, speed (number of points acquired per second), the field of view, resolution, accuracy, weight and cost, among other characteristics [2, 26, 80, 81].

3D laser technology is used for movable and immovable objects, including sensors with time-of-flight, phase difference or triangulation using laser points, fringe, or other projection patterns. Depending on the specific type of LiDAR hardware, laser scanners can record small objects or large terrain areas. High-resolution hand scanning systems can record sub-mm detail on the surface of an object, whereas terrestrial laser scanners are typically used for the documentation of buildings. Unfortunately, at the time of writing this report, there is no single TLS system capable of covering all sizes.

The Historic England guide to laser scanning for archaeological and architectural applications [12, 67] highlights how the process related to the use of TLS technology can be difficult due to occlusions and obstacles in scanning the object(s), which may limit available data if incorrectly addressed. Laser scanners cannot see through solid objects and this can cause problems in sites with excessive amounts of mobile objects blocking the planned capture areas or in locations with elevations or with health and safety considerations, such as evidence of asbestos or sulfur, unsafe buildings, adverse environmental conditions and vegetation that prevent optimal display of the analysed building or site.

The evaluation of the accuracy and precision of measuring equipment is critical in order to achieve results that meet the specifications of a given project. Standard calibration models and field procedures exist for all traditional surveying instruments, but are still lacking for recently developed technologies like terrestrial laser scanners. The main reason is limited knowledge of errors that affect these systems, owing to the proprietary design of the scanners and their software, and the integration of many potential sources of error.

Mobile Laser Scanners (MLS)

Mobile Laser Scanners are also commercially available. Such systems include those equipped with GNSS and Inertial Measurement Unit[19] (IMU) sensors and – often - optical cameras and can be mounted on moving vehicles (cars, floating or airborne platforms etc.) or may even be carried by a person to perform range measurements in continuous or static (stop-and-go) mode. Mobile laser scanning collects geospatial data from a mobile vehicle fitted with LiDAR, cameras and other remote sensors. This mobility can be provided by cars, trains, trucks, manned and unmanned aerial vehicles and boats. It is used in emergency response situations to quickly assess the conditions on the ground, as well as for popular mapping projects such as Google Maps[20] and Street View.[21] Manufacturers now also offer scanners that can be submerged; these underwater scanners use laser beams of advantageous wavelength for propagation in water, giving better results than sonar systems used previously in underwater applications. At the moment of writing this report, their range is short and accuracy relatively low, but MLS is an evolving and promising technology.

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[19] Inertial measurement unit (accessed Jun. 11, 2021).

[20] Google Maps (accessed Jun. 11, 2021).

[21] Google Street View (accessed Jun. 11, 2021).

Structured Light Scanning (SLS) Systems

Structured light scanning[22] (SLS) systems project coded light patterns on the object surface, recording the scene from one or more points of view and thus compute the depth based on the deformation of the pattern on the object's surface using the triangulation principle. Coded patterns facilitate easy correspondence establishment between image points and points on the pattern (pattern decoding), resulting in dense 3D point clouds of the scene. A typical SLS system usually comprises low-cost off-the-shelf hardware, permitting ad-hoc, easy to deploy, and custom-made solutions. One or two digital SLR cameras or machine vision cameras mounted on a rigid base and supporting tripods and an LCD or DLP projector are needed. The whole system is operated through current technology computer software, which undertakes the system calibration, fully controls the data acquisition and signal/data processing and the local or remote storage of data. The distance between the scanner and the CH object, i.e., the base, may vary according to the size, location and condition of the object of interest [54-84].

SLS systems are usually compact, lightweight and easy to implement. They provide high accuracy and dense resolution results, making them a robust alternative to laser scanners or even outperforming them. Among the advantages of the method is its capability to acquire depth information for the entire field of view and not just one point per time, enabling fast and efficient acquisition, as well as faster scan times. The method also produces dense and accurate data, applies all the safety regulations in higher detail levels and is safe for people to use, even to the naked eye.

Optical 3D Triangulation Scanners

Optical triangulation scanners[23] usually consist of a projector and a camera, project a known pattern onto the object, and measure the surface via triangulation methods and the deviation of the pattern from the original. These systems are mostly used in the car and aero industries and can provide sub-millimetre detail but give only a limited field of view and short distances. They are also usually susceptible to the lighting conditions of the environment.

Hybrid Systems

Hybrid systems are optical triangulation scanners and usually consist of a projector and a camera. The system projects a known pattern onto the object and digitises the surface via triangulation methods and the original pattern's deviation. Hybrid systems can likewise provide sub-millimetre detail but give only a limited field of view and at short distances and are usually susceptible to environmental lighting conditions in a lab.

Depth or Range Cameras

The term is broad enough to include a variety of sensors with different working principles. Depth or range cameras are sensing systems (also known as RGB-D cameras) capable of retrieving the depth information of an object almost in real-time. They capture simultaneously the colour and depth values of every pixel of the scene resulting in dense point clouds. The depth value either comes directly from the sensor (ToF cameras) or is calculated from stereo algorithms (passive or active stereo). Time-of-flight cameras acquire 3D information by using near-infrared (NIR) light cast on the object and measuring the time delay between the emission and detection of the light. Passive stereo vision setups are based on the triangulation principle, having a fixed base distance between the two cameras.

Depth cameras are more applicable in indoor scenes for objects at relatively close distances due to their limitations. Several applications on CH objects can be found [25, 26, 80, 81],

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[22] What are the advantages of using a structured-light 3D scanner? (accessed Jun. 11, 2021).
[23] 3D scanning (accessed Jun. 11, 2021).

but problems such as accuracy constraints have restricted their usage to mainly visualisation purposes rather than metric reconstructions.

During mapping applications, Simultaneous Localisation and Mapping (SLAM) algorithms[24] are commonly in use for frame registration, i.e., camera pose estimation and sparse 3D reconstruction. SLAM algorithms calculate the movement of the sensor with a simultaneous reconstruction of the 3D points. The main idea is to use the environmental features (landmarks) to calculate the position of the system in real-time using EKF (Extended Kalman Filtering[25]). A typical SLAM pipeline consists of the following steps: landmark extraction, data association, state estimation, state and landmark update.

2.5.2. Passive Recording Systems

Passive or image-based documentation methods record the light or radiation which originates from an independent source (e.g., the sun or artificial lighting) and is reflected from the object of interest. Image-based techniques process optical images to extract metric information for the object. Especially for CH applications, image data acquisition is usually preferred to other methods because it is efficient, non-intrusive, easily deployable both indoors and outdoors and low-cost.

A big challenge is the development of new smart algorithms in photogrammetric techniques that automate the traditional manual procedures enabling at the same time the usage of any type of camera, thus achieving cost reduction. Computer vision[26] has emerged as the research field that addresses these problems towards automating the work chain and cost minimisation [80, 81].

Compact consumer cameras and free or open-source software can be used to achieve results comparable to traditional techniques or even to outperform them in precision, time consumption and cost. Aerial photogrammetry (using satellites, aircraft, and UAVs as platforms) and close range (terrestrial) photogrammetry are commonly applied to document CH objects since these methods sufficiently capture the geometry along with the texture of an object. The image-based techniques can be divided into single, stereo, or multiple views, according to the number of images they use to retrieve the metric information for the 3D space.

A multi-view 3D reconstruction generates a 3D point cloud (and model) from several overlapping images using robust automated algorithms. At the time of writing this report this is a rich research area of increased interest in computer vision and photogrammetry and a widely used technique due to its time- and cost-effectiveness and the accuracy of its results. The existing Structure from Motion, Multi-View Stereo or dense stereo matching algorithms are robust enough to reconstruct any set of overlapping images in 3D space, if they depict the object scene from various viewing angles, even with unordered sets of random photos taken by different sensors (such as the ones found in Internet repositories[27]). The pre-condition is that the images are overlapping (for high quality results an overlapping factor over 85% is required). The resulting 3D models may be used for metric information extraction, architecture, preservation, visualisation purposes and many other applications, such as augmented or virtual reality. Furthermore, accurate 2D products such as orthoimages and vector plans can be generated.

Suitable 3D documentation methods [80, 81] should be determined once the stakeholder and project requirements are defined - in particular the level of detail that needs to be captured. While it is always desirable to capture the best possible detail and resolution, this

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[24] Simultaneous Localisation and Mapping (SLAM) algorithms (accessed June 12, 2021)
[25] Extended Kalman Filtering (accessed Jun. 12, 2021).
[26] Computer vision and 3D reconstruction (accessed Jun. 11, 2021).
[27] Four Dimensional Cultural Heritage World (accessed Jun. 11, 2021).

is a matter of the technologies to be used, the duration of the documentation, the data size, and cost. For each object, the parties involved need to agree on the required level of detail to be achieved. For example, with a sculpture, it might be interesting to look at chisel traces, while when documenting the smooth walls of a building, this level of detail might not be of such relevance [81]. Therefore. data size increases with the level of detail. Larger numbers of close-up photographic images of a wall will provide more meaningful information. Still more data is generated than with a single image, requiring more processing and data storage capacities.

It is, therefore, necessary to establish a level of detail at the outset of any documentation project. The level may be consistent for the entire project or relative to specific features of the project. The selection of technology or technologies, duration of the documentation, data size, data processing, and cost will impact the project's level of detail, resolution, and accuracy. With time and budget allowing, it may be desirable to capture the highest possible detail, resolution, and precision, influencing these selections. Each SfM technology has individual strengths and weaknesses. It is essential to be aware of the technical background to decide on the most suitable technology for a project.

Aerial Photogrammetry

Aerial photogrammetry[28] includes imagery systems situated within satellites, aircraft, and UAVs. At the time of wroiting this report, it constitutes a vivid research area in computer vision and photogrammetry and is a widely used technique due to its time and cost-effectiveness along with its accurate results. The image-based methods can be divided into single, stereo, or multiple views according to the number of images they use to retrieve the metric information for the 3D space. A multi-view 3D reconstruction generates a 3D point cloud (and model) from several overlapping images, using robust automated algorithms [100, 101].

Photogrammetry

Photogrammetry can be used also for the digitisation of small CH objects, achieving sub-millimetre accuracy and resolution. A wide variety of digital cameras are available for use, equipped with sensors of various functionality and ever-improving resolution capability. The hardware may require custom adaptation for CH objects – involving other imaging principles like panoramic cameras, fisheye systems, catadioptric imaging systems and rotating cameras [80, 81, 96, 99, 100, 101].

2.6. Multi-Sensory and Multi-Spectral Scanning Technologies

The digitisation of CH tangible objects (especially small objects in museums, paintings in art galleries or frescoes and mosaics in monuments and sites) for conservation and analysis consists of a wide palette of methods and techniques offering complementary information. The use of spectroscopic digitisation is important for the determination of material properties, while ultrasonic microscopy is used to obtain structural information of an art object. Combining these methods with imaging produces an information-rich map, where every pixel contains various spectra, image and stratigraphy information.

The techniques to study materials used in CH artefacts and frescoes are significant in understanding and preserving these CH assets. Curators, restorers and conservators routinely use those approaches and exploit information on materials to gain insights about the way an artwork has been made, when it was made, the techniques used, the environmental conditions of preservation, previous conservation interventions and to gather indications for planning future interventions. Materials in CH are studied from many different viewpoints, ranging from the acquisition of basic information, such as surface average

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[28] Aerial survey (accessed Jun. 11, 2021).

colour and roughness, to the analysis of their molecular and elemental components. State-of-the-art study and conservation practices (see also H2020 MSCA CHANGE Project), thus combine a wide variety of measurement probes and analytical techniques. Moreover, to study dynamic processes, such as the effects of aging, weathering, and restoration treatments, laboratory studies are often done on appropriately prepared samples and mock-ups.

Among the various surface and material characterisations, the study of surface appearance, in terms of reflectance and geometric meso- and micro-structure is of particular importance since most cultural information is conveyed through optical signals from the viewed artwork to the human vision system. Characterising surface structure and appearance is thus paramount for a variety of CH applications, from the assessment of the visual effects of restoration treatments, to the high-fidelity virtual and physical replication of cultural objects through graphics and fabrication.

Multi-light reflectance acquisition and processing techniques, such as Polynomial Texture Maps (PTM), Reflectance Transformation Imaging (RTI) and Photometric Stereo (PS) aim to visually characterise objects by observing them from a fixed point of view under different lighting conditions - an important issue in the impact of complexity in data acquisition. At the time of writing this report, they are emerging as a de-facto standard in appearance and geometry acquisition due to their cost-effectiveness and flexibility. Their range of application goes from qualitative estimation of image formation models, for applications such as visual enhancement or relighting, to the quantitative recovery of shape and material properties. While RTI and related techniques are mostly applied in the visible spectrum, increased effectiveness is being achieved in combining them with analysing visible and invisible optical properties of artworks, e.g., through multispectral imaging (MSI) - which is routinely employed to study material composition (mixture of pigments) and under-drawings.

While 3D surface analysis aids understanding of surface material deterioration over time, the status of internal 3D structures ensures stability of the statue, building, or other CH tangible object over time.

Table 1 below summarises the advantages and disadvantages of various recording technologies.

Table 1: Advantages and disadvantages of various recording technologies.

TECHNOLOGIES	ADVANTAGES	DISADVANTAGES
Tactile-Architectural survey	Low-level instrumentation and processing Low experience Low accuracy Quick	Requires an accurate reference frame (topography – photogrammetry) Mainly suitable only for objects of limited extent (e.g., interior spaces, excavation holes) and of low complexity Requires a long time for fieldwork Point-wise mapping, no texture mapping
Topographic surveys	High accuracy Homogeneous overall accuracy Scientific indicators for quality assurance Suitable for plans cross-sections	Mainly good only for objects of low complexity, otherwise not cost/time effective Requires more time fieldwork than photogrammetry Point-wise mapping, no texture mapping
Photogrammetry	High accuracy Homogeneous overall accuracy Scientific indicators for quality assurance 3D and texture mapping Requires less time for fieldwork	Use in close-range, terrestrial, low-altitude/UAV, aerial, or stereo-satellite mode Requires an accurate reference frame LA large amount of data to handle
Laser Scanning	High accuracy 3D and texture mapping Suitable for complex continuous surfaces Good for surface analysis and visualisation	Edges cannot be extracted Line drawings cannot be derived Massive amount of data to handle Requires an accurate reference frame
Satellite Remote Sensing	Cost-effective for large areas 3D and texture mapping	Low to Medium resolutions and related accuracies Extensive experience and infrastructure Require an accurate reference frame

2.7. Indoor and Uncontrolled Acquisition

Studio Image Acquisition

Indoor acquisition, usually for objects or artefacts in museums or collections, such as paintings, pottery or sculptures - typically small (up to a few centimeters) or medium size (up to a couple of metres) - requires “mm” accuracy. Indoor image acquisition presents several difficulties because of special stakeholder permissions, illumination conditions and the properties of the artefacts themselves (size, complexity, surface, colour, reflectance, material etc.). For in-studio acquisition campaigns, special equipment, tripods and distant triggers are commonly adopted to achieve optimal results [94-97].

Video Frames Extraction

This includes cases in which images are extracted from video sequences (max. 30 images/sec) as single frames. Video data sets can be practical in some cases due to the enormous amount of data produced and the extensive overlap between the frames, despite their lower quality compared to regular images.

2.8. Outdoor Acquisition

Accessibility

Physical access may be limited by the environment, requirement for special skills of the survey operators, special equipment, need for permits or certifications, or physical barriers (for example in underwater or cave missions). Operating hours can be limited to a specific daytime period because of the potential necessary illumination and temperature. Changing lighting conditions may also influence the appearance of the output and the data quality. Operational time might also be limited by the local authorities (which must be considered during project planning). Other factors affect data quality during the survey and should be taken into account, for example the material firmness of the recording platform and the survey tripod's placement and stability.

Uncontrolled Environment Image Acquisition refers to typical outdoor scenes or any other environment where the conditions (shadows, illumination, weather etc.) are not under complete control. Large scale objects such as buildings, structures, excavations, or archaeological sites still with high accuracy demands (mm-cm) are classified in this category. Image acquisition may be handheld or use various terrestrial and aerial platforms such as different types of vehicles, stands/tripoids and UAVs

Object/site Recording

Depending on the geometric dimensions and complexity of an object, building interior or exterior, the position of the recording device is likely to require several locations or setups, noting that the more articulated the surface, the greater the need for more documentation position points. The acquired data from each scanner device position point is then aligned to register the data. Registration is possible if a significant amount of the point cloud data shares coincidental features. The more these features are spread across the point cloud, the greater the accuracy during the registration process. Redundant recording of the same points from several setup positions directly influences the overall project accuracy. The scene's sensitivity to alteration by a survey event (e.g., footprints) may affect the planning and movements on site. Modifications to the location may cause problems with registration when combining datasets from different survey times.

Distance

Although optics may be an issue in digital photogrammetry, the camera's resolution is determined by the number of pixels on the sensor, expressed as "megapixels", indicating how many millions of pixels[29] are recorded in a single image. Depending on the recording system and format, the operator should consider the distance from the sensor's surface. Objects closer to the camera will be recorded at a higher level of detail, whereas objects at a distance have fewer pixels and a lower resolution.

With TLS, the laser beam has a three-dimensional physical extension, and the spot of a laser beam has a specific diameter that increases with distance.

The recording device's positioning requires special awareness of the relation between the sensor's distance to the object and the sensed object's height. When choosing vantage points, the operator must consider the angle of incidence between the recording sensor and the object surface. Steeper slopes will cause a decrease in data quality, especially regarding static spherical instruments.

The physical surface dimensions and object's location in relation to the sensors may limit compatibility with some technologies due to technical specifications (e.g., minimum and

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[29] Pixel (accessed Jul. 14, 2021).

maximum range). Different recording technologies may need to be employed, meaning that integrating other data types into one digital model is required.

Circumstances/Environment

Location, access permits and physical barriers may restrict physical access to a site, and production may be limited to a specific length of daytime due to necessary weather conditions. Changing lighting conditions can also influence the output and data quality, mainly if imagery integration exists. Local authorities might also limit operational time. All these factors require consideration when planning a documentation project. Wind may affect the stability of the sensor setups and erroneous measurements. Light conditions should be constant and of low contrast.

The environmental temperature needs to match the one specified in the operating guidelines of survey instruments and ideally be constant throughout the survey duration. Reduced visibility, such as rain, snow, and fog, may induce artefacts and cause discontinuities in the data. The operator should avoid dynamic surroundings such as visitors, vehicle traffic and animals during the documentation process. Alien objects such as scaffolding, safety nets, trees, and signage may cause a discontinuity in the data. Almost always the term ‘conditions of operations’ denotes external influences on the 2D/3D measuring system. These include for example: temperature and its gradient, humidity, vibrations (mechanical), electromagnetic interference and/or environmmetal lighting conditions.

2.9. State of Condition and Remedy Options

Geometrical Simplicity

Modular geometries may induce ambiguities[30], which can increase the complexity of computation algorithms during the registration process.

Surface Reflectivity

Reflectivity has a direct influence on the ‘noise’ present in the data. A low reflectance means reduction of the sensing signal’s total absorption, causing increased noise levels and even discontinuities in the capturing data. Shiny or highly reflective surfaces can cause an oversaturation of the sensing signal, which leads to decreased accuracy or even wrong measurement. The reflectivity also depends on the wavelength used in the sensing system and is also limited by the incidence angle (mirror effect). Polished finishings generally emphasise the mirroring impact for acute angles to the sensor signal, an important factor to consider when using a laser data acquisition system.

In recent years, cross-polarised photography has emerged within the wider 3D capture community as a recognised way of removing ‘specular’ reflections from surfaces of photographed objects. In principle, this takes care of the negative impact that reflective surfaces have on data processing by eliminating any shine.

Light Transmittance

Translucent material properties induce uncertainties and range measuring errors for optical sensors. Especially glass or mirrors will cause measurement errors, as the sensing signal is refracted or reflected. The adapted technology must be non-destructive for the surveyed object (e.g., avoiding degradation by illuminating). In general, transmittance of the surface of a material is its effectiveness in transmitting radiant energy. It is the fraction of incident electromagnetic power that is transmitted through a sample - in contrast to the transmission

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[30] A Survey of Geometric Analysis in Cultural Heritage

coefficient, which is the ratio of the transmitted to incident electric field. Internal transmittance refers to energy loss by absorption, whereas (total) transmittance is that due to absorption, scattering and reflection.

Surface Characteristics

Most materials have significant limitations for being digitised, depending on their condition. In addittion, whether the object can be physically touched (for logistics) and actively used (e.g., mounting tie-points to the surface) may cause an impact on survey planning and data quality. The stability of the structure and physical firmness during the survey also affects data quality. Moreover, surface cleanliness, obstructions by flora (e.g., moss), fauna residuals (e.g., spider webs) or alien materials (e.g., moisture) may affect the data quality negatively. Often vegetation can also limit the visibility of the object and deliver non accurate measurements.

2.10. Derived Project Data

The data quality and project complexity topics are interlinked and not easy to separate, as discussed elsewhere in this study. If higher data quality is required, the complexity of the project increases. For example, higher resolution scans or photos must be acquired if more detail is needed. The following are parameters often used to measure or determine data quality. These parameters are applicable to geometry data and additional layers, such as RGB colour, infrared, or other coatings.

Resolution

Digitisation is a discrete method to obtain a digital approximation of the exterior and interior surfaces of a tangible CH asset. The higher the resolution is during acquisition, the better the original will be represented. When choosing the correct resolution, it should be twice as acceptable as the required smallest detail.

Distance to the Object – Image Scale

The resolution varies with distance. If a resolution is set that samples the object taking points every 5 mm on 10 m distance, surfaces at 100 m will be tested with a resolution of 50 mm, while at 1 m, this will be 0.5 mm.

Angle of Incidence

The resolution of the data varies also with the angle of surface incidence. The flatter the rise, the more coarse the resolution of the data. It is preferable to have a straight view of the object. A direct, perpendicular view will help to guarantee the best detail. Most laser scanners have an ideal capture distance based on the physics of the optical system. This is important in the field of photogrammetry, as well as in 3D digitisation.

Safety Regulations

Various data acquisition equipments require regulated use, e.g., laser-based equipment, such as the terrestrial laser scanner, may involve limitations for the operator, the public, and others (e.g., use of barriers, protection lenses), which affect data contents. It is essential to understand safety regulations and Laser Class restrictions[31].

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[31] Laser Class restrictions (accessed Jun. 13, 2021).

3. Defining Complexity

The complexity of CH objects and 3D data has been the subject of studies since ancient times and continues to be of research interest today. The challenge of defining complexity has been explored in several recent EU projects and actions, of which a few were the FP6 Network of Excellence EPOCH[32], the FP7 Integrated project 3D-Coform[33], the EU COST Action C5 Urban Heritage – Building Maintenance solutions[34], and the FP6 Coordination and Support Action EU CHIC (European Cultural Heritage Identity Card)[35]. Additionally, significant understandings have been gained from the H2020 project INCEPTION (Inclusive Cultural Heritage in Europe through 3D semantic modelling)[36], the H2020 project PARTHENOS[37] the H2020 project Scan4Reco[38], the FP7 project 3D-ICONS[39], the FP7 project CARARE[40] and the FP7 Marie S. Curie Fellowship project ITN-DCH[41].

A general description of the term complexity is “the state or quality of being intricate or complicated”, or “the state of having many parts and being difficult to understand”. Consequently, complexity characterises a system’s behaviour or an object whose components or elements interact in multiple ways and sometimes follow local rules, meaning there is no reasonable higher instruction to define the various possible interactions. This has led further to the proposal [51] of two-forms of complexity: disorganised complexity and organised complexity; many researchers distinguish between them, depending on whether the multiple elements of the object follow specific patterns or not. Complexity is, however, an abstract term that has variable meanings in different contexts, for example, computational complexity[42], Kolmogorov complexity[43], complexity of adaptive systems and so on.

The number of hits obtained by searching for ‘complexity in 3D’ using Google’s search engine (taken as a proxy of overall diffusion of the concept) was 157,000,000, and in Google Scholar (taken as a proxy of academic interest) 2,480,000. According to Google Trends (Figure 6), there is an almost constant use of the term ‘complexity’. Therefore, it is not surprising that it quite often used by the multidisciplinary community in CH documentation literature and practice [54-84].

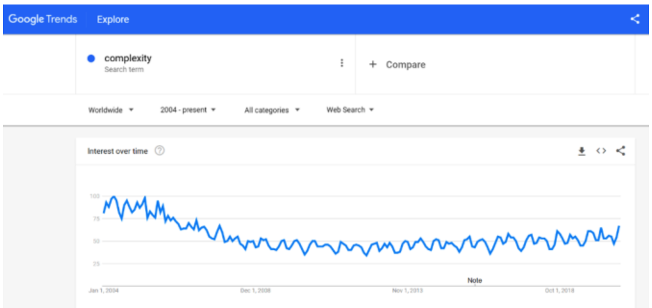

Figure 6: Screen capture from Google Trends for the term ‘complexity.’

If a problem is considered complex, it has many interwoven components that affect one another. Something that is regarded as ‘complicated’, on the other hand, mainly suggests

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[32] Excellence in Processing Open Cultural Heritage (accessed Jun. 12, 2021).
[33] Tools and Expertise for 3D Collection Formation (accessed Jun. 12, 2021).
[34] COST Action C5 Urban heritage – Building maintenance (accessed Jun. 12, 2021).
[35] European Cultural Heritage Identity Card (accessed Jun. 12, 2021).
[36] Inclusive Cultural Heritage in Europe through 3D Semantic Modelling (accessed Jun. 12, 2021).
[37] PARTHENOS (accessed May. 9, 2021).
[38] Scan4Reco (accessed Jan. 13, 2021).
[39] 3D-ICONS (accessed Jan. 13, 2021).
[40] Connecting ARchaeology and ARchitecture in Europeana CARARE (accessed Jan. 13, 2021).
[41] Initial Training Networks for Digital Cultural Heritage (accessed Jun. 12, 2021).
[42] Computational complexity (accessed Jun. 24, 2021).
[43] Kolmogorov complexity (accessed Jun. 24, 2021).

that is difficult and time-consuming. However, from the Study's online questionnaire results as well as from interviews conducted, it was clear that the words 'complex' and 'complicated' are frequently used in the CH domain of work without a clear distinction.

Complexity is a quality inherent in CH artefacts, monuments and sites, and a critical consideration when planning a geometric documentation project. As an evaluation method to determine the scope of a project, how can the complexity of heritage objects, movable or immovable, be better defined and made easily understandable?

Defining object complexity is essential because:

- The level of difficulty - or how challenging the data acquisition is - will determine to a high degree the technology and equipment to be used for a documentation project and the expertise needed to deploy them.
- Complexity is the missing connection between quality and the purpose of use. For example, at the time of writing this report, it would be inefficient, to use a UAV system to map a sizeable archaeological site or a large urban conservation area - an aerial or satellite system would be more practical.
- Complexity imposes constraints on both the technology and the eventual intended use of the data. For example, in case of surface transparency, photogrammetry is ineffective, whereas a TLS's beam can travel through the glass or translucent surfaces of an artefact.
- Complexity during digitisation connects the stakeholder's requirements, quality, accuracy, expertise available and completeness, where it enables expression of specific parameters like object size and random requirements.
- Elaborate interiors call for a fusion of technologies, utilising the benefits of each one. Simultaneously, multiple resolutions and accuracy requirements are often dictated by various uses of the same 3D acquired material.

A definition of complexity in 3D digitisation should apply to both movable and immovable objects, refer to geometric, surface/texture and material complexity and be scale/application-variant. Complexity does not reside in the geometry of a 3D model or the final number of points and vertices, but derives from the stakeholder requirements, its location and state of condition. Also highly relevant are the set-up of data acquisition, know-how of the operators in place and the integration of multiple datasets from different devices into one archive that can be visualised in an easily accessible and searchable way to retrieve and communicate knowledge. A difficulty may occur in gaining a sufficient end-user/stakeholder definition of complexity to establish equipment needs and acquisition methodology – and in client comprehension of additional costs in complex processes and post-processing.

A definition proposed [51, 100-105, 196] for tangible object complexity as a property is:

- Containing multiple parts;
- Possessing several connections between the parts;
- Exhibiting dynamic interactions between the parts and the behaviour produced from those interactions cannot be explained as the parts' simple sum.

A comprehensive understanding of object complexity is crucial, since it has a high impact on various aspects of 3D digitisation, although it may now be an overused term (see also 3.2). The term suggests different technologies to be used and directly reflects on the required results or achievable quality, and/or whether a data acquistition project can be implemented. It may limit the intended purpose of use and impacts the time and budget of a dimensional survey.[44]

However, the use of the term has remained vague in the multidisciplinary community and lacks clear definition, a subjective methodology of calculating, and evident connections and mathematical relation to quality, purpose-of-use or other imposed restrictions.There is thus a gap in the collective understanding of ‘object complexity’ as a decision support tool.

The purpose of a definition is to clarify a concept, ideally leading to a productive decision-making workflow and opening the horizon for standardisation. However, object complexity as a value can be defined only after all the measurements of the object are known, meaning it is not useful for 3D digitisation planning and decision-making. Being neutral to the intended use, it is rendered impractical for choosing the best technology or setting up the technical specifications for 3D digitisation.

For example, a model produced for a detailed 3D digitisation of 3m statues with a complicated marble surface,will be seen on a computer screen at a maximum of 3× zoom factor and a maximum scale of 1:50 of the original statue. This translates into a model with a dimension of 6 cm (= 3 m × 1:50 scale), which can be zoomed by a factor of 3 (thus, the final model should be seen in full detail corresponding to a virtual object of size 18 cm (= 6 cm × 3). This should be examined seamlessly at an average viewing distance, which corresponds to a typical optical resolution of 0.2 mm or 200 µm – dividing the maximum dimension of 18 cm by this resolution. We end up with 9,000 surface-defining triangles of a max size of 200 micrometres each as the model fidelity defined as fit-for-purpose.

Returning to the original physical object, if the modelling process degrades the fidelity of the initial measurements by a relaxation factor of, for instance, $\lambda = 2$, the actual measurements are smoothened and generalised through the modelling phase to lose half of their original accuracy of representation. In this case, to make sure that the final model keeps its intended characteristics, we need to create initial measurements twice as accurate as the model specifications, i.e., requiring 18,000 triangles to describe the object surface. Dividing the object dimension (3 m) by the number of triangles (18,000), we end up with a resolution (or max size of the triangle side) of 1.67 cm for the 3D digitisation measurements.

The conclusion is that no matter what the complexity of the original object is, details or measurement errors lower than 1.50 cm on the object surface will not be seen. This is the actual complexity that matters. According to this, the use of the optimum technology and the recording strategy can be planned.

It follows that any definition of object complexity should have the following characteristics:

- Estimated before the data acquisition phase;
- Calculated objectively;
- Refers to both 3D data capture and data processing/modelling;
- Provides alerts and limits to recording and processing phases;
- Connects to quality, technology, the purpose of use;
- Provides the basis of a meaningful tool for planning both the data acquisition and the 3D modelling processes;
- Enables a clear understanding about the requirements, conditions and parameters in place during data acquisition.

3.1. Uncertainty

At the end of last century and at the beginning of the first digital revolution during the 1980s/90s, along with industrial automation (GPS navigation, manufacturing, car-, aircraft production, shipping, etc), organisations around the world, recognising the challenges and

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[44] Object Complexity vs. Model Complexity (accessed Jun. 24, 2021).

lack of international consensus on the expression of uncertainty in measurement, started to work together with the world's highest authority in metrology, the Comité International des Poids et Mesures[45] (CIPM) in order to address the missing definition. They requested the Bureau International des Poids et Mesures[45] (BIPM) to brainstorm, discuss and address the problem in conjunction with the national standards authorities and to make the first recommendation, which was verified in 2008 and has since been modified several times.

In many industrial as well as commercial applications (especially in the area of health and human safety, where digitisation/measurement belongs to the state of the art of diagnosis and finding), it is often necessary to provide an interval of error about the result. This may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the quantity, subject to measurement. Thus, the ideal method for evaluating and expressing uncertainty in measurement should be capable of readily providing such an interval (+/-), in particular, one with a coverage probability or level of confidence that corresponds in a realistic way with what has been required by the stakeholder.

According to the Joint Committee for Guides in Metrology (JCGM), the best method for evaluating and expressing the uncertainty of the result of a digitisation/measurement should be universal - the methodology should be appropriate to all kinds of measurements and to all types of parameters used.

The actual quantity used to express uncertainty should be:

- Internally consistent: it should be directly delivered from the components and parameters that contribute to it, as well as independent of how these components are grouped and of the decomposition of the components into subcomponents/parameters;
- Transferable: it should be possible to use directly the uncertainty evaluated for one result as a component in evaluating the uncertainty of another measurement in which the first result is used or to calculate the final uncertainty of the digitisation.

According to the Theory on Measurement for Engineers[46], we define measurement as the assignment of a number to the *measurand*, using special technical means (measuring instruments) and a specified technical procedure.

Our starting point will be a museum object which is characterised by one or more properties, each of a quantitative nature. Consider for example an artefact made by marble and a jewelery made of silver. A complete characterisation of any of these objects demands specific information. We will be interested in a single (one-dimensional) parameter or quantity. For example, we will be interested in:

- the thickness of the artefact measured in a certain position;
- a physical constant termed the specific weight, measured in grams per cubic centimetre of silver by the jewelery.

Therefore, the quantity whose value we want to evaluate in each case is called the measurand (thickness and weight) and the measurement values for our two examples are accordingly 25.6 cm and 4.5 g/cm^3. It is also important to take into account that a measurement has imperfections, which give rise to an error in the final measurement result. Traditionally, an error, which can never be eliminated in the area of digitisation, has two important components, namely, a random and a systematic component. The terms "uncertainty" and "error" should not be confused with one another, or misused. They are not synonyms and they represent completely different concepts. For example an error of the

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[45] Comité International des Poids et Mesures and Bureau International des Poids et Mesures (accessed June 16, 2021)

[46] Theory on Measurement for Engineers (accessed Feb. 22, 2021)

nature of an incorrectly calibrated instrument which has been used in the digitisation of an object, may have caused the uncertainty to be wrong!

Our concern in this study is the expression of uncertainty in the measurement of a well-defined physical quantity: the measurand, which can be characterised by an essentially unique value and is always included in the stakeholder requirements. If our approach (phenomenon of interest) can be expressed and represented only as a distribution of values or is dependent on one or more parameters, such as budget, time, human resources, object characteristics, etc, then the measurands required for its description are the set of quantities describing that distribution or that dependence. It is also applicable to evaluating and expressing the uncertainty associated with the conceptual design and theoretical analysis of test methods of measurement/digitisation (in chemical engineering, in cases of the estimation of material quantities in non-destructive technologies), and complex components of an object.

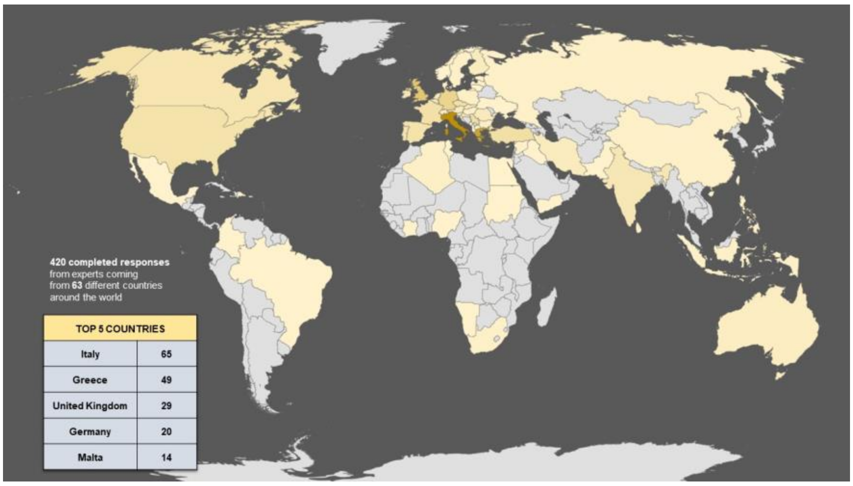
3.2. The Public Survey on Quality

The main objective of the study's questionnaire entitled '*Survey on quality in digitisation of tangible cultural heritage*' was to support the work by collecting data from cross-disciplinary experts in the domain of digital acquisition data, about the use of acquisition technologies, metadata, paradata, and their opinions about the definitions of quality and complexity for 3D. The survey was run online on CUT's LimeSurvey platform in the period 21/10-31/12/2020 (circa 10 weeks). It was advertised through the DHRLab social network profiles (Facebook, Twitter) and through its network of contacts.

The questionnaire consisted of a combination of 40 questions, grouped in four sections:
- sample description
- general overview of techniques and technologies used
- insights from projects
- insights on quality and complexity.

The survey required a minimum of 15 minutes to complete and was scalable in that respondents had the option to describe up to three digitisation projects, answering the same set of questions each time. Respondents were asked about professional background, years of experience, affiliation to relevant organisations and other background information. Data was collected about the most popular acquisition technologies, successful digitisation projects involving immovable and movable objects and specifics uses, limitations and problems associated with technology, metadata and paradata. Open-ended questions also enabled respondents to provide insights on the definitions of quality and complexity. These data have been used to enrich and validate that provided by the experts subcontracted by the study and to support the findings by showcasing best-practice 3D CH digitisation projects.

In total, 944 responses were received from $n = 420$ survey respondents (Figure 7).



TOP 5 COUNTRIES	
Italy	65
Greece	49
United Kingdom	29
Germany	20
Malta	14

Figure 7: Countries of survey respondents ($n = 420$).

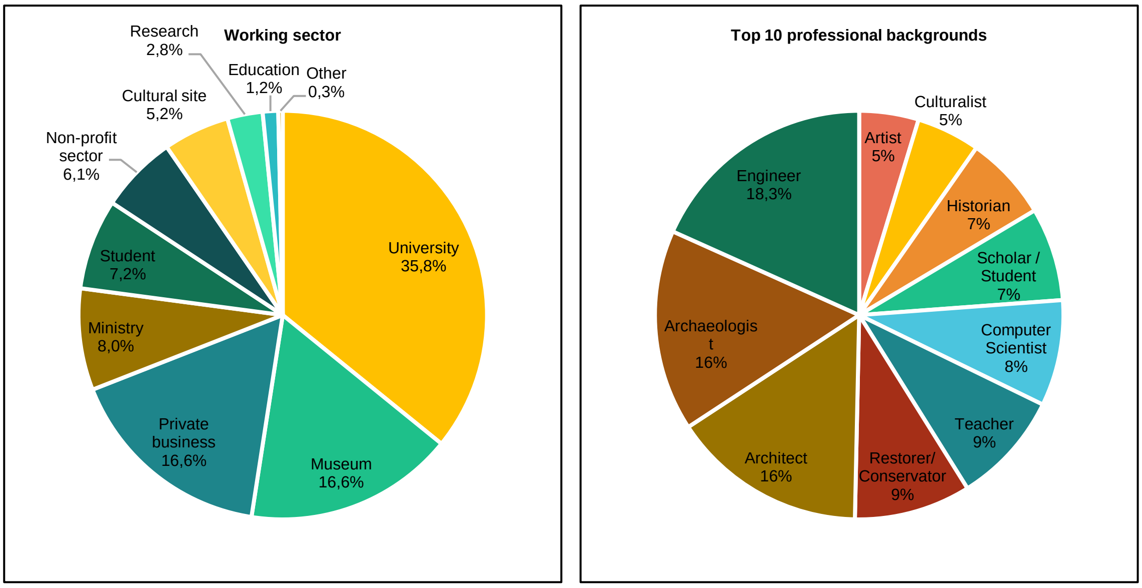


Figure 8: Working sector (left) and professional experience (right) of respondents.

The majority of survey participants worked in the higher education, museum and industry sectors (Figure 6). The most common professional backgrounds were engineering, architecture, conservation and archaeology. 85% of respondents had completed a related post graduate course (MSc, MA and/or PhD). 64% had at least 6 years of experience in CH data acquisition and conservation. 45% were actively involved in digitisation of monuments and sites, while 29% were engaged in data acquisition for movable objects in the museum sector. 51.9% were members of professional organisations dealing with CH conservation, protection and documentation (Figures 7 and 8).

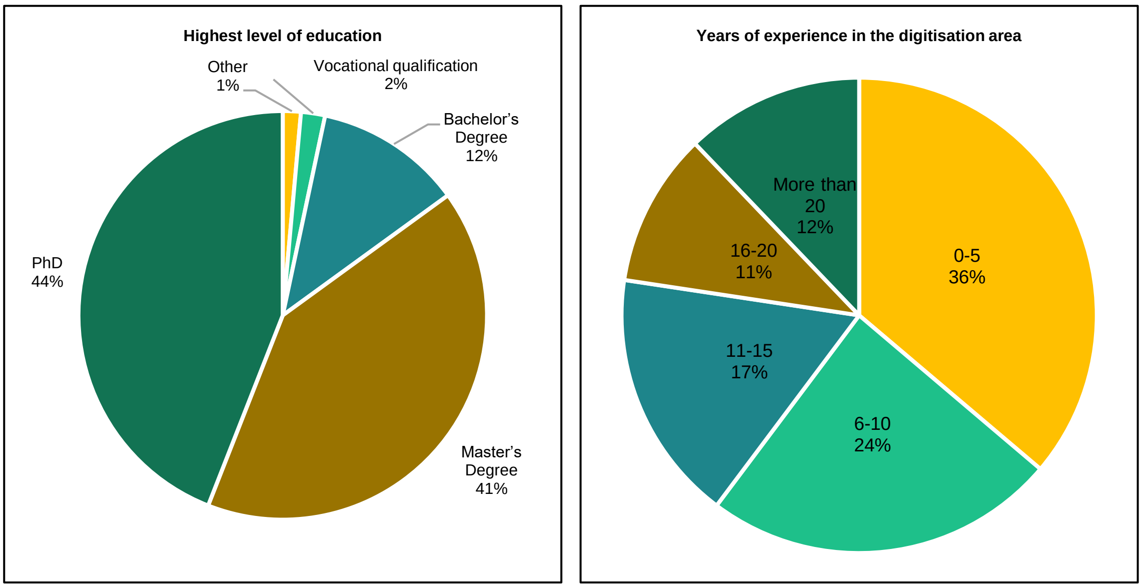


Figure 9: Education (left) and years of experience (right)

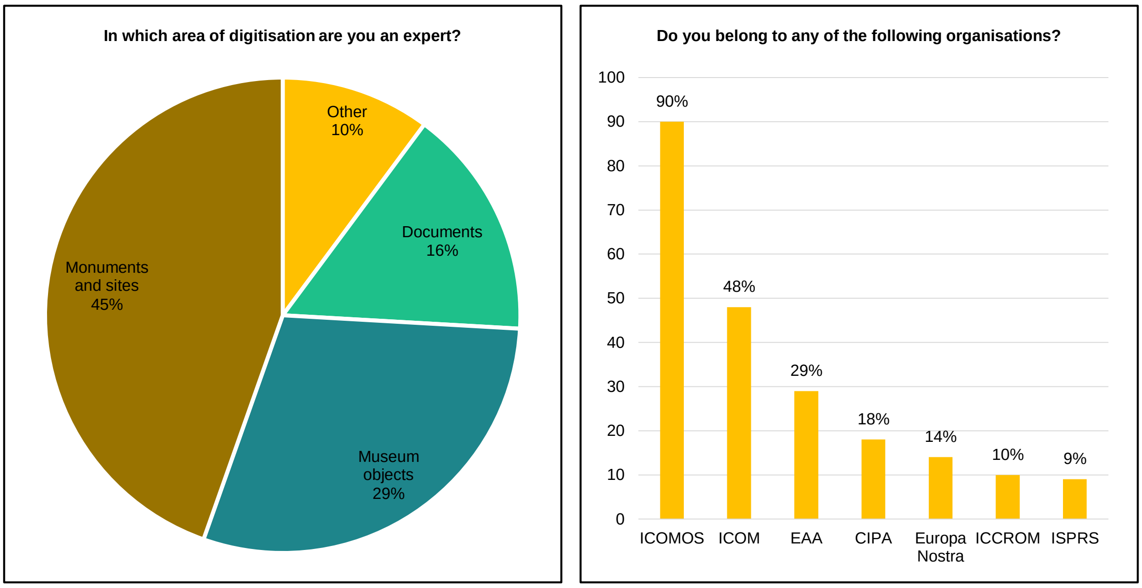


Figure 10: Digitisation expertise (left) and organisation membership (right)

Figure 9 illustrates the willingness of the respondents to support the Study, while Figures 10 and Figure 11 summarise their expertise in different disciplines related to CH data acquisition.

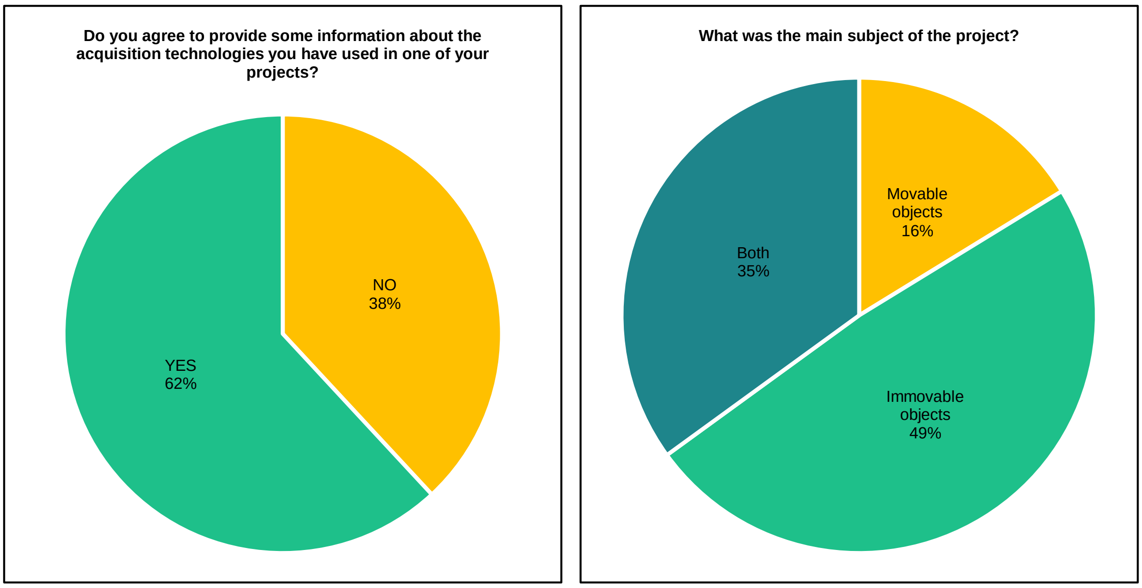


Figure 11: Respondents' willingness to provide technical information (left) and project subject (right).

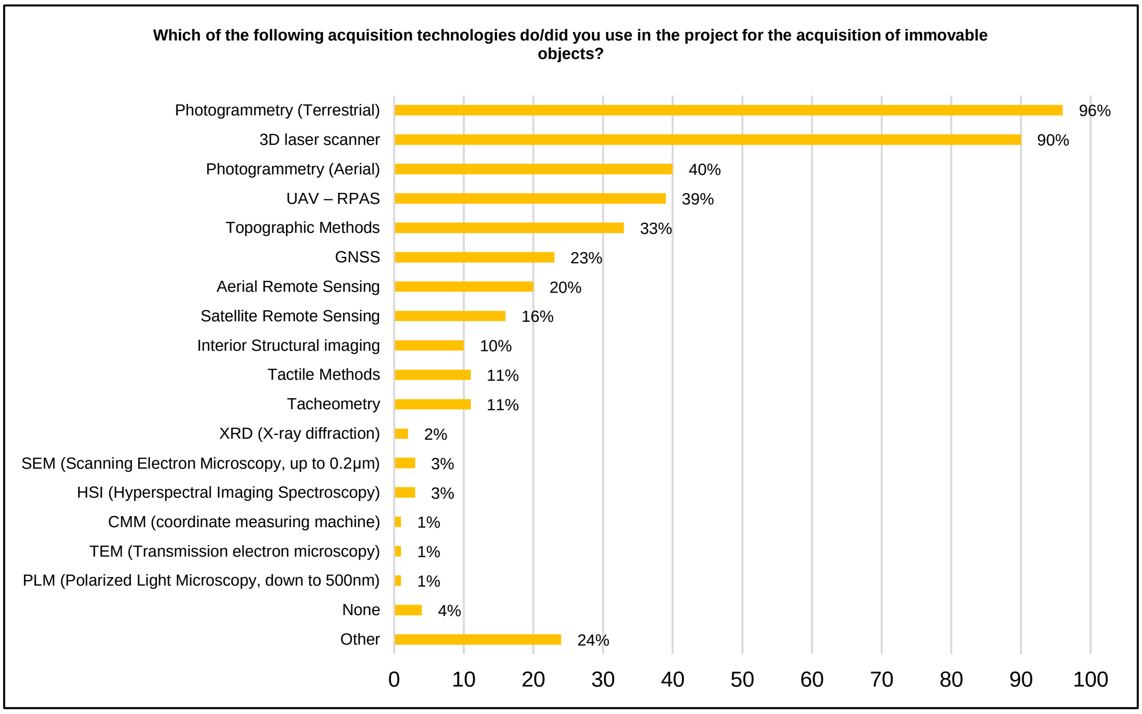


Figure 12: Acquisition technologies used in projects relating to immovable objects

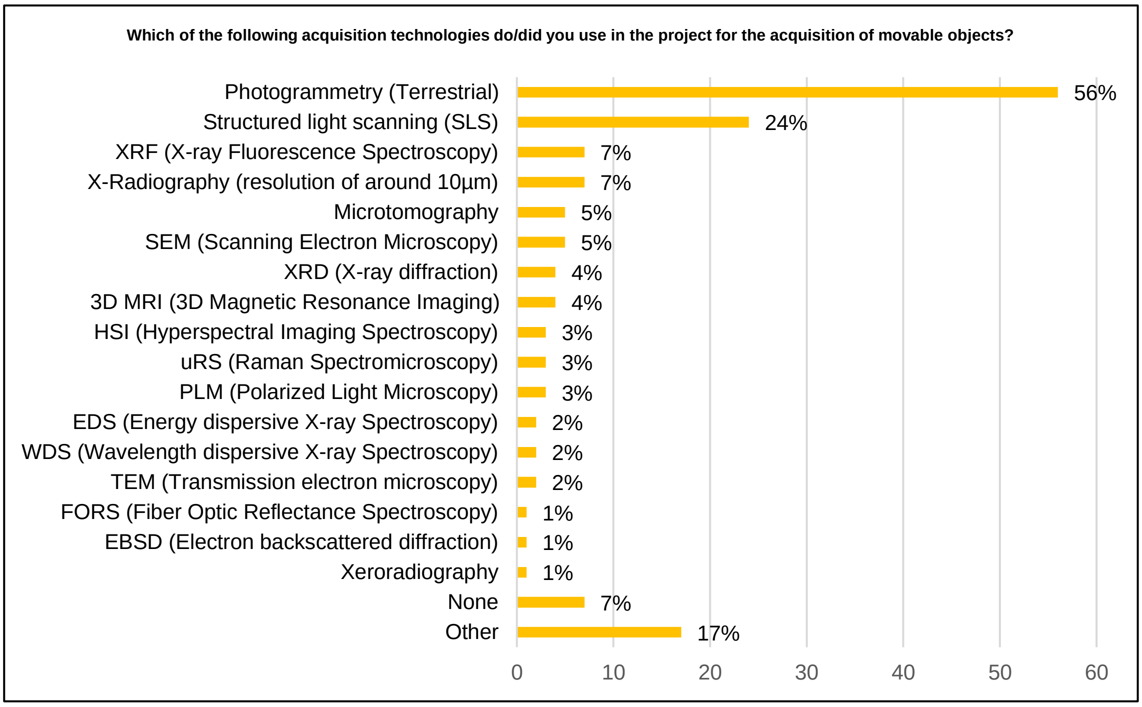


Figure 13: Acquisition technologies used in projects relating to movable objects

Without descriptive information (metadata), digitised content and data are simply a meaningless collection of files, values and characters. 70% of respondents used one or more metadata schema to describing and document their content (Figure 12).

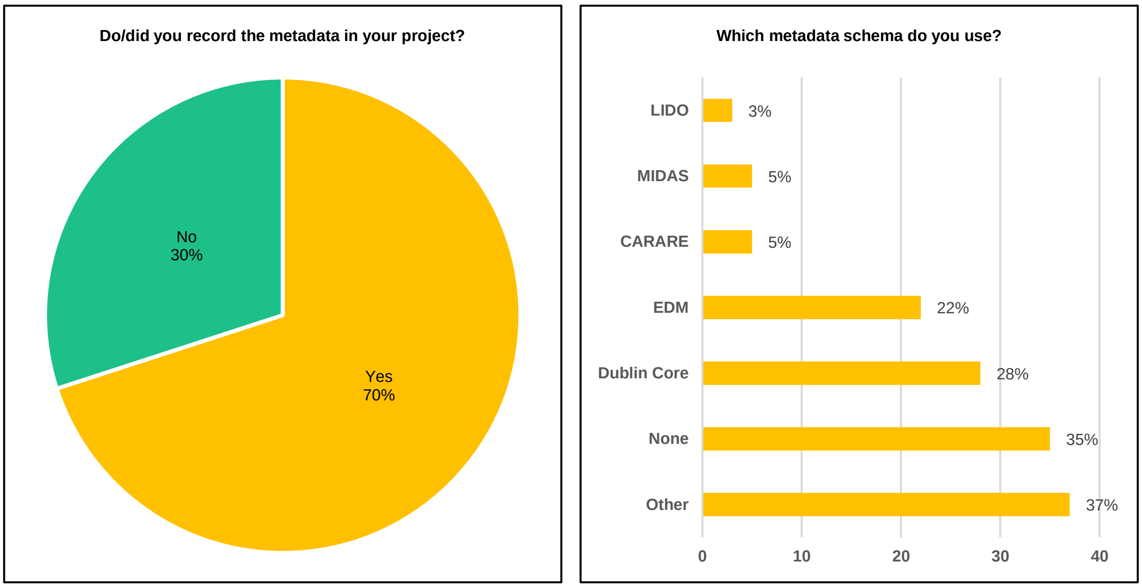


Figure 14: Recording of metadata (left) and metadata schema used (right) in projects

The term ‘paradata’ refers to auxiliary information collected in a survey that describe the data acquisition process. Most respondents did not collect any data related to the process of 2D and 3D digital documentation in CH (Figure 13).

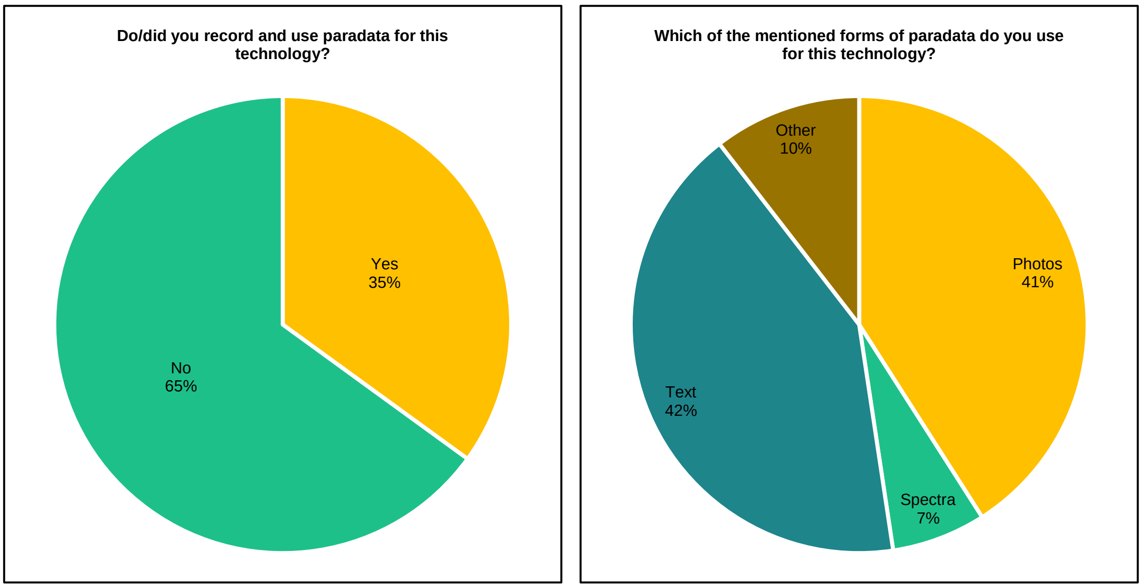


Figure 15: Record/use (left) and forms (right) of paradata for technologies.

Most importantly from the perspective of this study, Figures 16 and 17 illustrate that ***most respondents were not aware of complexity*** being a measure of the interactions of various parameters used in 3D CH data acquisition or its role in indicating data *quality*, time and costs.

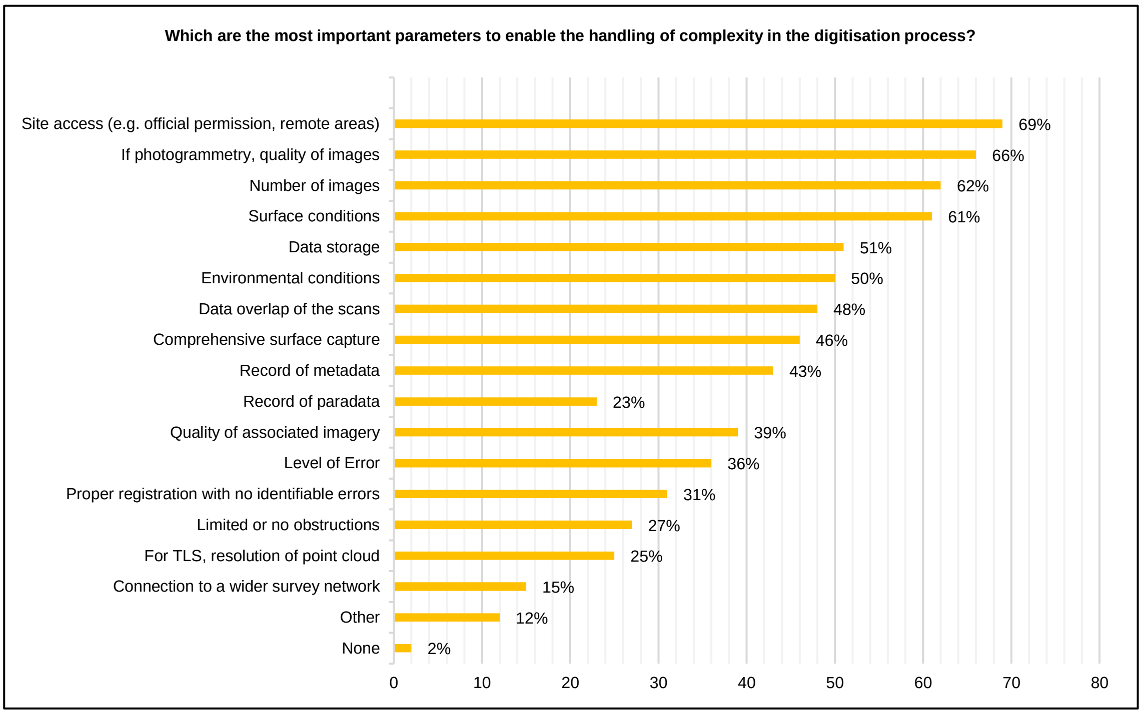


Figure 16: Most important parameters for handling complexity of the digitisation process according to respondents.

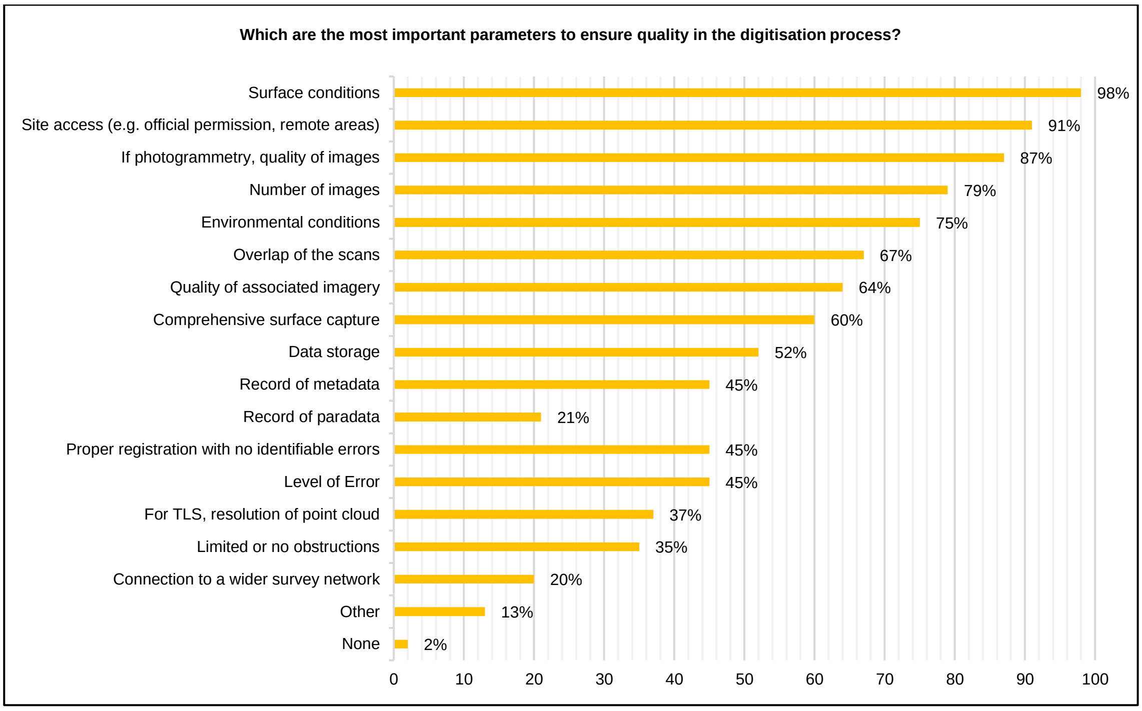


Figure 17: Most important parameters for handling quality of the digitisation process according to respondents.

3.2.1. Statements from Respondents about Complexity

The following are selected comments in resonse to the question, "*The definition of the term 'complexity' is the state or quality of being intricate or complicated. What does complexity mean to you and your team during the planning and data acquisition stages of a recording project? If it is a consideration, how does it impact your work?*"

Defining complexity

Respondents defined complexity through both general and more detailed statements, and by referring to the process of digitisation and to the objects to be digitised. About the former, they focused both on the entire process of digitisation and on specific phases (acquisition, interpretation) and issues (environmental conditions and access to the site). On digitisation, respondents mentioned both the type of objects (immovable, movable) and specific facets (geometry, colouration, surface).

To address complexity for immovable and movable objects, respondents highlighted the need to understand the object to be digitised, its geometry, its materials and specific features that can then inform the planning phase. For some of them, production procedures were crucial, for others, not an issue.

In general, there was a consensus that complexity combines an object's characteristics with the scope of the digitisation. The challenge is to manage all the related activities that run together during the acquisition phase and reproduce aspects of an object, without losing any information.

General statements

- 'The complexity of an object is synonymous with accurate illustration and greater interest.'
- 'Complexity lies in ensuring the quality and completeness of the initial raw data for future analysis.'
- 'Complexity helps achieve a better understanding of phenomena requiring data-heavy and often multidisciplinary research'.

- ‘Complexity is a puzzle to be solved. All pieces must fit together, for a project to be successful.’
- ‘Complexity is a difficulty encountered in accomplishing a task. Its impact on a job can affect the end goal, the result.’

Detailed statements

- ‘Complexity and complicatedness are not the same things. If a problem is complex, it means that it has many interwoven components and affects one another, but not necessarily that it is difficult. Something complicated is difficult and time-consuming. They are only marginally related.’
- ‘Complexity is not a synonym of complicated. Complexity is a characteristic of everything that can be assimilated to a system, and it is the capability of describing an object with a holistic approach.’

The following subsections show a selection of some of respondents’ statements on various aspects of complexity.

The whole process

- ‘Complexity is the related activities that go simultaneously and in many cases are governed by actions and parameters outside the sphere of the individual project responsible but can influence and impact on the own work – sometimes not predictable sometimes it might be anticipated.’
- ‘The complexity of a project is in its planning and coordinating the team carrying out the various specialisations.’
- ‘ Complexity of a project can be defined by how many parts there are in a documentation project, and how many people are needed to process them.’

Acquisition

- ‘The complexity of a documentation project implies the problems to be solved in the acquisition of data.’
- ‘Complexity means having to take specific and situationally different steps to capture the data.’
- ‘When a variety of information is available, each necessitates different measures and applications for data acquisition. It might be due to the nature of the site or its significance or the scale.’
- Complexity for us is how difficult it will be to acquire the relevant data for photogrammetry. It is often taken care of and affects how and how many acquisition points we take.’

Interpretation

- ‘Complexity is necessary, current documentation techniques can record this complexity; however, it is the output, the interpretation that counts that object complex.’
- ‘Complexity is the need to reproduce the significance and physical aspects of CH without reducing their overall meaning and values.’
- ‘Complexity does not reside in the geometry of a 3D model or by the number of geometric vertices. However, it integrates multiple datasets from three different specialisms into one archive that can be visualised in an easily accessible and searchable way to subsequently retrieve and communicate new knowledge.’
- ‘Complexity is to capture the "big picture" of the cultural object, which means the holistic approach to studying the object.’

Environmental conditions and access to site

- ‘Complexity relates mainly to getting access to the works to be digitised. After that, the rest is a technical nuisance.’
- ‘Generally, complexity to us determines the number of positions / locations needed to ensure scanning provides a complete dataset. Access to these locations are also considered.’
- ‘Complexity involves the objects and the site themselves, how difficult it is to record depending on the terrain and the objects' reflective properties.’
- ‘The complexity of the project varies from case to case. Sometimes it refers to the object, other times to the object’s surroundings.’

Immovable objects

- ‘Complexity may refer to different aspects of the data acquisition, restitution and analysis, mainly when dealing with Built CH. The main issue is interpreting the geometrical, material and cultural complexity of the building and finding the tools to represent it, with its embedded values.’
- ‘For ancient buildings, complexity means the complexity of wood material strength changes over time, the geometric non-linearity of the wood structure, the contact non-linearity and the structural non-linearity.’
- ‘For heritage work, it should be enough information to see how the building was constructed. Requires carefully planning of where to set the scanner to minimise 'shadows'.’
- ‘We take complexity as having large-size objects with lots of information like 2D images, coordinates, and different formats.’

Movable objects

- ‘Objects can be considered complex by having intricate geometry or shiny/reflective surfaces.’
- ‘It is more related to the nature of the physical object, not so much to the procedures. It is more important to understand the item than to understand the procedure.’
- ‘Complexity has to do with the object’s characteristics in conjunction with the specifications and the scope of the digitisation’.
- ‘Complexity means the size of a site or artefact set, and the brief’s requirements in terms of fullness of coverage.’

Facets

- ‘Complexity is something that is present in the object (shape, details, undercuts, material) you would like to digitise.’
- ‘Complexity is referred to as how complex the geometry of the object/surface is.’
- ‘Complexity on the digitisation of heritage objects and of the state of preservation of the surface may mean complex geometry or complex surface features (roughness, high reflectivity, cracks, decay, occlusions)’.
- ‘In our project, complexity relates to morphology as well as colouration.’

Technical impact

- ‘Complexity can hurt the ability to replicate and interoperate with other software systems.’
- ‘It is unreasonable to presume that replicas can provide an ability to carry out analysis and interpretation like the original object.’
- ‘Different data acquisition tools needed for other materials or surface ornaments (scales).’

- ‘ During data acquisition, the complexities go far beyond the tools used. For example, photogrammetry is dependent on lights and shadows to generate an accurate point cloud imagery.’
- ‘Need to choose correct instruments to cover intricate or poorly preserved surface features for digitisation at necessary resolution and quality.’
- ‘In photogrammetry, complexity typically means the geometric complexity of an object and surface material properties, directly impacting how many poses are needed for the equipment to calculate the best possible coverage of the surface and surface information.’
- ‘Complexity means determining the number of positions/locations needed to ensure scanning, providing a complete dataset and gaining access to them.’

Knowledge management impacts

- ‘Understanding the complexity of data projects is fundamental in designing adequate ontologies for data architectures.’
- ‘Ensuring the accuracy of metadata so that images and artefacts may be readily retrieved when required.’
- ‘Geo-referencing data is a powerful tool to organise and understand complex information.’
- ‘The complexity is in connecting and visualising this and subsequently retrieve and generate new knowledge and communicate that knowledge and share the data with peers and the public to expand that knowledge.’

Resource impact

- ‘Time and effort needed to plan and capture complex environments in concise detail, e.g., morphology and colouration issues.’
- ‘Documentation of heritage sites built in phases and ends in a complex result requires a larger research project than only archiving or digitising a monument.’
- ‘Management of data (categorising, transcribing, linking and recovery) that span or transcend simple classification strategies can add time-consuming processes or require structured workflows that simplify and overcome it.’
- ‘Project planning and DMPs (data management plans) should: ensure experts in the team, access to required hardware and software; logistics, development of mitigation plans; resources/ tools/ expertise, to provide a firm foundation for the project, reducing risks and minimising impacts.’
- ‘Different techniques used in more complex captures require costly, proprietary and inflexible software.’
- ‘Complexity can require a combination of construction, fabrication and abilities to disassemble digitally.’
- ‘It can interrelate immoveable heritage with moveable and oral history/context, including Maker-skills.’

Complexity in specialised conditions

- ‘Complexity exists in non-uniform architecture such as underground cave complexes that significantly affects spatial acoustics and demands digital acoustic calculation requiring on-site measurement, including planning key positions for capturing with minimal site contamination.’
- ‘For ancient buildings, complexity can mean the use of wood. It's strength changes over time and nonlinearities of geometry, contact-nonlinearity and structure.’
- ‘Excavation fieldwork recording requires multi-tasking in a restricted time and often adverse conditions (e.g. weather, lighting etc.). It is challenging to keep up digital documentation with excavation progress, and in many cases, parts of the recorded data processing happen off-site and/or during post-excavation.’

- ‘Complexity, for example, involves capturing the 3D documentation and experimental condition of (1) CH damaged by a disaster e.g. earthquake, fire, or rains/ floods, (2) intricate architectural details/ancient carvings on supporting structural elements at a heritage site, (3) complex architectural/structural forms e.g. cupolas/vaults...both inside and outside, and (4) museum objects including the glass-enclosed display cases housing museum objects of art and culture.’

Complexity	**Selected responses**
In general, there is a consensus that complexity combines an object's characteristics with the scope of the digitisation. The challenge is to manage all related activities that run together during the acquisition phase and reproduce aspects of an object, without losing any information.	**What does complexity mean to you and your team during the planning and data acquisition stages of a recording project? If it is a consideration, how does it impact your work?** 1. Complexity is the related to activities that go simultaneously and in many cases are governed by actions and parameters that outside the sphere of the individual project responsible but can influence and impact on the own work (such as **Environment, Technology, Location, Materials**). 2. Complexity means having to take specific and situationally different steps to capture the data. 3. Complexity is the need to reproduce the significance and physical aspects of CH without reducing their overall meaning and values.

Figure 18: Highlights from responses on the issue of complexity.

Table 2 summarises how the respondents defined complexity itself both through general and more detailed statements and by referring it to the process/methodology of digitisation and to the objects to be digitised. Among the issues mentioned were the objects digitised (immovable, movable) and specific facets (geometry, colouration, surface), focusing both on the whole process of digitisation and its distinct phases (acquisition, interpretation) and issues (environmental conditions and access to the site).

To adequately address complexity for immovable and movable objects, respondents highlighted the need to understand the object as digitising its geometry, materials, and specific features (such as production / construction). Therefore, for 32% of respondents, production procedures are crucial; for 26%, procedures were not an issue.

Table 2: Results from the online survey concerning complexity

ISSUE OF CONCERN	RESPONSES	%
Surface conditions (e.g., reflectivity, material)	98	10.4%
Site access (e.g., official permission, remote areas)	91	9.6%
Quality of images (photogrammetry)	87	9.2%
Number of images (photogrammetry)	79	8.4%
Environmental conditions (e.g., temperature, humidity, dust)	75	7.9%
Data overlap of the scans	67	7.1%
Quality of associated imagery	64	6.8%
Comprehensive surface capture	60	6.4%
Data storage	52	5.5%
Level of error	45	4.8%
For TLS, resolution of point cloud	45	4.8%
Record of metadata	45	4.8%
Proper registration with no identifiable errors	45	4.8%
Limited or no obstructions	35	3.7%
Record of paradata	21	2.2%
Connection to a wider survey network	20	2.1%
Other	13	1.4%

3.2.2. Statements from the Respondents about Quality

The following are selected comments to the question “*The definition of the term 'quality' is the standard by which something is measured against others of a similar kind. Is quality an issue to you/your team during the data acquisition stage of a recording project, and if so, how does it impact your work?*”

Defining quality

Respondents defined quality by itself through general and more detailed statements, and in relation to the project to be carried out, to accuracy and to the concept of quality standards. The following subsections present a selection of the definitions provided by respondents in each topic.

- Quality is needed, else we lose the details. For us, loss of details was a major concern with quality.
- We need the best quality we can achieve so that our final product is useful.
- It is an important tool to safeguard the collection for further generations to come.
- The more quality the more information can be derived from object.
- ‘Quality means achieving repeatable high quality with our autonomous 3D scanning systems, so if I place the same object in my scanning system, I get the same result (the same mesh, the same colours) within measurement deviations.’
- ‘Quality has been interpreted and documented by a correct and synthetic description of the used technologies and instruments, of the processing steps, and of the quality assessment for each phase of the process.’
- ‘Quality impacts the number of experiments needed to conduct to achieve acceptable point cloud quality.’
- ‘We consider the final quality of the work to be paramount and the entire "chaine operatoire" is based upon evaluating confirming the highest quality of data for all steps of the project in order respect and archive the object.’

Quality in relation to the project

- ‘Quality is related to the desired outcome and the purpose of that heritage record. Quality can be reported and described; provenance information is very important in heritage recording.’
- ‘Quality is everything, but quality should be goal-oriented. The heritage sector is "plagued" by what I call a 3D-datafication wave. 3D models are made of everything, without really considering the need for these models.’
- ‘Quality is of utmost importance, hence we strive for high quality data, so that the (final) products, as well as the process itself can be useful, durable, presentable, and overall able to set and follow standards.’
- ‘The quality aimed depend on the purpose of the digitisation. We aimed to find a way to measure and ensure quality of our data but is difficult to assess. We haven't found a method or a protocol that satisfies us completely to perform quality control for all acquisition.’

Quality and accuracy

- ‘Quality is often related to a margin of fault measurement. It's easy to ask a high accuracy. This is difficult to deliver, specially within a tight commercial budget. The accuracy can be achieved on big parts of the project but on details it's next to impossible.’
- ‘Quality is used as index of geometric accuracy and referencing of the object, and thus this has impact to the selection of the appropriate software and methodologies needed to be used.’
- ‘Quality is the main challenge. It is specified in terms of accuracy, definition, resolution, precision. Each one as to be chosen according to the abilities of current technologies, data size and of courses the specifications of the study.’
- ‘As a survey requires projects and specific planning, quality is one of the defined goals, and it is the combination of many aspects concerning not only accuracy and precision but also enhancing the research.’

Technologies, equipment, and quality

- ‘Quality is impacted by a misunderstanding of what technology can do. It can also be determined by the budget.’
- ‘High quality of drone images and the use of ground control points has allowed us to obtain results that have a high level of definition.’
- ‘As the automation and accessibility of technologies introduce more and more people to geomatics tools and their application to the digitisation of heritage case studies, the need for experts in the field is ever-increasing, to guide non-specialists on how to use these technologies. A big part of this process should be teaching how to obtain and store metadata and paradata at every stage of multidisciplinary documentation.’
- ‘Quality dictates equipment and acquisition methodology, as well as processing.’
- ‘The quality of digitised objects refers to how closely the 3D visualisation represents the physical object in terms of morphology. The incremental increase in the rate in this sense relates to the fact that scans are now useful as a teaching collection, where forming traces can be reliable without needing to first conduct extensive in-person training.’
- ‘Not many techniques of photography are helpful for light correction or reaching inaccessible surfaces unless paired with another device. No documentation so far was completed without the need for physical intervention of a human or a combination of many devices that drive the total cost of the project up.’
- ‘Audio fidelity to the site's acoustics is a measure of quality in our projects. It is imperative to capture the room's acoustics as faithfully as possible to contextualise foreign sounds when digitally placed inside the virtual representation of the site.’

- ‘Developments in GIS data management and representation, as well as the advent of photogrammetric techniques, have impressively improved results, though the problem of trying to balance metric accuracy with GIS output rendering limitations means that in many cases (i.e. mostly 3D photo textured meshes) simplified products enter the final GIS excavation data archive.’
- ‘Focusing on AI-based analysis of Archaeological Remote Sensing data, It is always desirable to obtain a big amount and high-resolution data With low-quality data, the AI-based automation approaches may fail in terms of achieving high accuracy results.’
- ‘The objects we digitise are small, and the digitisation process must ensure high standards of accuracy, precision and resolution. It affects our work in terms of choosing the optimal solutions, instruments and acquisition setup for our purposes.’
- ‘Comparing different devices, relating to geospatial data, and to historical records, compression and performance for VR or 3D digital environments.’
- ‘Quality of the device that can be used on a budget can be a problem. Smaller project areas cannot afford to buy/rent or use large devices. This reduces the quality of objects that might have more cultural value.’
- ‘Achieving a high texture quality for photogrammetric 3D models is really difficult sometimes. Sometimes the team has to do a new series of photographs, delaying the teamwork.’

Standards, metrics, and quality

- ‘Standards are actually more important than quality. For example, what are the standards of a point cloud (resolution, equipment used, accuracy etc).’
- ‘Quality means to be able to compare and exchange 3D models, knowing according to which protocols and standards they were scanned and cretated.’
- ‘Only by defining and associating a certain standard to the results of a scan can we ensure comparability years from now.’
- ‘Slightest error will result in misalignment of the scans, making the whole model unusable. When it comes to the aggregation of digital CH data, it is essential that everyone is using the same standards.’
- ‘Quality should be measured with standards like FADGI Guidelines and ISO/TR 19263-1:2017 and ISO/TS 19264-1:2017.’
- ‘Measurable Quality standards are still lacking in our discipline - especially at the stage of transfer from original acquisition data to processing and storing. There are no quality-controlled processes defined for our field (other than in, e.g. mechanical engineering).’
- ‘A quality metric which interests us is 3D positional accuracy in recording, requiring both planning and validation.’
- ‘Quality is the most crucial factor in our geospatial survey work for data capture, post-processing, output generation and archive deposition for the project. We are the authors of the 'Metric Survey Specifications for Cultural Heritage' (12). our survey work follows the requirements of this document. It guides our choice of technology, accuracy, resolution and output generation against the needs of the client to ensure a set of data that is generated once but (potentially) used many times.’
- ‘How documentary heritage and historical documentation were gathered and digitised for us was a parameter for the quality of the project. For the digitised document and drawings, for example, we tried to use CIDOC-CRM[47] standard mapping in the creation of metadata and paradata.’
- ‘Whenever a survey is conducted, we always try to validate the results achieved through comparisons in order to evaluate the accuracy and precision with which the work was carried out.’

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[47] CIDOC-CRM (accessed Jun. 14, 2021).

- ‘Quality, as a standard, needs to be more defined for clarity. Standards vary from techniques, intuitions, and needs. At my current post, quality is not always the top priority and quantity can be more rewarded than quality, and this disturbs me greatly.’
- ‘Quality standards are still an issue that requires shared tools and should be applied not only on the 2D restitution but also to the 3D modelling. Quality standards would help to improve a transparent sharing of data.’
- ‘Quality is a vague term, which neither I nor any of my clients, who are generally administrators, have objective criteria to assess.’

Data and quality

- ‘The main issue is the processing of more than 4000 images due to software limitations and the considerable size of the resulting data.’
- ‘Quality in data acquisition is essential, and its sufficiency for project goals has to be regularly checked.’
- ‘Photographs of some artefacts having gleaming/reflective surfaces cannot be obtained to a desirable level of detail: this is noted in the metadata to be addressed through future re-processing.’
- ‘Both in terms of metric accuracy and quality of the raw data (e.g. radiometric quality of a digital image acquired for photogrammetric purposes, or the noise of a LiDAR point cloud).’
- ‘We have strict guidance and acquisition criteria set out to ensure data generated/procured meets our standards.’
- ‘The primary issue is concerning the storage of the data captured during the process.’
- ‘When we made our project data acquisition, usually we employed the public in the form of Community-Based Crowdsourcing (CBC) which tends to give a decent quality of data acquisition to our work.’
- ‘Advances in techniques, methods and theories help me in gathering data and digest it enough to become a piece of information.’
- ‘Quality scan data usually means less data being altered by software algorithms. Hence making the geometry of a digital replica more accurate.’
- ‘High resolution is required for the computational automated 3D joining aspects of our research. Many reduced solutions are used for web delivery and AR apps.’
- ‘Data quality is paramount at the data acquisition stage. Without quality data, it is impossible to reconstruct the 3D model, so the number of images, their resolution and orientation are crucial in guaranteeing a high-quality model afterwards.’
- ‘To compare different 3D models, the exact same workflow should be followed to reach similar outputs. The high in high-resolution is something we omit, as it is a temporal, subjective parameter. Indeed, to identify sub-mm details in the recorded geometries, absolute stability in data quality is required.’

Quality in special fields

- ‘The ability to measure surfaces, and especially surface movement, with accuracy, is essential for the understanding of the structural behaviour of heritage buildings.’
- ‘Quality assessment in film and video digitisation projects ensures that the content on the medium is fully transferred to the digital domain.’
- ‘In tourism-related applications, quality has to do with the expectations of the travellers, how to provide materials to learn about the destinations/attractions and how to enrich their visit (e.g. through mixed realities).’

Quality	**Selected responses**
The experts acknowledged that there is a difficulty in objectively identifying a level of quality during the recording process. They mentioned issues with the standards, while most of them stated that there are no issue about the technologies.	**Is quality an issue to you/your team during the data acquisition stage of a recording project and, if so, how does it impact your work?** 1. Quality dictates equipment and acquisition methodology, as well as processing. 2. We consider the final quality of the work to be paramount and the entire "chaine operatoire" is based upon checking the highest quality of data for all steps of the project in order to archive the object. 3. Quality means to be able to compare 3D models, according to which standards they were scanned.

Figure 19: Highlights from responses on the issue of quality.

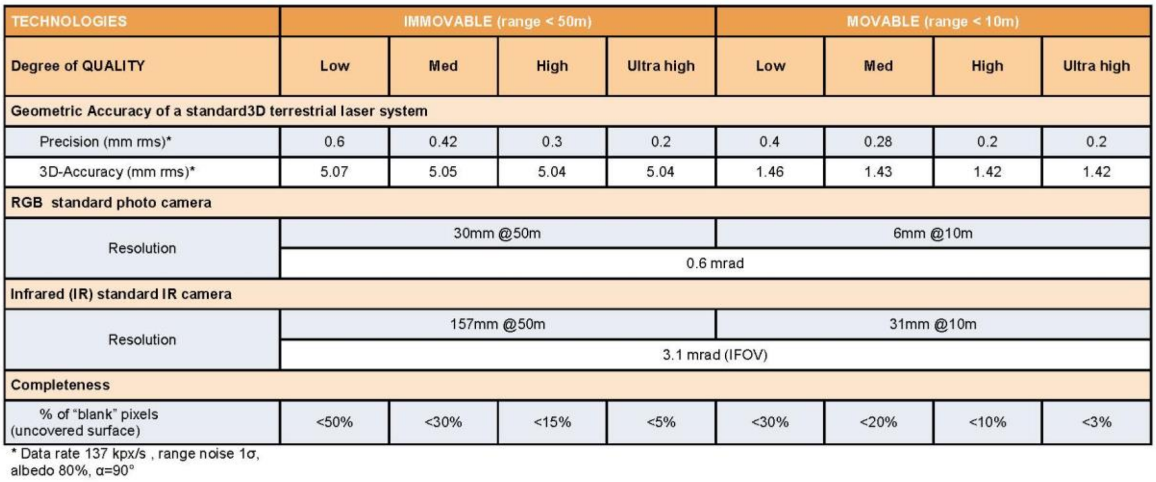
From the responses of the study's survey, the parameters shown in Table 3 were identified by respondents as the most important for ensuring quality in the digitisation process.

Table 3: Responses from the online survey specific to the issue of quality (see also Figure 17).

ISSUE OF CONCERN	RESPONSES
Surface conditions (e.g., reflectivity, material)	24.24%
Quality of images (photogrammetry)	23.23%
Environmental conditions (e.g., temperature, humidity, dust)	17.17%
Number of images	17.17%
Quality of associated imagery	16.67%
Overlap of the scans	15.15%
Comprehensive surface capture	13.64%
Level of error	13.13%
Proper registration with no identifiable errors	12.63%
Record of metadata	11.62%
For TLS, resolution of point cloud	10.10%
Data storage	9.60%
Limited or no obstructions	7.07%
Record of paradata	4.04%
Connection to a wider survey network	3.03%
Other	2.02%

Survey recipients were also asked, “The definition of the term ‘quality’ is the standard by which something is measured against others of a similar kind. Is quality an issue to you/your team during the data acquisition stage of a recording project, and if so, how does it impact your work?”

Table 4: Degrees of object quality (from two UNESCO WHL studies - Asinou in Cyprus and Cologne in Germany – see also Annex 2).



TECHNOLOGIES	IMMOVABLE (range < 50m)				MOVABLE (range < 10m)			
Degree of QUALITY	**Low**	**Med**	**High**	**Ultra high**	**Low**	**Med**	**High**	**Ultra high**
Geometric Accuracy of a standard3D terrestrial laser system								
Precision (mm rms)*	0.6	0.42	0.3	0.2	0.4	0.28	0.2	0.2
3D-Accuracy (mm rms)*	5.07	5.05	5.04	5.04	1.46	1.43	1.42	1.42
RGB standard photo camera								
Resolution	30mm @50m				6mm @10m			
	0.6 mrad							
Infrared (IR) standard IR camera								
Resolution	157mm @50m				31mm @10m			
	3.1 mrad (IFOV)							
Completeness								
% of “blank” pixels (uncovered surface)	<50%	<30%	<15%	<5%	<30%	<20%	<10%	<3%

* Data rate 137 kpx/s , range noise 1σ, albedo 80%, α=90°

3.3. Interviews with Key Professionals

During the study, we contacted 49 key stakeholders and highly skilled professionals in CH 3D digitisation in CH (17 female / 32 male) of whom 88% were in the European Union and actively involved in digital documentation in museums, monuments and archaeological sites for at least eight years. The main objectives and goals of the Study were explained as part of a semi-structured interview, lasting for an average of 1.5 hours.

These interviews underlined the perception of missing standards and highlighted the importance of the stakeholders’ and owners’ requirements for the 3D digital documentation (setting the limits and framework of digitisation: budget, accuracy, duration, standards, data preservation, etc.). They drew attention to the conditions of the object before/during the recording process and the location and environmental conditions during digitisation. Around 67% of the experts underlined the importance of know-how/expertise available through the coordinator/team/operators. The relation (indirect association) of the project’s complexity with high quality results (geometry, texture, material, structure) and importance of the level of hardware and software, as well as expertise, were also seen as crucial in 3D data acquisition. There was consensus that complexity combines the object’s characteristics/conditions with the stakeholders’ requirements and that the challenge is to manage all the logistics and related activities that run simultaneously during the data acquisition phase and to reproduce high-quality results of an object without losing any information.

These considerations were taken into close account when establishing the study’s operational findings (see section 3.6).

3.4. Limiting Factors in a 3D Digitisation Process

There is a direct relationship between the type of acquisition system and the level of acquired complexity. As indicated in Table 5A, the current data acquisition or recording limits of existing hardware solutions can be categorised based on maximum accuracy (idealised) and, at the same time, as indicated in Table 5B, by listing the highest level of output based on the purpose of use.

The capabilities of contemporary recording systems such as the high-resolution digital camera or terrestrial laser scanner can support even the most demanding documentation needs. This current hardware evolution requires a more particular attention to data aquistition and available infrastructure. Not all technologies are equal: some are more suitable for specific recording situations and conditions than others.

Table 5A: Current technology recording limits.

AVAILABLE TECHNOLOGY	MAXIMUM ACCURACY
Micro-scanning	~1 µm
GNSS topography/surveying	~ 1 cm
Photogrammetry	~0.5 cm
Laser scanning point cloud	~ 0.5 cm
UAV imagery	~ 2 cm
Satellite imagery	~ 30 cm

Table 5B: Current fit-for-purpose resolution limits (production).

PURPOSE OF USE	MAXIMUM LEVEL OF RESOLUTION
3D printing replica 1:1 of small objects-dgital archive at maximum resolution	~ 0.002 mm
3D printing replica 1:1 of large objects - digital archive at maximum resolution	~ 1 cm
Web viewing	~ 0.2 mm at a viewing distance
CNC[48] and Robotics Production Systems (average)	~ 0.01 mm
Contemporary commercial manufacturing systems (average)	~ 0.03 mm

3.5. Types of Heritage and Forms of Complexity

Movable Cultural Heritage

Movable heritage ranges from photographs and paintings to metals, ceramics, glass, wood, leather, textiles, and other composites. It can be two- or three-dimensional, made of one or multiple materials and consist of a single layer or multiple layers.

An object’s material or materials adds a further dimension of information and complexity (see

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[48] CNC (accessed June 10, 2021)

Table 6). Various interrogation technologies can determine the specific type or types. In cases where an object consists of different parts, its internal configuration may not be visible: data acquisition technologies are needed for 3D documentation that make the invisible evident. The method of construction is a further important parameter in a holistic approach to documentation.

Table 6: Provisional classification of degrees of complexity for movable objects.

INTERIOR / EXTERIOR	MATERIAL/ COMPOSITION AS VISIBLE FROM THE EXTERIOR	SIZE	COMPLEXITY	CONDITION
Internal	Metal	Small (<32cm)	High	Good
External	Ceramic	Medium (0.33m-2m)	Medium	Medium
Both	Glass	Large (2.1m-5m)	Low	Poor
	Stone		Considerations: • surface geometry • texture • interior structure of geometry • number of parts • composition (more than one material, refinement of the material, etc.) • decoration	Considerations: • corrosion • erosion • abraded, fragments • cracked • unstable paint layers • moisture • effects of light system • micro-organims/insect pests • atmosperic pollution / presence of dust • temperature (microclimate conditions)
	Minerals			
	Textiles			
	Leather			
	Shell			
	Bone			
	Antler			
	Wood			
	Pigments			
	Organic Material			
	Manmade Material			
	Animal Product			
	Wax			
	Obsidian			

Immovable Cultural Heritage

According to UNESCO [47], immovable CH includes the following:

- **monuments:** architectural works, works of monumental sculpture and painting, including cave dwellings and inscriptions, and elements, groups of features or structures of particular value from the point of view of archaeology, history, art or science;
- **groups of buildings:** groups of separate or connected buildings which, because of their architecture, their homogeneity, or their place in the landscape, are of particular value from the point of view of history, art, or science;
- **sites:** topographical areas, the combined works of man and of nature which are of particular value because of their unique beauty or their interest from the archaeological, historical, etymological, or anthropological points of view.

Therefore, Immovable heritage consists of buildings, land, and other historically valuable items, typically with fixed foundations connected to the terrain. In addition to castles, houses, mansions, and towers, it also includes churches, monasteries, rectories, townhouses and palaces, rural folk architecture, technical and industrial monuments, theatres, museums, plague columns and shrines, among other objects. This category also includes caves and underwater CH such as shipwrecks, underwater ruins and buildings, which hold structurally complex architectural objects, structures and historically-rich movable interior furnishings.

Immovable, tangible CH is often heterogeneous (made of different materials) and has an inherently complex geometry and surface texture. Structures (monuments and sites) with sculptural or pictorial decoration can also have a complex stratigraphy. Representing these traits in 3D can pose significant challenges.

Georeferencing

Georeferencing is the process of assigning locations to geographical objects within a geographic frame of reference. It is fundamental to geospatial technologies in general, and geographic information systems (GIS) in particular. Depending on the spatial resolution in effect, these mechanisms can be classified into metric- and indirect georeferencing. Metric georeferencing, also called continuous georeferencing, is coordinate-based. Every location on the earth surface can be specified by a set of values (coordinates) in a coordinate system. Metric georeferencing underpins GIS databases, which contain collections of spatial features referenced by coordinates. Based on existing metrically georeferenced GIS databases, indirect georeferencing methods retrieve the metrically georeferenced locations through attribute data [169].

Therefore, one of the main objectives of survey control is to relate the network for the subject to either a wider site system or a national grid and height datum. A very accurate site system can provide the basis for long-term documentation, observation and structural health monitoring. For surveys of a big site or a group of a high number of monuments, a network related to the national system can also provide a monitoring service over a wider area. The georeferencing of found artefacts, barrows and structures can lead to studies of their spatial relationship and more extensive archaeological analysis. If successive scans of an archaeological site are taken as the excavation progresses (over time), the control can function as a framework within which the point clouds are placed. In this way, an accurate 3D model can be built up of the underground spatial relationship between artefacts, bones, deposits, etc., which can provide invaluable information for the analysis, monitoring and long-term preservation of a site/monument [12, 67].

3.6. Object Complexity and Process Complexity

Since most 3D survey technologies are light-based active or passive sensors, only the visible surfaces are recordable. Although they use different recording techniques, they all create photorealistic and spatially accurate representations of any type of CH objects, buildings, and sites.

Developing a thorough, highly detailed, dimensionally accurate and realistic 3D model from raw point data or imagery can be challenging, particularly for large and complex sites. The location of the recording device requires special attention to the relation between the distance from the sensor to the object and the height of the sensed object. Depending on the surface articulation, dimension and complexity, the recording system will require several vantage points (setups) to capture the object thoroughly. Obstructed or hidden surface areas that are not observable by the recording device will not be captured.

For laser scanning, the acquired raw data is typically a point cloud, consist of a set of 3D Cartesian dimension points. With most recording projects, multiple scans are likely to be required, resulting potentially in multiple point cloud data files. During the post-processing production stage, the individual point cloud files are aligned and then stitched together in a process called point cloud registration. This process is only possible if all point clouds share standard features such as physical markers, survey targets or coincident physical features (feature registration). Redundant observations from several setup positions directly influence the overall project accuracy. The alignment and integration of the various scans can affect the overall accuracy and error of the final point cloud dataset.

An object's size is relevant, also useful for subsequent analysis since the object size dictates certain data collection technologies. With the size of the CH object, the necessary number of setups of the instrument increases or decreases and indirectly limits the selection of possible vantage points, since physical access is required. While it might be possible to walk around an object, higher elevated surfaces are more complicated to reach and may require the use of e.g., scaffolds, extension arms or surrounding buildings.

3.7. Aspects of Object Complexity

Geometric/Structural Complexity

Geometric complexity (2D/3D) refers to the resolution of points, degree of detail, number of features, number of surfaces or faces of a tangible object or structure. Given that the 3D point clouds and, in few cases, triangles are the fundamental geometric unit used by many graphics systems as a final result, the 2D and 3D points and triangles are crucial for complexity. According to [9], "Faces and surfaces describe more complex structures that may have arbitrarily large numbers of triangles and thus cannot reliably be used to assess model complexity".

When choosing vantage points, the angle of incidence between the sensor signal and object surface must be considered. Sharp positioning angles may cause a decrease in data quality. Especially regarding static spherical instruments, the planning of sensor setups on the ground thus requires special awareness of the relation between the distance from the sensor to the object and the height of the sensed object. In addition, the physical dimensions may limit compatibility with some technologies due to technical specifications (e.g., minimum, and maximum range). Thus, different technologies might need to be employed, requiring the integration of heterogeneous sensor data into one digital model.

Surface/Texture Complexity

In the 3D digitisation context, 'point or surface complexity' or 'roughness' is relevant. Roughness metrics use a surface roughness index or variability in normal 3D point, surface vectors (or components of norms such as slope and aspect). The metric is quantified by the deviations in the normal vector of a surface from an ideal plane and mainly used in metrology/mechanics. If these deviations are large, the surface is rough; if they are small, the surface is smooth

Material Complexity

This refers to object complexity originated by the material and its chemical and physical characteristics (e.g., reflectance, transmittance, absorbance, etc.), limiting or preventing barriers to active or passive data capture technologies and is directly related to the complexity and quality of 3D data acquisition in CH.

Structural Health Monitoring

Qualitative and non-continuous methods have long been used to evaluate structures for their capacity to serve their intended purpose. Historic buildings, monuments and elements are a very important part of art, architecture and CH. There are many solutions for the structural health monitoring of the heritage, to assess the structural safety and possible pathologies of this kind of buildings and big artefacts exhibited in big public places and museums in real time.

Structural health monitoring (SHM) involves the observation and analysis of a system over time using periodically sampled response measurements to monitor changes to the material and geometric properties of engineering structures such as sites, buildings including heritage ones.

Although Structural Health Monitoring (SHM) techniques can be considered relatively mature, at least from the scientific point of view, they have not yet become a standard practice because of several reasons. One of them is the lack of comprehensive standards addressing the complete SHM process and especially potential utilisation. However, standards related to material testing (ISO Standards, CEN Standards[49]) and structural assessment and analysis developed for the new-built structures (EUROCODES[50]) can be used. Within CEN/TC 346[51] new standards related to conservation of CH are issued and are under development.

3.8. How is Complexity Connected to Technology?

Some data capture technologies and recording methods are more suitable for specific applications than others. Selection of the optimum digitisation technology such as the sensor, hardware, and software, are usually related to the desired technical specifications: size, complexity, material, texture, accessibility, and required accuracy. In Tables 7 and 8, a description of mainstream technologies used is presented in terms of degree of complexity of the 3D model/object to be documented.

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[49] CEN (accessed Jun. 18, 2021).
[50] The EN Eurocodes (accessed Jun. 14, 2021).
[51] CEN/TC 346 (accessed Jun. 14, 2021).

Table 7: Provisional classification of degrees of complexity.

TYPES The type of space, structure and environment is the starting point in determining the amount of effort required in a 3D digitisation project. Parameters include the overall size and the requirement to record the interior, exterior, or both. These features will influence the selected 3D technology and methods.	GEOMETRIC COMPLEXITY The level of the geometric complexity will directly impact the selection of a suitable 3D recording system and the overall project logistics, such as time and the number of stations/set-ups.	IMAGING COMPLEXITY Using a LiDAR-based system, surface reflectance, transmittance, and absorbance will affect the laser return and potentially, the overall quality of data. The level of the surface complexity will also directly impact the selection of an appropriate 3D recording system, documentation method, and project logistics. Alternative, passive-recording procedures such as photogrammetry may be necessary, although the contrast of the surface will be considered.
TYPE AND SIZE	LEVEL	LEVEL
Underwater	Low	NA*
Subsurface	Low	NA*
Fixed, non-moving object	High | Ultra High	High | Ultra High
Architectural Interior – Small	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Architectural Interior – Medium	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Architectural Interior – Large	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Architectural Exterior – Small	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Architectural Exterior – Medium	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Architectural exterior – Large	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Engineering Structure – Small	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Engineering Structure – Medium	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Engineering Structure – Large	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Environment – Small	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Environment – Medium	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Environment – Large	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High
Environment – Extra Large	Low | Medium | High | Ultra High	Low | Medium | High | Ultra High

Table 8: 3D data capture technologies in connection to object complexity.

TECHNOLOGIES	IMMOVABLE				MOVABLE			
Degree of Complexity	**Low**	**Med**	**High**	**Ultra High**	**Low**	**Med**	**High**	**Ultra High**
Tactile								
Hand Survey	*				*			
Architecture	*				*			
Topography								
GNSS		*	*	*				
Traditional Topographic Survey	*	*	*	*				
Photogrammetry								
Close-range	*	*	*	*	*	*	*	*
Terrestrial	*	*	*	*	*	*		
Airborne	*	*	*	*				
UAV	*	*	*	*				
Laser Scanning								
Terrestrial Laser Scanner	*	*	*	*	*	*	*	*
Airborne LiDAR	*	*	*	*				
Mobile System	*	*	*	*				
Satellite Remote Sensing								
Low Resolution-LR (>5 m)	*							
High Resolution-HR (<5 m)	*							
Very High Resolution-VHR (<1 m)	*	*						
Specialised Technology								
Desktop Scanner					*	*	*	*
Hand-held Scanner	*	*	*	*	*	*	*	*
Underwater Systems	*	*	*	*				
Subsurface Systems	*	*	*	*				
Specialised Hardware (X-Radiography, CT scan, Stereography)	*	*	*	*	*	*	*	*

3.9. 3D Digitisation Process Complexity

It was argued earlier that object complexity cannot be estimated subjectively; it can be defined only after all measurements of the object are conducted, which means that object complexity is not useful for 3D digitisation planning and decision-making. Likewise, its neutrality to the intended use re renders it impractical for choosing the best technology or setting up the technical specifications for 3D digitisation.

Regardless of the definition applied, an indication of complexity can only occur after the 3D digitisation of a CH object has been completed. This includes obtaining all surface detail, texture characteristics and accuracy metrics and making a subjective guess at the object complexity. In practice, this would be a fruitless exercise. Theredore, it makes sense to reverse this thinking and start from the technical specifications which are dictated by the purpose of the 3D digitisation activity in question.

In accordance with this argumentation, there is a need to shift attention from “Object Complexity” to “Model Complexity”. This means that the focus is not on the complexity of the actual object (which is connected only to the data capture phase) but on the complexity of the produced model, which is connected to the entire process of data acquisition and processing. This may look like a conceptual compromise, but the alternatives are worse. In effect, one would have ti chose between ignoring this factor or making subjective guesses.

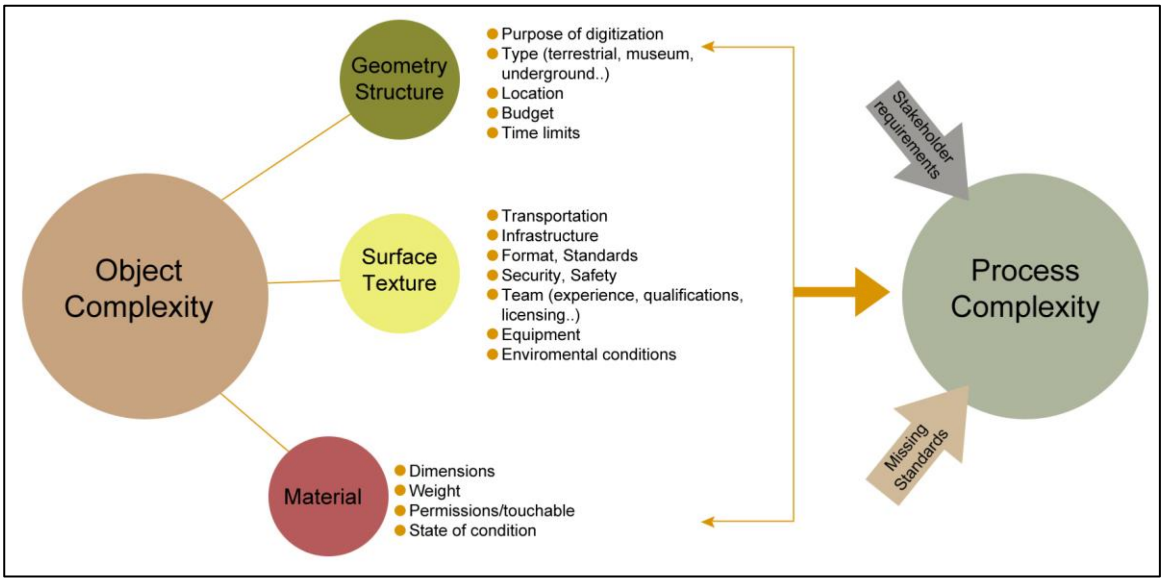


Figure 20: Moving from Object Complexity to Process Complexity.

We therefore define *process complexity* as the degree to which a process is difficult to analyse, understand or explain. One way to analyse it is to use a process control-flow complexity measure which examines the control-flow of consecutive processes and can be applied to data acquisition processes and workflows; then to evaluate the control-flow complexity measure to ensure that a high quality of results can be achieved on time.

In this study, a 'process' is defined as a sustained series of events or actions that effects change through a series of stages. It resembles an interactive algorithm where elements such as the stakeholder requirements, the 3D object properties (such as professional expertise, equipment) interplay with environmental parameters (see Figure 21a) and reorganise, or rearrange entities such as activities, decisions or contexts.

Therefore, the proposed **Data Acquisition Process Management System (DAPMS)** provides for the first time, a fundamental infrastructure to define and manage different processes in the area of 3D digitilisation of tangible CH objects.

The proposed approach and the steps to be followed are illustarted in the sequence of graphics within Figure 21a-21i:

- Figure 21a provides an overview of the parameters to be considered, starting with the requirements for the 3D object by the owner / stakeholder and moving through aspects related to object description, project definition, team characteristics, environment, equipement and pre-processing to the final deliverables
- Figure 21b outlines the owner's / stakeholder's requirements, in terms of: (a) the tangible object, (b) the project related stakeholder requireemts amd (c) the quality of the final results to be achived (minimum requirements needed for a public tender in 3D digitisation of tangible objects); for the latter, the requirements are grouped under main categories, referring to Geometry (2D, 3D), Image (texture, scale, spectral), Materials and Structural Health Monitoring.
- Figure 21c illustrates the minimum information required for the description of the 3D CH tangible asset.
- Figure 21d outlines the extended version of a 6D metadata structure to be used to describe the final results for Quality (Geometry: 2D, 3D, Texture: Image, Scale, Spectral,

Material and Structural Health Monitoring) together with the definition of the movable and non-movable objects.

- Figure 21e presents the main parameters to be considered for defining a 3D CH data acquistion project.
- Figure 21f is about the often underestimated role of human resources, putting emphasis on criteria to assess the level of qualifications and experience acquired through formal (professional) or other (amateur/hands-on) training.
- The environmental conditions to be considerd for a 3D data acquisition mission are presented in figure 21g taking into account different possible locations where the project can be conducted.
- As shown in figure 21h, the equipment has two broad categories: Software and Hardware. For the Software part, one may have to choose among open source, customised, commercial, or combinations of these. For Hardware, a key differentition comes from wether the project is conducted in an indoor or an outdoor environment. The parameters/technologies to be considered for an indoor project are shown in figure 21h and those for an outdoor projet in figure 21i.

Figure 22 represents a logical dynamic graph for a 3D digitisation project and summarises visualy the relation of complexity to quality.

Figure 23 then shows the Radial Pie Chart tool developed by this study to represent the complexity of a digitisation project. This tool lies at the heart of our efforts to obtain a concrete measurement of complexity in 3D projects that can be used forpractical purposes. Outside the direct remit of the study, a DAPMS Application (App) has been developed and at the time of wroiting this report is in the final stage of revision and testing in a series of 3D digitisation CH case studies.

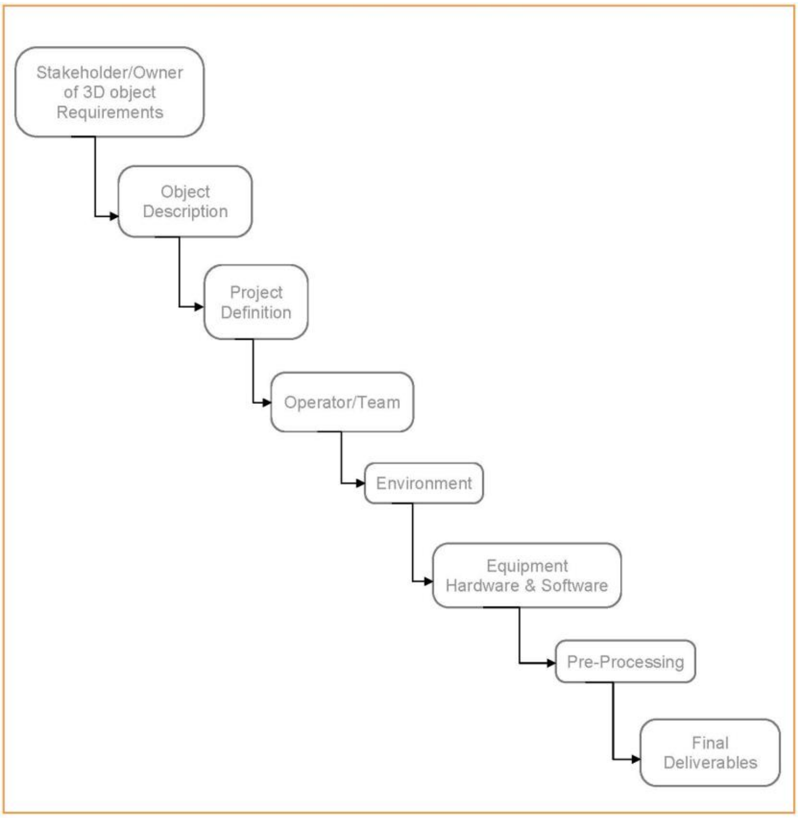


Figure 21a: Overview of the VIGIE2020/654 proposed DAPMS.

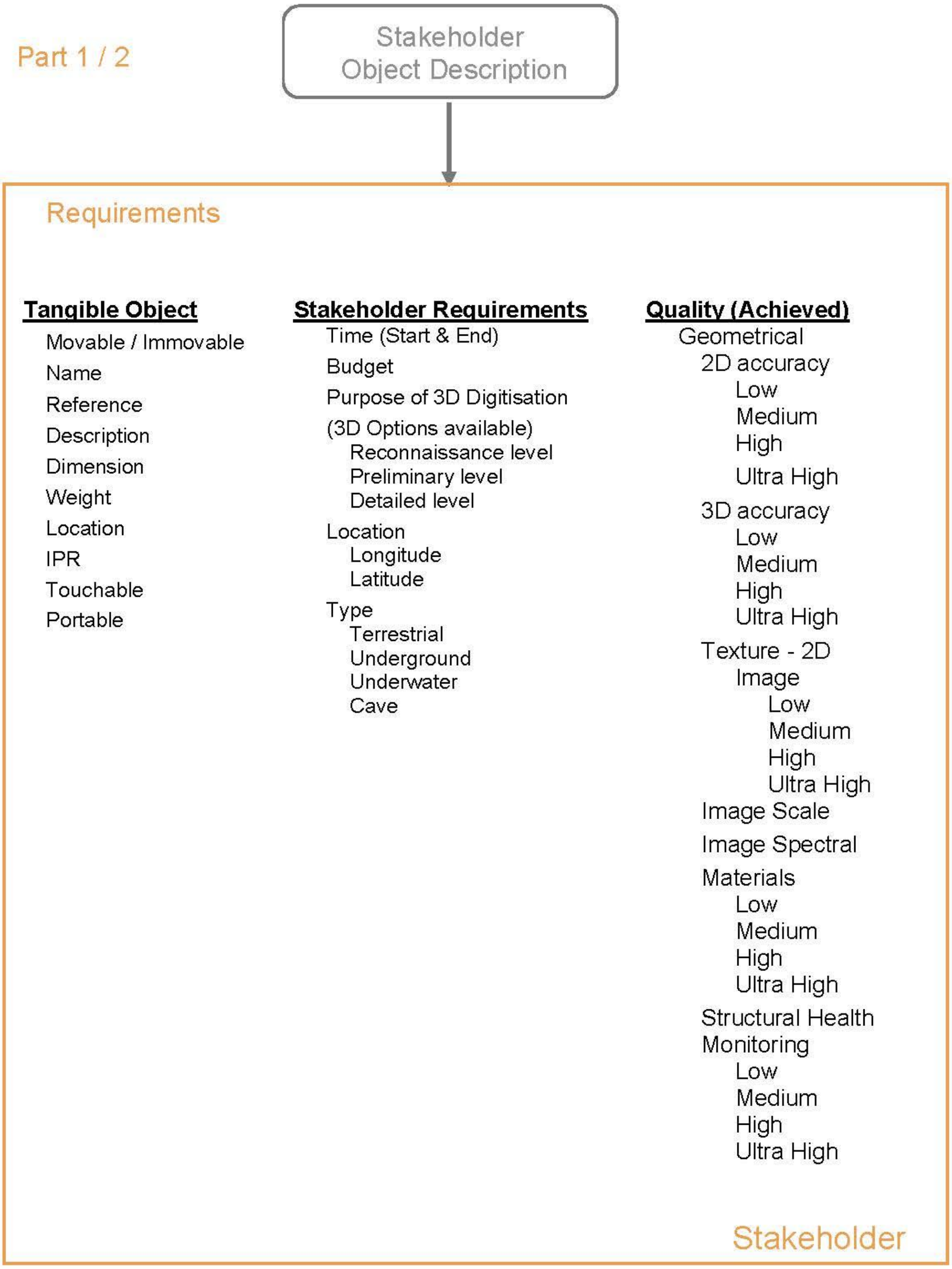
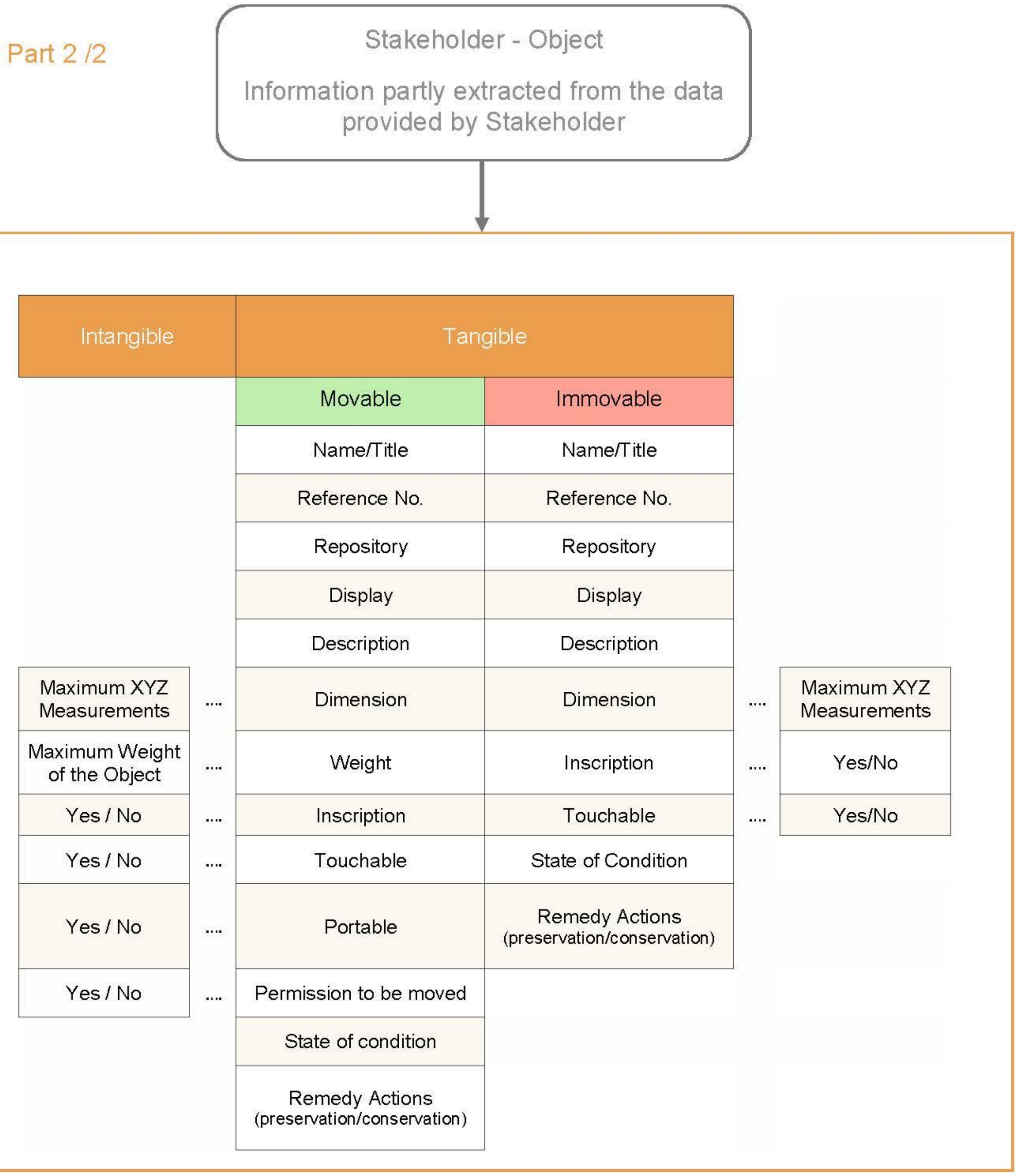
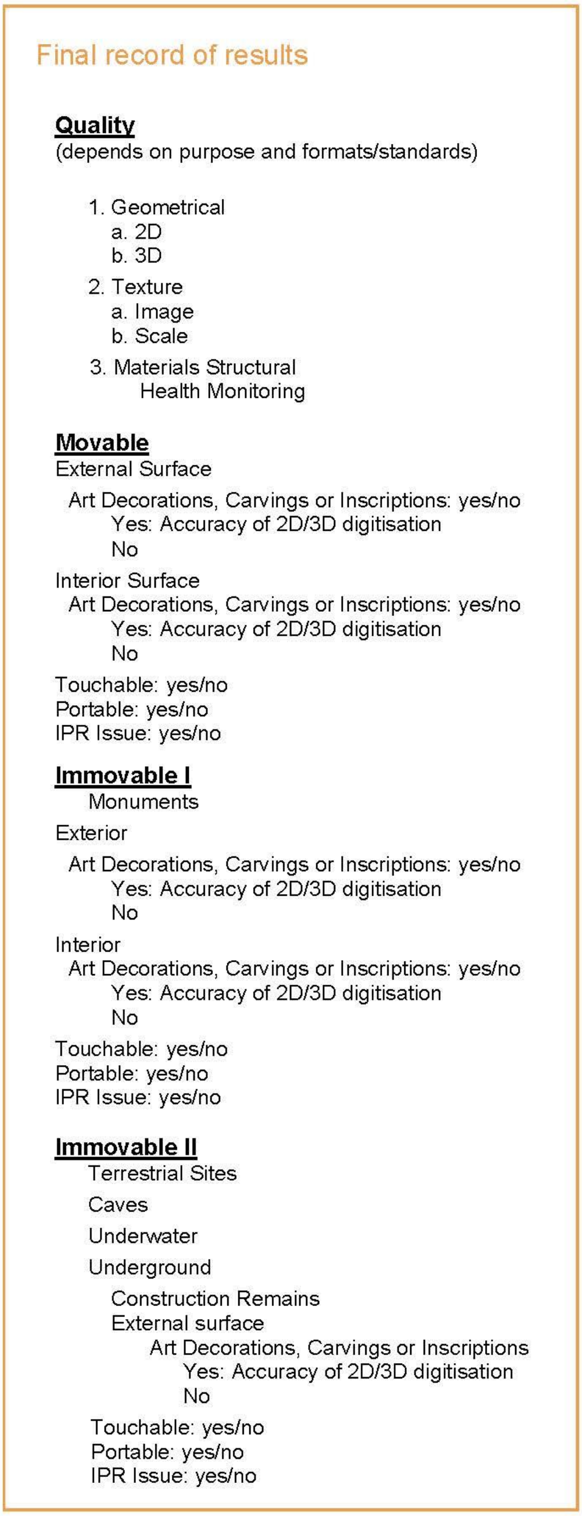


Figure 21b: The Tangible Object as a parameter of complexity.



Intangible		Tangible			
		Movable	Immovable		
		Name/Title	Name/Title		
		Reference No.	Reference No.		
		Repository	Repository		
		Display	Display		
		Description	Description		
Maximum XYZ Measurements	....	Dimension	Dimension	....	Maximum XYZ Measurements
Maximum Weight of the Object	....	Weight	Inscription	....	Yes/No
Yes / No	....	Inscription	Touchable	....	Yes/No
Yes / No	....	Touchable	State of Condition		
Yes / No	....	Portable	Remedy Actions (preservation/conservation)		
Yes / No	....	Permission to be moved			
		State of condition			
		Remedy Actions (preservation/conservation)			

Figure 21c: The Stakeholder Object's description as part of the complexity



Final record of results

Quality
(depends on purpose and formats/standards)

1. Geometrical
    - a. 2D
    - b. 3D
2. Texture
    - a. Image
    - b. Scale
3. Materials Structural
   Health Monitoring

Movable
External Surface
  Art Decorations, Carvings or Inscriptions: yes/no
    Yes: Accuracy of 2D/3D digitisation
    No
Interior Surface
  Art Decorations, Carvings or Inscriptions: yes/no
    Yes: Accuracy of 2D/3D digitisation
    No
Touchable: yes/no
Portable: yes/no
IPR Issue: yes/no

Immovable I
  Monuments
Exterior
  Art Decorations, Carvings or Inscriptions: yes/no
    Yes: Accuracy of 2D/3D digitisation
    No
Interior
  Art Decorations, Carvings or Inscriptions: yes/no
    Yes: Accuracy of 2D/3D digitisation
    No
Touchable: yes/no
Portable: yes/no
IPR Issue: yes/no

Immovable II
  Terrestrial Sites
  Caves
  Underwater
  Underground
    Construction Remains
    External surface
      Art Decorations, Carvings or Inscriptions
        Yes: Accuracy of 2D/3D digitisation
        No
  Touchable: yes/no
  Portable: yes/no
  IPR Issue: yes/no

Figure 21d: Quality as a 6D record of information/metadata

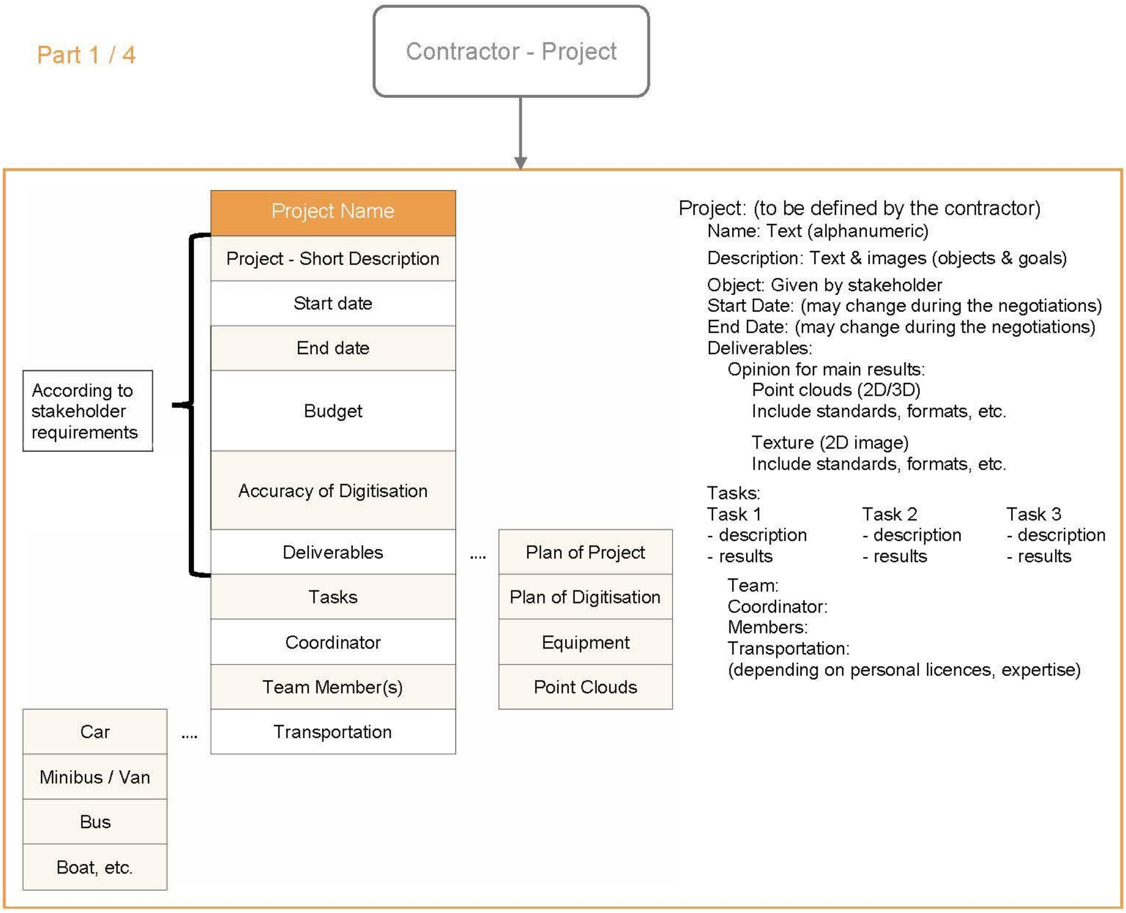


Figure 21e: The Project as a parameter of Complexity

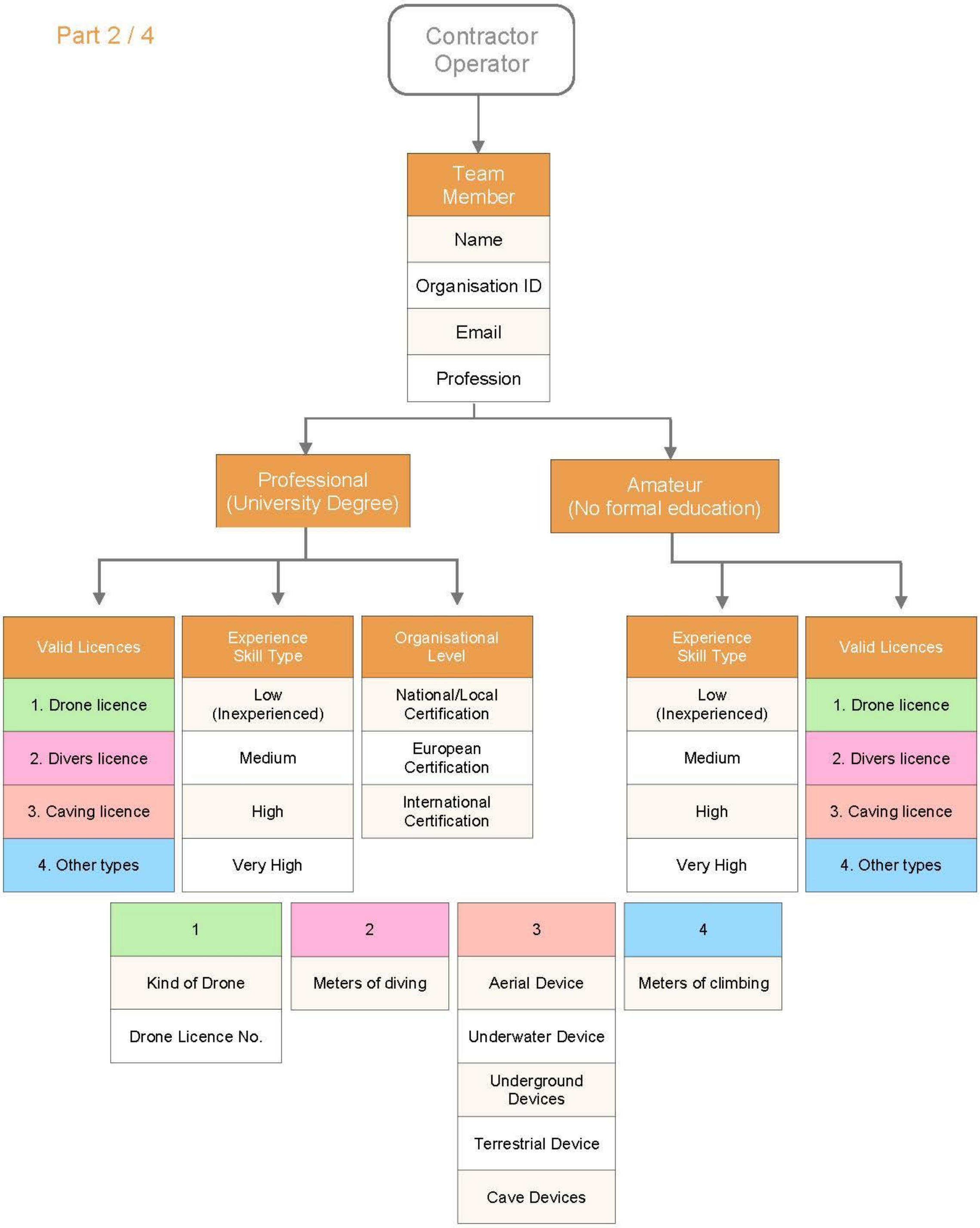


Figure 21f: The Human Resources as a parameter of complexity

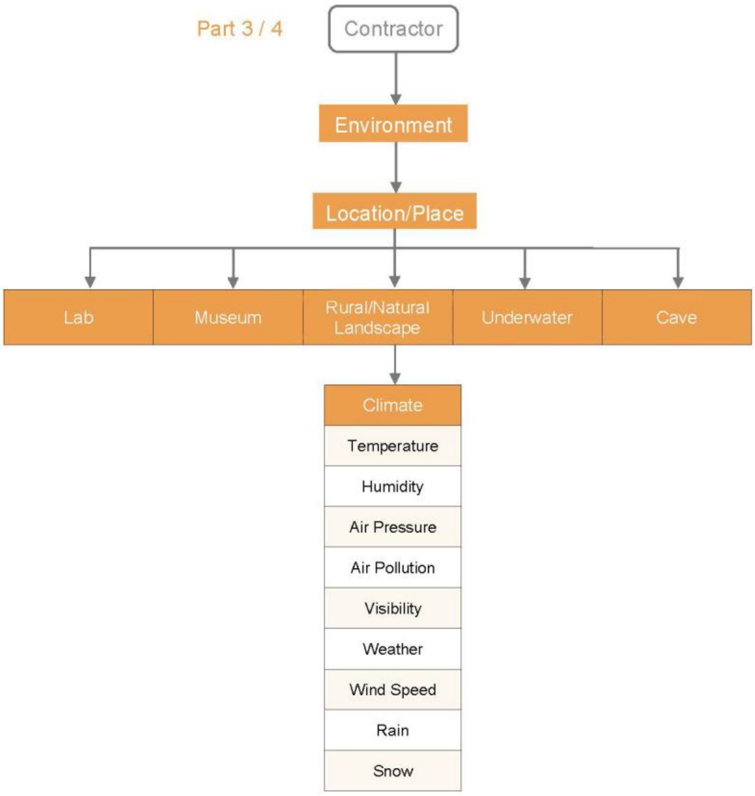
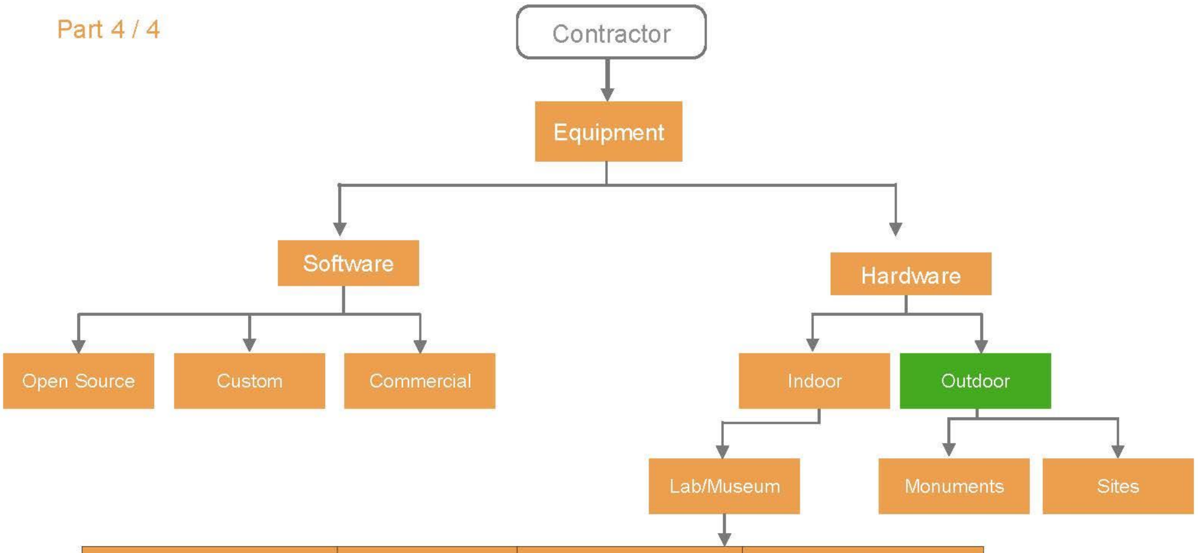


Figure 21g: The Environmental Conditions as a parameter of complexity



Analytical technique	Destructiveness	Portability	Compatibility with synchrotron radiation sources
OM: Organic Matter Tech.	Micro-destructive/non-destructive	Portable	No
AFM: Atomic Force Microscopy	Micro-destructive	Not portable	No
SEM: Scanning Electron Microscopy	Destructive	Not portable	No
ESEM: Environmental Scanning Electron Microscopy	Destructive	Not portable	No
TEM: Transmission Electron Microscopy	Destructive	Not portable	No
UV-vis: Ultraviolet-Visible Spectrosophy	Destructive	Portable	No
LIBS: Laser-Induced Breakdown Spectroscopy	Micro-destructive	Not portable	No
FTIR: Fourier Transform Infrared Spectroscopy	Micro-destructive	Portable	No
Raman: Raman Spectroscopy	Micro-destructive	Portable	No
TG/DTA/DSC	Destructive	Not portable	No
XRF: X-ray Fluorescence	Destructive / Non-destructive	Not portable	Yes
XRD: X-ray Diffraction	Destructive	Not portable	Yes
XPS: X-ray Photoelectron Spectroscopy	Destructive	Not portable	No
XAS	Non-destructive	Not portable	No
PIXE/PIGE	Non-destructive	Not portable	No
CT / CAT	Non-destructive	Not portable	No
MS-based techniques	Destructive	Not portable	No
2D – Camera/Texture	Non-destructive	Portable	No
3D - Scanner	Non-destructive	Portable	No

Figure 21h: Data Acquisition Techniques (equipment) for indoor and outdoor 2D/3D digitisation as a parameter of complexity

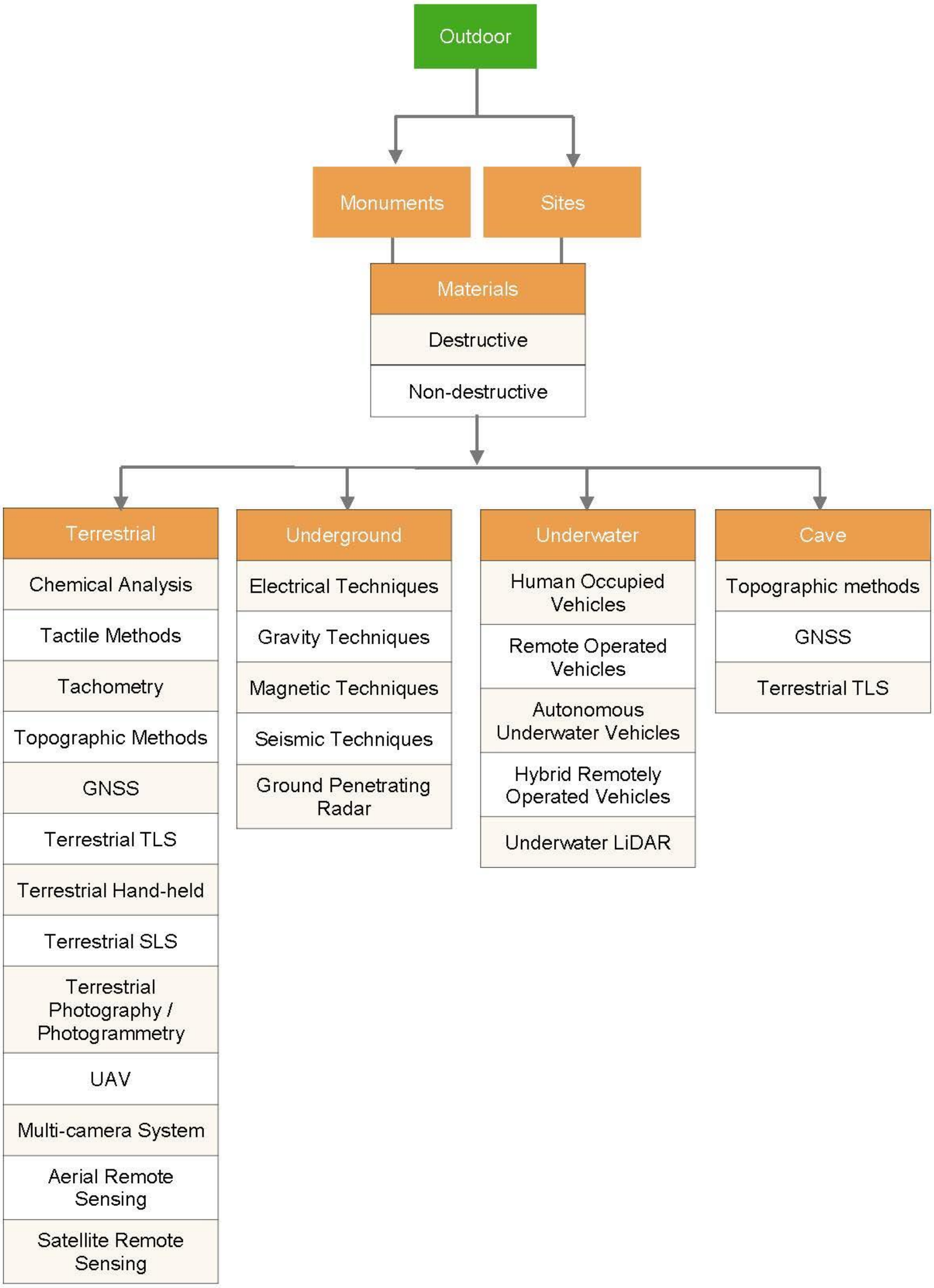


Figure 21i: The Location of the tangible object as a parameter of complexity

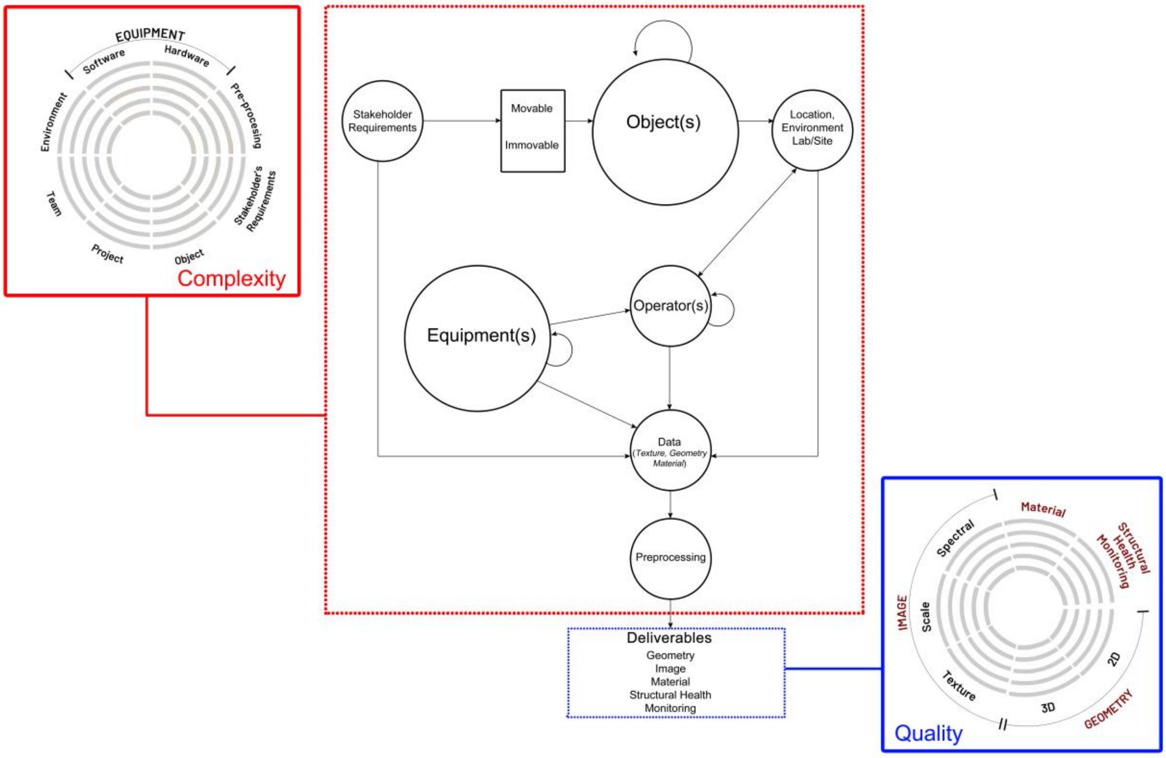


Figure 22: Overview diagram illustrating the relation of complexity to quality.

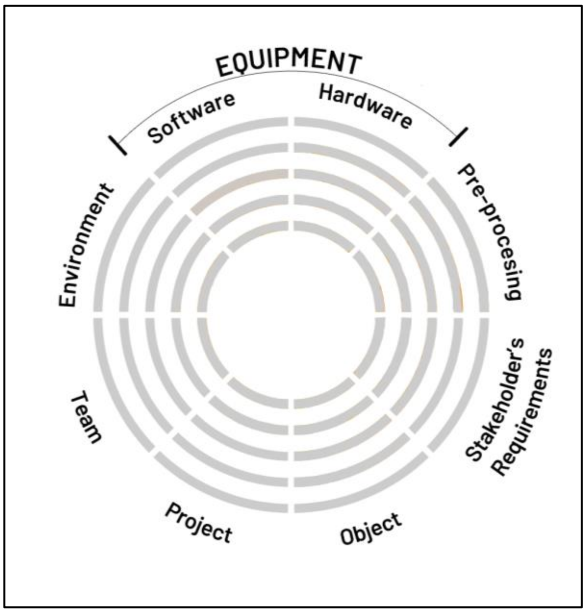


Figure 23: Radar chart depicting the parameters for complexity.

3.10. Layering Complexity Parameters

Apart from the apparent suitability issues that come with task-specific sub-steps in 3D digitisation projects (see Figure 21a), digital CH software requirements tend to differ in terms of reliability, operability, compatibility, maintainability, quality of resuts, security etc.

The demands in computational power, bandwidth, memory, time and cost are, however, always determined in relation to the corresponding hardware constraints. Digital CH data acquisition alone (multi-sensing), can call for considerable variance in hardware selection (cameras, scanners, drones etc.). Additionally, demands in storage capacity (cache/physical memory, disk drive and partitions, cloud capacity, etc.), processing power (operation/network configurations) and representation (monitors, printers etc.) are often determined ad hoc. The constraints in computational power, bandwidth, memory, time and cost restrictions are always decided in relation to the corresponding software demands (Figure 24).

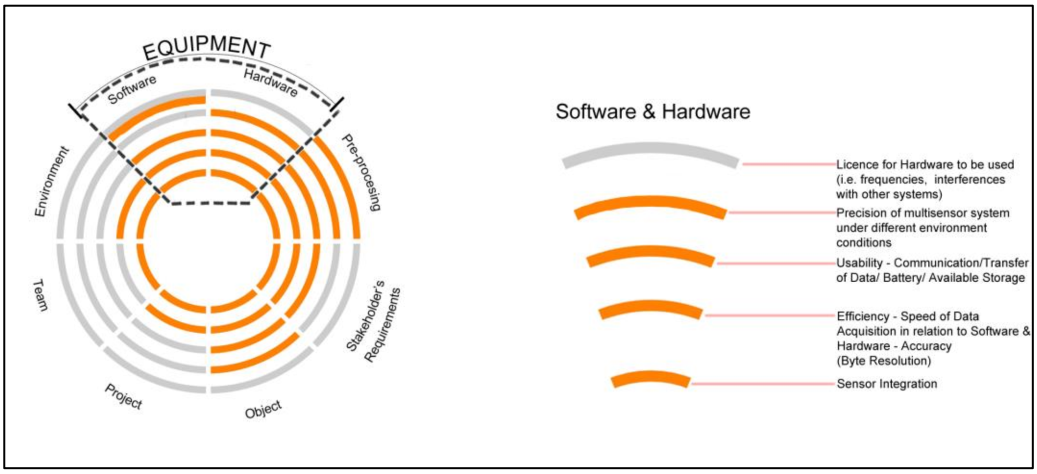


Figure 24: Layers of the Software and Hardware Equipment complexity parameter.

Digital CH ***Data Preprocessing*** requirements tend to vary significantly, depending on the scalability associated with the data to be acquired (often recorded from different sensors, as part of disparate sources, in different formats etc.). This in turn imposes changes in demand for Data Consolidation / Registration (collection, selection, merging or integration), Cleaning (missing value imputation, noise control), Transformation (normalisation, aggregation/discretisation) and Reduction (decreasing number of variables/cases, balancing skewness); each coming with additional hardware and software implications (Figure 25 and Figure 26).

- *Structure from Motion (SfM*) is a technique in computer vision to acquire 3D geometry from 2D images, used in the Data Preprocessing phase. It utilises photogrammetric range imaging for estimating three-dimensional structures from two-dimensional image sequences [98]. This technique constraints often exist in relation to the accessibility of a site and the impossibility of installing invasive surveying pillars which permit the use of traditional surveying routines (like total stations). SfM provides a non-invasive approach for the structure, without direct interaction between the structure and any operator. The method is accurate where only qualitative considerations are needed. It is fast enough to respond to the monument's immediate management needs. The first operational phase is dedicated to a precise preparation of the photogrammetric surveying to establish the relation between the best distance from the object, focal length, the ground sampling distance (GSD) and the sensor's resolution. With this information, the programmed photographic acquisitions must be made using vertical overlapping of at least 85% between two images.
- *Traditional surveying* is widely used for archaeological excavations. The entire process needs to be documented and surveying equipment as GNSS receivers, total stations are part of the tools Archaeologists use. Any dense 3D scanning equipment, as laser scanners or photogrammetry solutions, have excellent functionality to define and use a local coordinate system which is defined by archaeological landmarks, i.e. ground control points measured with GNSS or total stations. Registration, in this case become trivial, since all scanning devices work in that same local national coordinate system and are therefore by definition registered,
- *Drone based laser scanning* is a highly valuable trend and its going to be used more in the near future in the 3D CH data acquisition. At the moment the main challenge exist in a lightweight system with sufficient accurate GPS and IMU data to register the laser scans,

- *Photogrammetric reconstruction* of small objects on a turntable requires the object to be placed on the turn table in several locations. Each location will produce a partial 3D-model that will need to be registered and merged to obtain a complete 3D model with SFM processing,
- *Aerial/ terrestrial registration* is a real challenge by aiming at registering data from different sensors (Lidar, Images, Videos) and from different positions.

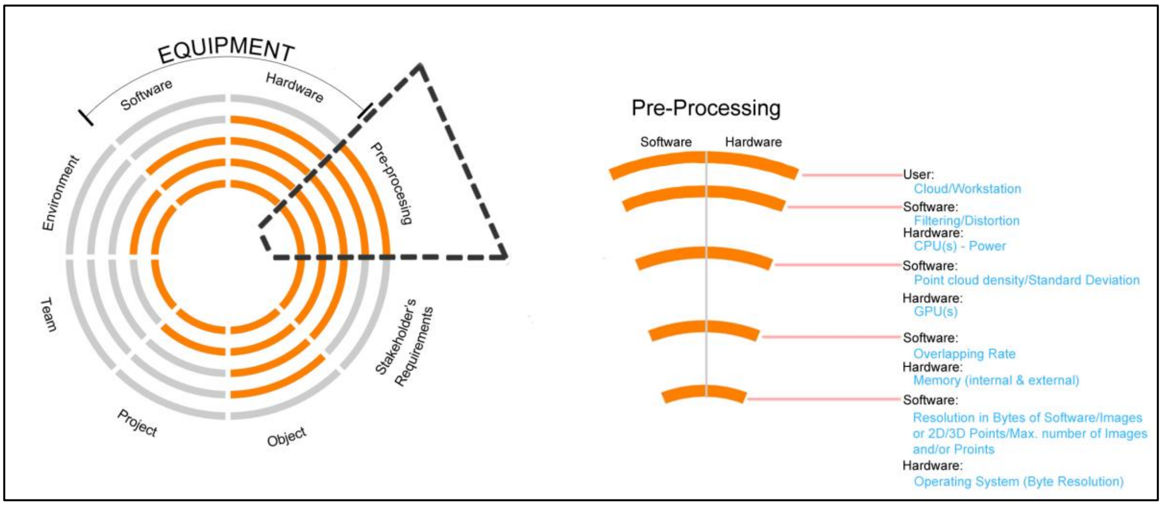


Figure 25: Layers of the Pre-processing complexity parameter.

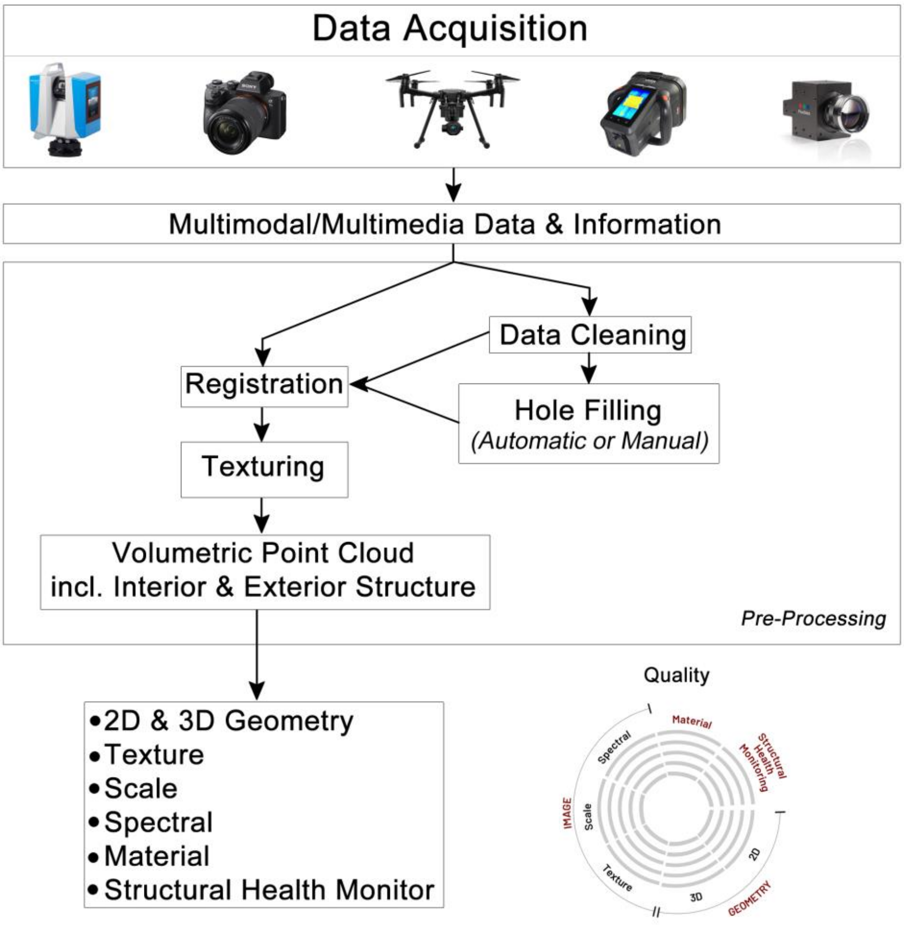


Figure 26. Overview of the Preprocessing steps

Every complexity factor resulting from ***stakeholder requests*** including the assigned time horizon, total budget availability/priority and overall vision indirectly controls time allotment and all resources allocation in general, based on the digitisation purpose, desired level of detail, location, type, etc. (Figure 27).

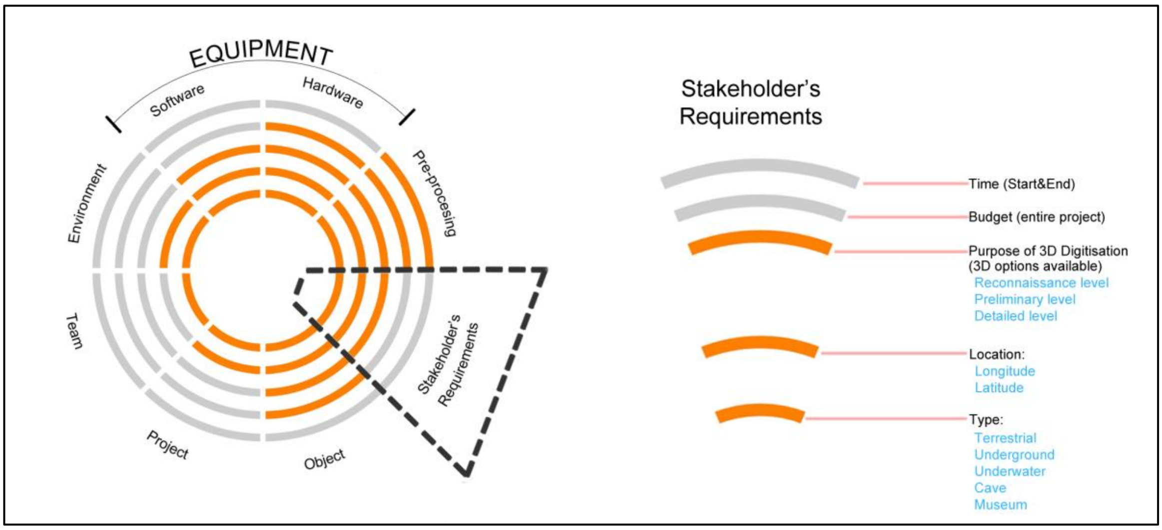


Figure 27: Layers of the Stakeholder's Requirements complexity parameter.

Complexity factors stemming from ***object*** attributes or specifications (Figure 28), including states of conditions, physical, chemical and functional properties as well as dimensions, classifications, permissions for transportation and any other object-specific concerns (health and safety, legal, ethical etc.) regulate the digitisation process. An increasing requirement of the CH community and corresponding research institutions (such as at the of writing this report running H2020 MSCA ITN CHANGE[52] project) relates to the fidelity of colours, ranging from the usual colour calibration within an image-based modelling pipeline, to more demanding reflectance measurements such as light-material interactions. Such a requirement is a novel complexity gap for the 3D modelling pipeline, including the visualisation step. At the moment of writing this report, there is still no universal consensus on the best format for rich colourimetry measurements.

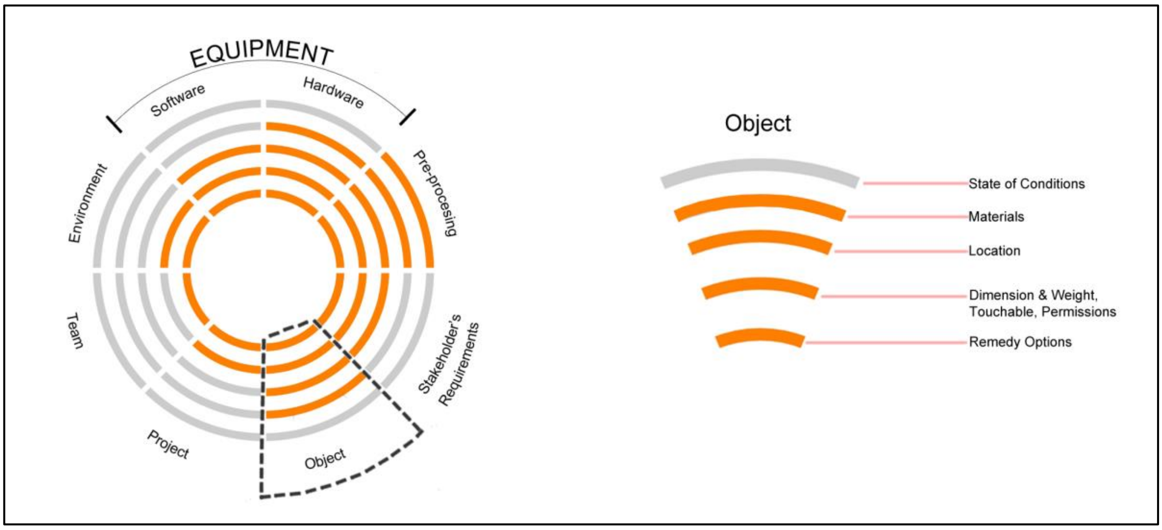


Figure 28: Layers of the Object complexity parameter.

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[52] H2020 MSCA ITN CHANGE project (accessed May 3. 2021)

The ***Project*** parameter includes all complexity factors pertaining to digital CH project planning, performance monitoring and management (Figure 29). This includes setting up an integrated management framework to effectively share resources, experience, knowledge and expertise in pursuit of collective intelligence, subjected to any physical, operational, technical or financial constraints and logistics.

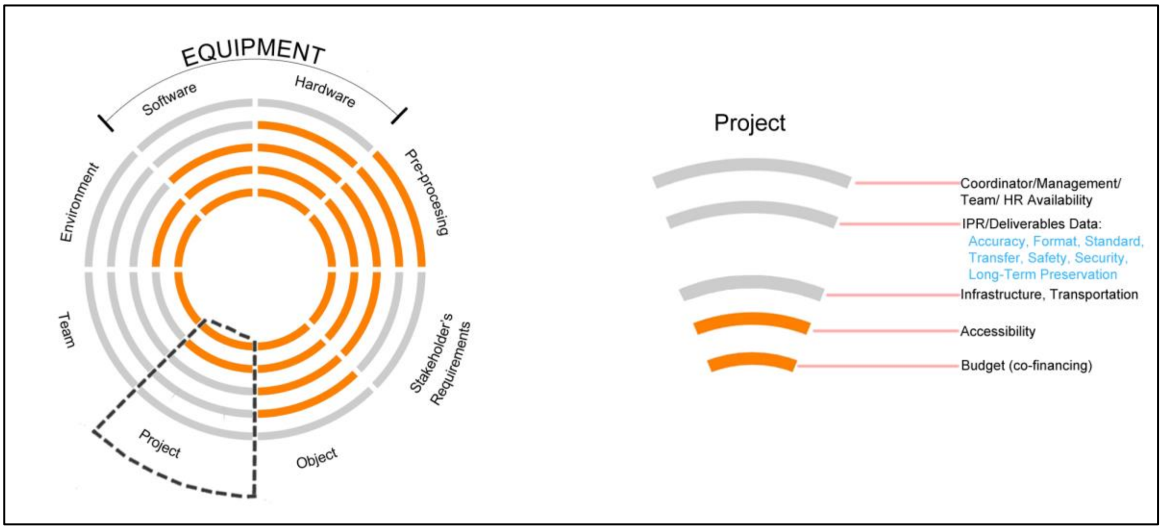

Figure 29: Layers of the Project complexity parameter.

The ***Team/expert*** parameter incorporates all complexity factors associated with personnel grouping (team formation, communication, interaction and collaboration) including HR responsibility and accountability (Figure 30). This ranges from user qualifications and corresponding worldwide recognised certification, licences and equipment/infrastructure distribution, to interpersonal coordination together with quality assurance implications in the field.

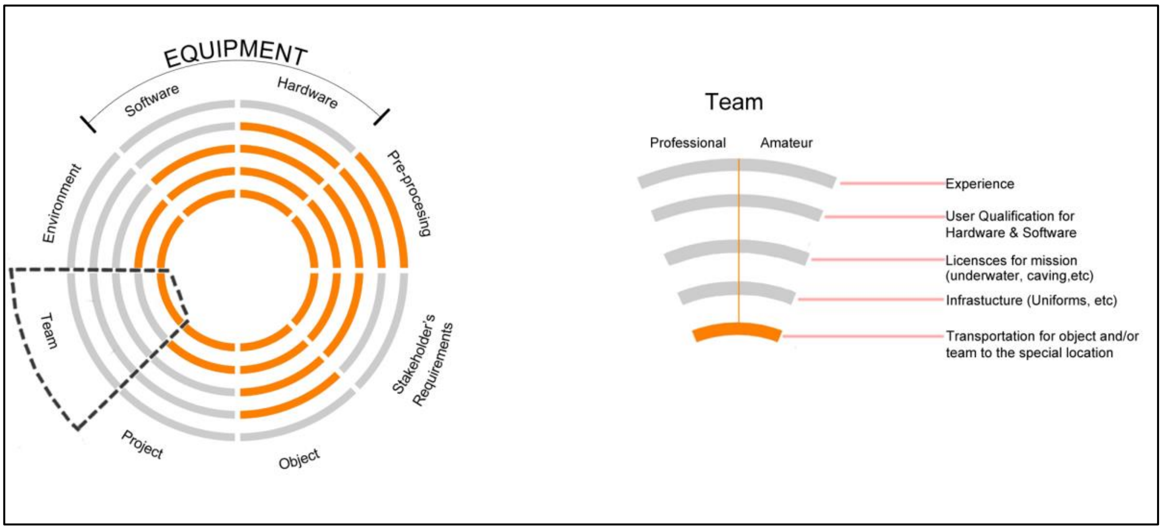

Figure 30: Layers of the Team complexity parameter.

Environmental conditions (controlled or not) that may be perceived as contributing factors of complexity are included here. Both long-term (climate) conditions known to interfere with 3D data acquisition in general, such as rain, snow, wind, frost, fog, and sunshine, as well as physical measurements that become critical in reporting, such as temperature, humidity, barometric pressure, wind speed/direction, air pollution, etc. are taken into consideration (Figure 31).

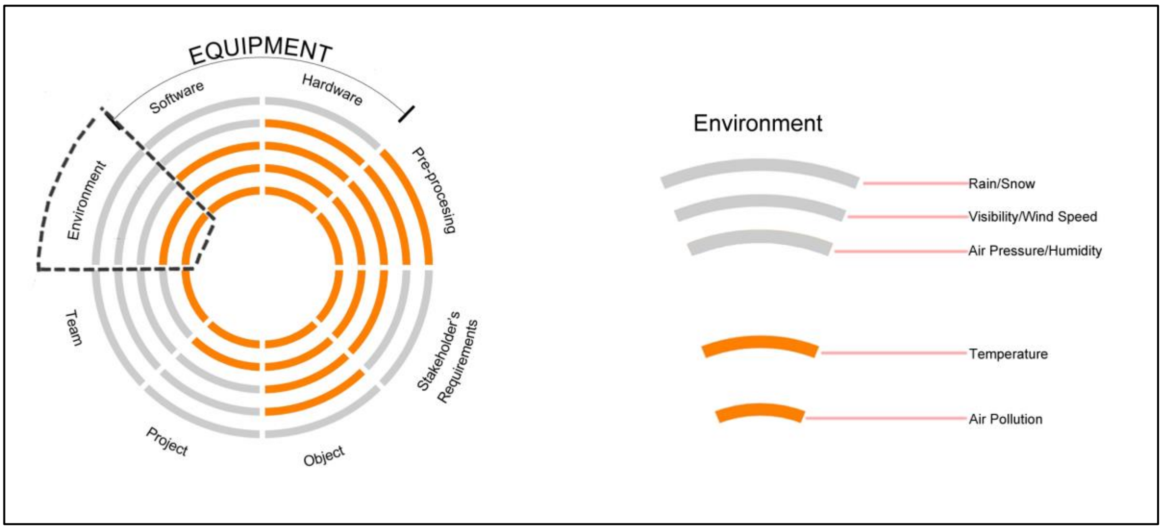

Figure 31: Layers of the Environment complexity parameter.

3.11. Impact of Complexity on Quality

A report[53] by the European Union's DCHE[54] states: '*It is important to consider what quality means in the context of 3D digitisation. It is not simply about the number of points, the accuracy with which a three-dimensional shape has been captured, or how well the asset's colour and surface texture is represented.'* Quality should also be a measure of fitness for purpose, usability, and whether the outcomes of a project are both sustainable and capable of longer-term preservation. The term quality is highly subjective and defining what it means is not straightforward. This document also describes several principles and recommendations which provide essential background for this study.

3.12. Parameters that Determine Quality

Quality is a fundamental consideration in the 3D digitisation of CH. Like 'complexity', the term 'quality' is used without a precise definition, and this presents a significant challenge since tangible CH is exceptionally diverse. For this study, quality comprises different parameters, such as the degree of detail, the geometric accuracy of the 3D shape, and the fidelity of the capture of colour/texture. These parameters - connected to complexity – fall under three main categories: geometry, radiometry/photometry, and completeness. In Figure 32, an overview of the parameters is shown and then applied to describe the different layers for each parameter in Figures 33-37.

Quality parameters are engaged at different stages of the 3D digitisation process and vary depending on the type of tangible CH and the equipment and methodology used. The possible purposes or uses for the resulting 3D material also determine different combinations and levels of those parameters to identify the minimum level of quality that fits the definition.

As stated earlier, there is no generally accepted framework for specifying the level of detail and accuracy in CH digitisation. In addition, critical quality indicators such as *resolution*, *geometrical accuracy, materials, structural analysis* and *uncertainty* are relevant in different case studies. A possibility is to embed them in a metadata structure in order to achieve easily the retrieval of specific information in the use of data analytics. However, a key challenge is to reach a widespread and objective agreement for such a quality assessment, bearing in mind the complexity described earlier.

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[53] DCHE Report on Basic principles and tips for 3D digitisation of cultural heritage (accessed Jun. 1, 2021).

[54] Expert Group on Digital Cultural Heritage and Europeana (DCHE) (accessed Jun. 17, 2021).

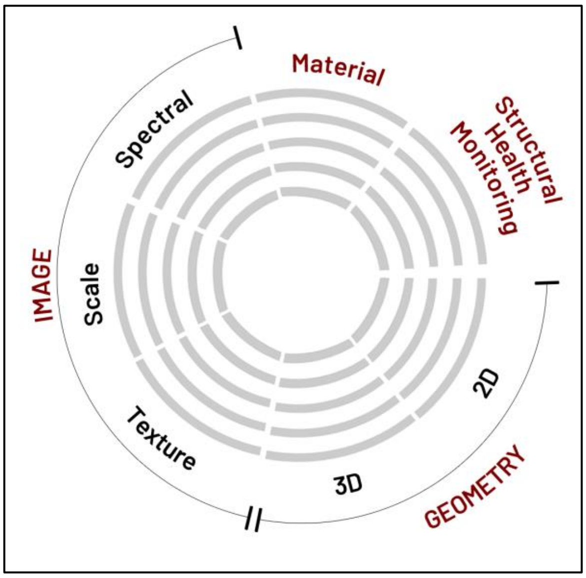

Figure 32 Radial chart illustrating the parameters for quality.

All quality aspects in answer to the complexity imposed by the characteristics of the ***material(s***) involved such as individual strength attributes like yield, fatigue, tensile or toughness could be directly or indirectly, individually or jointly interacting with the overall quality of the digitisation process. To mention a few, these include chemical composition, moisture, corrosion, carbonation, resistance and porosity (Figure 33).

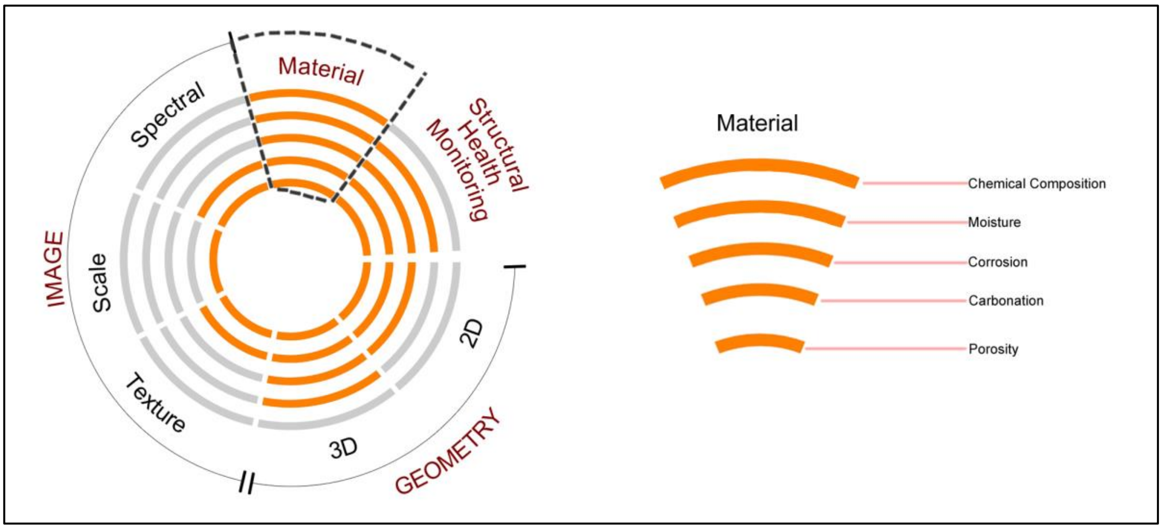

Figure 33: Layers of the Material quality parameter.

Another important DCH quality factor is the extent to which the digitisation process responds to adverse ***structural*** changes, looking for structural reliability and life-cycle management. This implies a meticulous condition assessment that goes beyond common compositional analyses to appropriately cover states of conservation, connectivity, foundation strength/integrity and material quality for large-scale built objects, monuments, and sites (Figure 34).

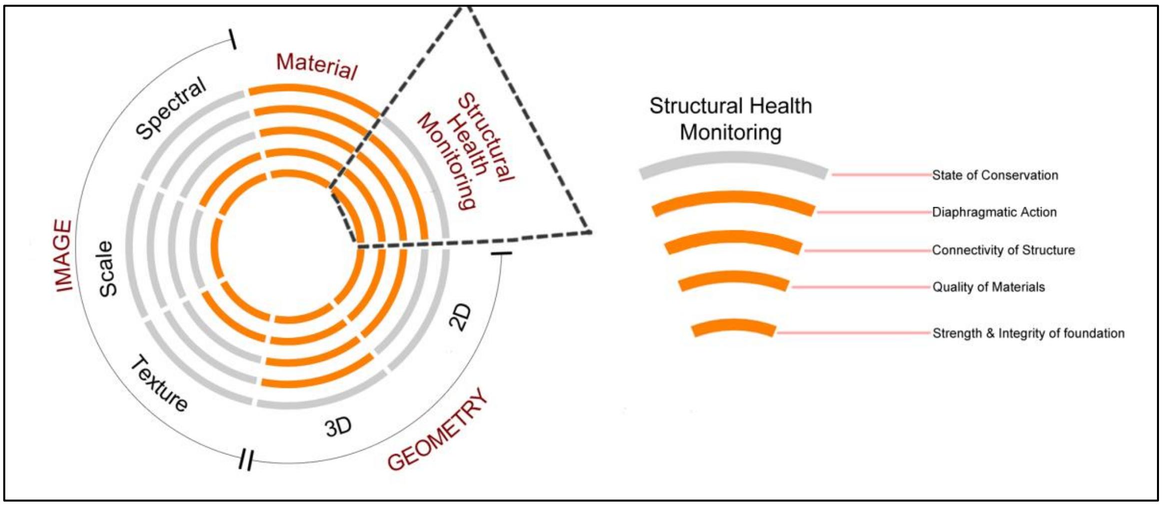

Figure 34: Layers of the Structural Health Monitoring quality parameter.

A substantial subset of quality factors relating to computational **geometry**, such as accuracy and precision, may coincide with **2D attributes** that could be efficiently represented on a coordinate plane. Relative measures are often estimated with respect to requirements in point density and corresponding (lack of) completion, with enhanced capturing resolution in mind (Figure 35).

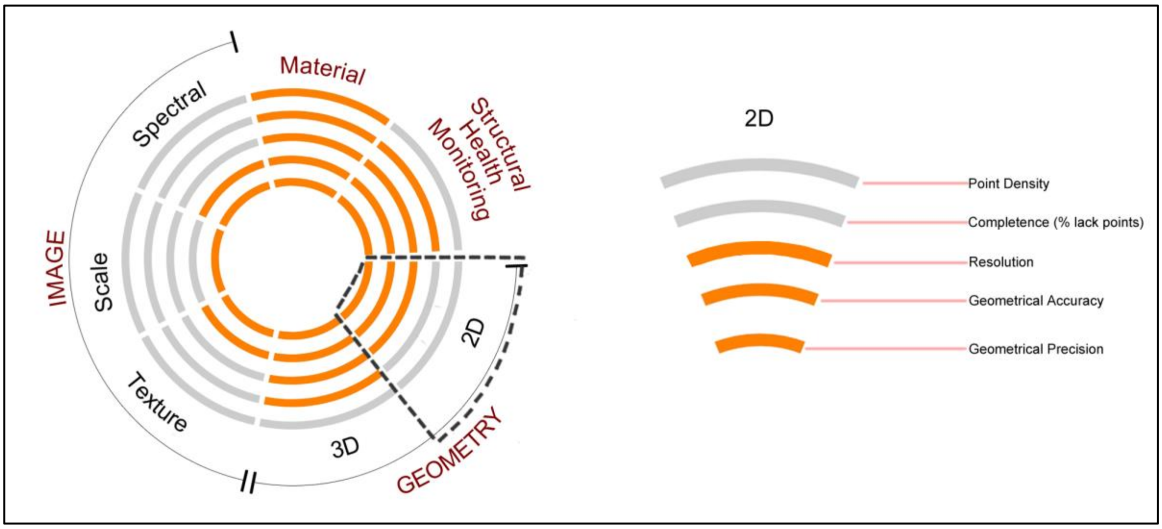

Figure 35: Layers of the 2D geometry quality parameter.

Similarly, those same quality factors could concern the ***3D aspects of geometry***, for when generating high-resolution point clouds via specialised equipment (multi-view cameras, depth sensors, TOF, etc.), often calling for advanced signal processing tools and (semi-automated) modeling practices. In cases of complex background or textures, 3D moving objects, and severe occlusions, relative measures might dictate computationally intensive self-calibration/registration and synchronisation methods (Figure 36).

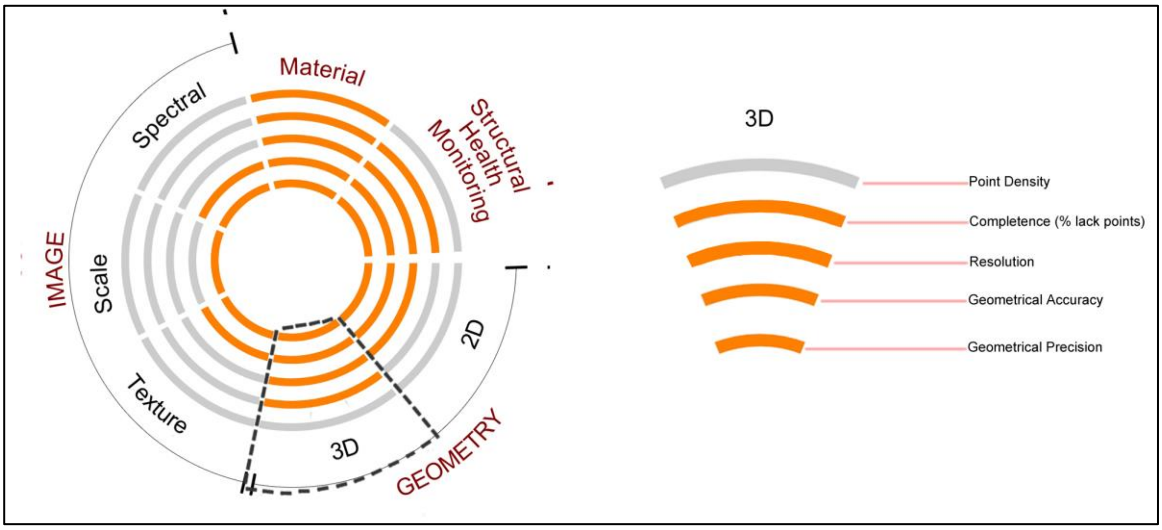

Figure 36: Layers of the 3D geometry quality parameter.

Image quality in DCH digitisation often comes down to realistic 3D visualisations, employing sufficiently detailed rendering techniques, to support object representation in multi-dimensional space. That is, calculating and adjusting textures based on recorded physical material characteristics such as opacity, contrast, and granularity, to a point where external structure approximations reflect the desired shape accuracy and color depth (Figure 37).

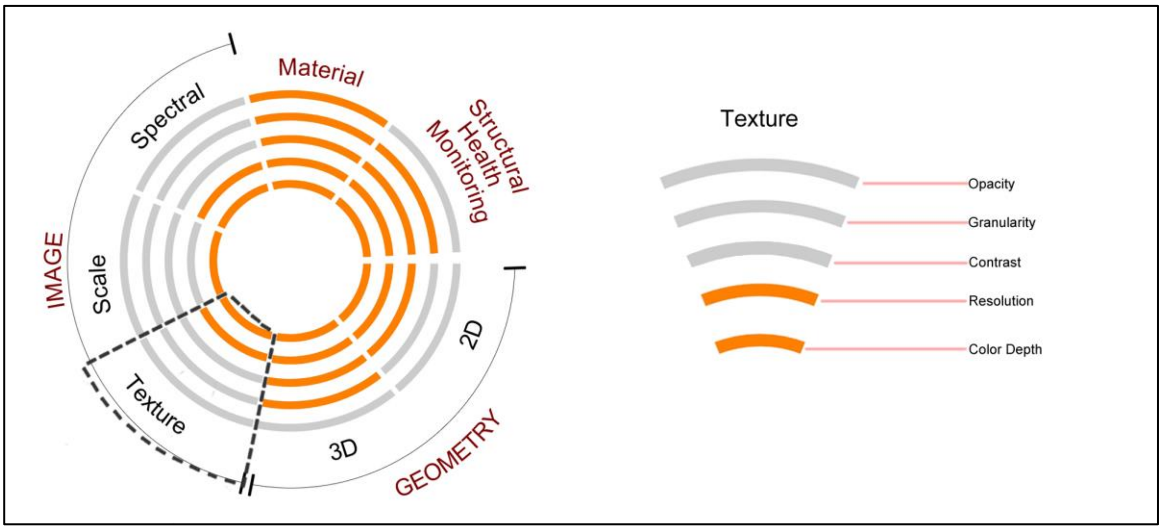

Figure 37: Layers of the Texture image quality parameter.

Quality in digital CH is often perceived as an indication of potential detail in an image, referring to the relative difference in size (or distance) between the image and the (radiometric) features represented on the ground. The quality of the calculated ***scale*** depends on the accuracy of the measured distance, as well as the spatial resolution (pixel ratio), affecting color range and (bit) depth (Figure 38). Image quality in DCH is often defined by ***spectroscopic*** features achieved via theoretical, experimental, and numerical techniques that strive to meet multi-objective photometric criteria (spectral regions). These include Absorbance, Transmittance, and Reflectance levels mapping to particular source, range, wavelength and frequency configurations (Figure 39).

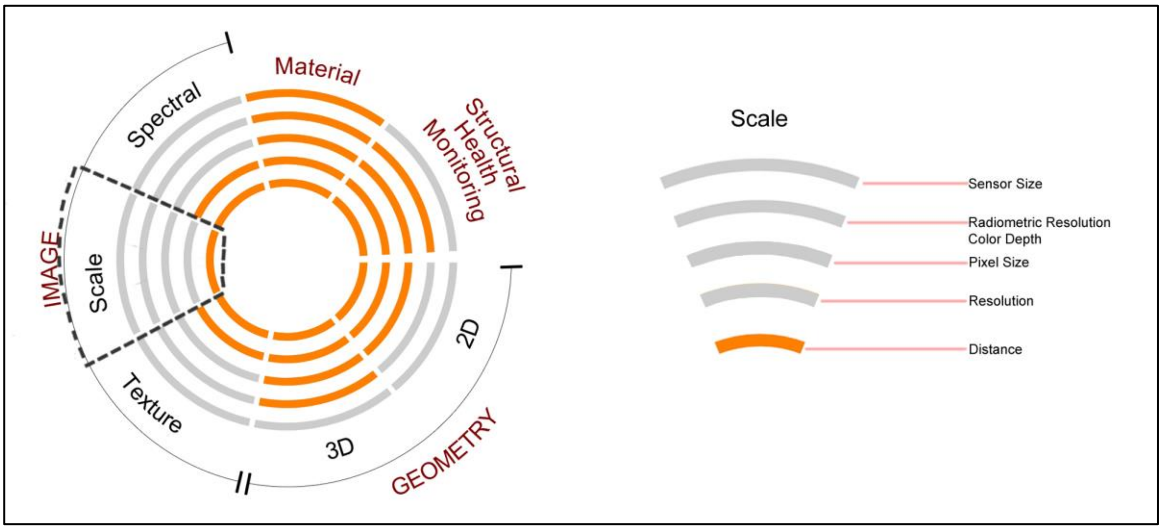

Figure 38: Layers of the Scale image quality parameter.

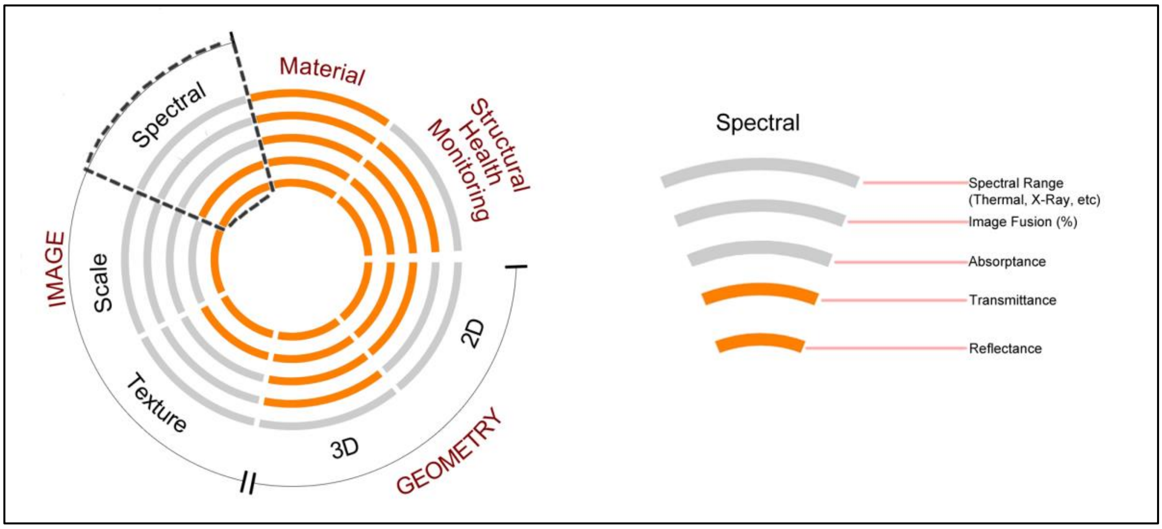

Figure 39: Layers of the Spectral image quality parameter.

3.12.1. Uncertainty as a General Expression of Quality in 3D Digitisation

We are proposing a general approach for evaluating and expressing *uncertainty* in the 3D digitisation/measurement that can be followed at various levels of quality. In this way, our principles are focusing on:

- maintaining complexity and quality control as well as quality assurance in the digitisation of tangible assets in CH;
- calibrating the standardisation of a methodology for the estimation of a complexity and quality in 3D digitisation of CH assets in order to achieve traceability to national standards on contributing with and imposing norms, guidelines, benchmarks in the domain of the study;
- promoting and stimulating advanced and applied research as well as innovation and further development, in the area of 3D digital documentation in CH.

In practice, there are many possible sources of uncertainty in a digitisation/measurement, including:

- stakeholder requirements – especially the time and budget available and the precision for the digitisation/measurement;
- non-professional and/or unskilled personnel in place;

- non-calibrated and inappropriate equipment to be used under the given location and environmental conditions;
- different resolutions and scaling factors in the case of different complex data acquisition devices;
- lack of available experience with / or lack of general knowledge on the behaviour and properties of relevant materials and instruments;
- inadequate knowledge of the effects of environmental conditions on the measurement, or imperfect measurement of environmental conditions;
- incomplete definition of the measurand, or in general misunderstanding of the main objectives of the project;
- wrong definition about the object's state of condition and remedy options;
- imperfect setup and definition of the measurand (misunderstanding of the stakeholder requirements for the project and object);
- inexact data and other parameters obtained from external sources and used in the data pre-processing, such as the merging of multisource data, or the point-reduction algorithm;
- inexact values of measurement standards and technical reference materials;
- non-valid approximations and assumptions incorporated in the measurement method and procedure;
- variations in repeated observations of the measurand under apparently identical conditions (but different personnel and/or devices).

In most cases, a measurand Y is not measured directly, but is determined from N other quantities X_1, X_2, ..., X_N through a functional relationship $Y= f (X_1, X_2, ..., X_N)$. In this way, the value of Y can be calculated by a mathematical formula that can also be used to estimate the uncertainty – in our case of the complexity.

3.13. Exemplifications of Complexity

During the second half of the study, the set of parameters determining levels of complexity and related more broadly to quality has been considered in the context of 43 cases (18 Immovable and 25 Movable Objects). A smaller selection of significant tangible CH 3D digitisation projects has been treated in greater depth. The radial device created by the Study team for use in measuring complexity in the context of the App which it is developing has also been applied to this selection, which can also be found in Annex 7.

This work has supported the development of a taxonomy of data acquisition technologies and their output formats. Other contextual taxonomies have been developed for Movable and Immovable heritage, based on several of UNESCO's World Heritage conventions and recommendations This approach aims to provide adequate descriptors, enabling to exemplify the different aspects and degrees of complexity of tangible CH from the point of view of 3D digitisation processes. It also provides an operative terminology allowing an adequate representation of the pertinent knowledge.

4. Standards and formats

The formal definition of a standard is "*a document, established by consensus and approved by a recognised body, which provides for common and repeated use, rules, guidelines or characteristics for activities or their results, aimed at the achievement of the optimum degree of order in a given context*"[55].

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[55] Standard (accessed Jun. 17, 2021).

Project standards are set to attain the project's goals in a planned and organised way. Therefore, they may vary from mission to mission, but the goals are usually similar - to complete the project according to the given requirements, within the set time-frame, under the defined conditions/requirements and without exceeding the allocated resources. Standards ensure reliability, consistency, interoperability and guarantee a high level of quality of results and data.

Any effective 3D data acquisition project must lay down project management methodologies, provide a step-by-step guide and a protocol for project management, administration and coordination, which facilitates project implementation with high quality results, clear reporting procedures and necessary documentation (deliverables) throughout its duration.

When planning or defining the deliverables of a CH 3D digitisation project, it is, for example, crucial to: understand the stakeholder/owner requirements and all various production stages during the 3D CH data acquistion; deliver the final data and results in associated file formats; apply health and safety regulations for all personnel; ensure equipment functionality under normal conditions; and protect, IPR and the CH objects. Furthermore, project deliverables should be clearly defined in terms of what stakeholders expect to get or achieve, especially the final data (which should be archived for long-term preservation) and be as precise as possible, since the information they provide will affect timelines, budget, and client expectations.

There are a series of production stages in a CH digitisation project, each of which can generate its data formats. Site-work will produce the original raw proprietary data, typically directly from the scanner or photogrammetric system. In-office processed output files can include the registered point data, processed photogrammetry, and converted imagery files. Final production data may consist of reformed 2D/3D CAD[56], HBIM[57,58], FEM animations, and other processed outputs.

For 3D modelling, photogrammetry and point cloud data, there are hundreds of different file formats (see also Annex 3 – formats). Other terrestrial laser scanners produce raw data in a variety of formats. Additional processing software can accept some of these file types, and each piece of software has different exporting capabilities. Relative to this study, two focus areas for formats are terrestrial laser scanning / 3D modelling and photogrammetry / digital photography. In Annex 3 we provide a thorough list of relevant 3D raster data and vector formats, together with an extensive listing of various types of current technology and equipment for documentation.

4.1. Data Types

It is essential to understand the distinction between proprietary and open format data, when we are using them and why? A proprietary format can also be a file format whose encoding is in fact published, but is restricted through licences such that only the company itself or licensees may use it. In contrast, an open format is a file format that is published and free to be used by everybody.

Proprietary Data

A proprietary file format is the property of a stakeholder that contains data that is ordered according to a specific encoding scheme (specific rules). User-generated data in this format

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[56] Computer Aided Design-CAD (accessed April. 17, 2021).
[57] Building Information Modelling - BIM (accessed Jun. 17, 2021).
[58] BIM for heritage science: a review (accessed Jun. 17, 2021).

may need proprietary software to read their files reliably. Users normally need to pay to use the software and are unable to read or modify the source code.[59]

Open Data

An open-source format is a file format for storing digital data, defined by a published specification usually maintained by a standards organisation, which everybody is allowed to use and implement. For example an open format can be implemented by proprietary and free and open-source software, under the typical software licenses used by each.[60] Open-source formats can be seen as neutral and not dependent on a commercial opportunity for their development. However, they can also be seen as vulnerable to the susceptibilities of the communities that support them [267-284].

4.2. Data Formats

All 2D / 3D data acquisition devices manufacturers have proprietary file formats containing captured raw point data, associated imagery and metadata. Some of these file types can be imported and readable with additional processing and registration software, and most have exporting capabilities. Moreover, few of them develop digital technologies that directly employ 3D object models, which are produced from diverse types of both visual and penetrating scanning, which individually provide only partial view of the object and hence they need to be integrated into a single model of the object, showing both its external shell as well as the interior and each of the material layers. Subsequently, those 3D structures and models are expected to be used in applications such as Virtual Museums, architecture, the creative industry, game industry, documentation films or XR tours, tourism, digital humanities, education, manufacturing, etc.

Within the framework of this study it was necessary to identify and analyse existing 2D and 3D data formats (as well as their related metadata) in view of determining the state of the art and the most suitable for the complete description of the 3D CH asset (the internal and external geometry, materials, etc) both multi-layer modelling, flexible enough to offer ways of adding new features required from the multidisciplinary experts. Moreover, the analysis was carried out from the perspective of universality (ability to be used without conversions among vast number of software applications), interoperability (ability to be imported and used without loss of information) and flexibility for extensions (ability to add more features) to fit the needs of the multidisciplinary CH community actively involved in the 3D digitisation.

- Common 2D, 3D model format[61]***:*** the same 2D, 3D format should be used among project components so as to avoid translations that might potentially lead to changed model representations and hence losses of information. Initially, the JPG, OBJ and 3MF formats have been selected as the most universal and flexible for extension to fit the needs of the multidisciplinary CH community actively involved in 2D/3D digitisation.
- 'Waterproof' 2D, 3D models are essential, i.e. without holes and undefined spaces/areas. This is a pre-condition for 3D models to be exported to STL and 3D printed correctly. It is also a condition for being able to perform registration from multiple 3D scans and then additional processing e.g. for simulated future deteriorations, etc.
- Integration of multimodal 2D and 3D scans may face problems when areas are overlapping. Hence, a detection of overlaps needs to be performed prior to integration (merging), in the simplest approach by performing weighted averaging, i.e. placing a common boundary midway between the overlapping areas using individual 2D/3D scan accuracy as a weighting factor.

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[59] File format (accessed Jun. 17, 2021).
[60] Open format (accessed Jun. 17, 2021).
[61] 3D Formats (accessed Jun. 4, 2021)

The results of a detailed analysis is included in Annex 3 and is outlined below, starting from a list of the most known and mostly used formats. Since 3D model formats are used in the creative industries, architecture, civil engineering and manufacturing for various specific purposes (long-term preservation, exchange between different software systems, communication with external ones), formats presented in this section also include those relevant for import/export and interfaces among project components, whereby internal data structures might vary depending on the specific needs of each component in the project architecture.

LAS/LAZ

LAS (LASer) is a binary open vector file format designed to exchange and archive LiDAR point cloud data. The American Society of Photogrammetry and Remote Sensing (ASPRS) originally developed it for the needs of the aerial sensing community. The open data format allows different LIDAR hardware manufacturers and software tools to exchange data in a standard format. However, the structure can be utilised for terrestrial laser scanner data by ignoring the inapplicable fields. LAZ (LAS Zip) is the widely used compressed version of LAS.

E57

The E57 format is a compact, open file format for storing point clouds, images, and metadata produced by 3D imaging systems, such as terrestrial laser scanners, developed by ASTM. In other words, E57 is a general-purpose, open standard for storing data produced by 3D imaging systems. The file format can store point cloud data from laser scanners. It can also encode data from flash LIDAR systems, structured light 3D scanners, stereo vision systems, and other devices that produce 3D measurements [240]. E57 is a more universal and flexible system than LAS and allows for the inclusion of, for example, image data, gridded data, and different coordinate systems. The E57 specification uses a subset of XML, extended to support the efficient storage of large amounts of binary data.

OBJ

OBJ is a geometry definition file format first developed by Wavefront Technologies[62] for its Advanced Visualiser animation package. The file format is open and has been adopted by other 3D graphics application vendors. It is a very simple data format representing 3D geometry alone - namely, the position of each vertex, the UV position of each texture coordinate vertex, vertex normals, and the faces that make each polygon defined as a list of vertices and texture vertices. Vertices are stored in a counter-clockwise order by default, making an explicit declaration of face normals unnecessary. OBJ coordinates have no units, but OBJ files can contain scale information in a human-readable comment line. Object files can be in ASCII format (.obj) or binary format (.mod)[63] and are widely used mostly for the exchange of models between different systems.

STL

The format developed by the 3D Systems[64] company in ASCII and binary form for the solid model creation and 3D printing. This royalty-free format was the first developed in the 80s and describes in a set of parallel layers the triangulated structure of the surface geometry of a three-dimensional object without any representation of colour, texture, or other common model attributes.

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[62] Wavefront Technologies (accessed Jun. 16, 2021).
[63] Wavefront .obj file (accessed Jun. 16, 2021).
[64] 3D Systems (accessed Jun 23,2021).

3MF

3D Manufacturing Format[65] (3MF) is the latest 3D printing format that allows applications to send full-fidelity 3D models to a mix of other applications, platforms, services and printers. The 3MF specification has the advantage to allow users to focus on innovation, rather than on basic interoperability issues, and it is engineered to avoid the problems associated with other 3D file formats. For example, STL, has significant limitations and issues, which the 3MF specification is specifically designed to avoid or overcome: mesh, textures, materials, colours and print ticket. It is an XML-based data format – human-readable compressed XML, which includes definitions for data related to 3D manufacturing, including third-party extensibility for custom data. The 3MF is a royalty-free format designed to be an additive manufacturing set of instructions, with the complete model information contained within a single archive.

PLY

The Polygon File Format (PLY) is a computer file format known as the Stanford Triangle Format[66], released in 1994, developed by Greg Turk from Stanford University. It was principally designed to store three-dimensional data from 3D scanners. The data storage format supports a relatively simple description of a single object as a list of nominally flat polygons. Various properties can be stored, including colour and transparency, surface normals, texture coordinates and data confidence values. The format permits one to have different properties for the front and back of a polygon. There are two versions of the file format, one in ASCII, the other in binary.[67]

X3D

Extensible 3D (X3D)[68] Graphics is the royalty-free open ISO standard[69] for publishing, viewing, printing and archiving interactive 3D models on the Web. It is an XML-based file format for representing 3D computer graphics and it is successor to the Virtual Reality Modeling Language (VRML) such as CAD, Geospatial, Humanoid animation, NURBS, etc.). The X3D extension supports multistage and multitexture rendering; it also supports shading with lightmap and normalmap. Starting in 2010, X3D has supported deferred rendering architecture. The user can also use optimisations including object volume oriented structures such as BSP/QuadTree/OctTree or culling in the X3D scene. X3D can work with other open source standards including XML, DOM and XPath.

As an open standard X3D can run on many platforms, but importantly can render 3D models in most web browsers without the requirement for additional or proprietary applications. Therefore, X3D is designed to be as integrated into HTML5 pages as other XML standards such as MathML and SVG.

2D Imagery

It is essential to understand the difference between “lossy” and “lossless” file formats for imagery, meaning respectively ‘throwing away information’ and ‘storing all information’. The most common photographic image file formats are JPG, TIF, PNG, and GIF. Camera RAW files are also used for recording CH, but they must be converted into conventional formats such as JPG or TIF for use (see also Annex 3 for more information).

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[65] 3D Manufacturing Format (accessed Jun 23,2021).
[66] http://paulbourke.net/dataformats/ply/
[67] PLY file format (accessed Jun. 16, 2021).
[68] X3D (accessed Jun. 16, 2021).
[69] ISO Standard (assessed Jul. 30, 2021)

JPG

A JPG file is an image saved in a compressed image format standardised by the Joint Photographic Experts Group (JPEG). It is commonly used for storing digital photos and used by most digital cameras to save images. Since its introduction in 1992, JPEG has been the most widely used image compression standard globally. Typically, a JPG file can be opened with any program that supports images. You can also view a JPG in a web browser by dragging and dropping it into your browser window.[70] The JPG is considered the most used image file format due to its small file size, almost 5% of its original size. It is a "lossy" format because some of the data is discarded when an image is converted. Lossy formats should not be regarded as archival.

TIFF

The TIFF format was initially developed by the Aldus Corporation, which merged with Adobe Systems in 1994. A TIFF file is a graphics container that stores raster images in the Tagged Image File Format (TIFF). It contains high-quality graphics that support colour depths from 1 to 24-bit and supports both lossy and lossless compression TIFF files also support multiple layers and pages. The TIFF format was released in the mid-1980s to be a standard image format for saving high-quality colour images on various computer platforms. Although it was widely adopted, the JPEG format surpassed it because it was more efficient and web-friendly. Nowadays, the TIFF format is typically used to store photos for editing and printing purposes. It is considered to be the highest quality format for professional recording work. TIFF files are also commonly seen with the TIF extension.[71]

GeoTIFF

The Open Geospatial Consortium recently published the GeoTIFF standards, specifying the "requirements and encoding rules for using TIFF for the exchange of geo-referenced or geocoded imagery." The GeoTIFF is an open format metadata standard that has the georeferencing information embedded within the image file. The georeferencing information is included by way of TIF tags that contain spatial information about the image file, such as map projection, coordinate systems, ellipsoids, and datums.[72]

Camera RAW

The Camera Raw image file is a proprietary format on most high-end cameras. It contains all the pixel information captured by the camera's sensors without compression or processing. The RAW file format is also "lossless" as it preserves all of the file's original data, Different camera manufacturers use many other raw formats, the specifications for which are not openly available. RAW files should be used to capture the most information and to have total control over the processing. However, because they are proprietary, RAW files should not be used for archiving, and the image data should be converted to an archive format such as Digital Negative (DNG) format or TIF.[73]

Digital Negative

The Digital Negative (DNG) is an available archival image format for raw files that various digital camera manufacturers generate. It is Adobe's proprietary RAW image standard, created to address the lack of an open standard for raw files created by individual camera models and ensures that photographers easily access their files.[74] Although DNG was developed by Adobe and supported throughout their applications, camera manufacturers

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[70] JPG File Extension (accessed Jun. 16, 2021).
[71] TIFF File Extension (accessed Jun. 16, 2021).
[72] What is a GeoTIFF? (accessed Jun. 16, 2021).
[73] Terminology (accessed Jun. 16, 2021).
[74] Digital Negative (DNG) (accessed Jun. 16, 2021).

such as Leica, Hasselblad, and Pentax adopted the standard and used it in their cameras as their native and supported RAW file format.

4.3. Metadata Schemas for 3D structures

There is growing demand for applications to address specific needs of 3D data stewardship. Central to this is the identification and creation of metadata models to describe digital surrogates. Preservation metadata - vital semantic data that supports the long-term preservation of digital object records - is a crucial step for CH stakeholders investing in digitisation, which is becoming more common in collections documentation. The greatest challenges in preservation metadata are to developing a uniform framework, including the semantic information needed; and in what format the objects should be modelled. At the time of writing this report, there are many organisations actively working in this area: a few of the most important metadata structures in use are described below:

Smithsonian 3D Metadata Model

The Smithsthonian metadata shema[75] is one of the most used for 3D CH objects, based on extensive experience of digitising resources from multiple collections. It describes the 'raw' source data from which 3D models are derived including information about provenance, origin, IPR, location, the technical processes going into data collection and model creation. The group focused primarily on modeling the metadata needed to fully document a 3D capture event, and specifically focused on photogrammetry capture as a test case, since it involves accessible, non-proprietary technology, 'raw' data and image files. The execution of a photogrammetry project also involves a high degree of complexity, compared to other 3D capture methods.

LIDO

LIDO[76] (Light Information Describing Objects) was proposed to handle museum-related content in the framework of Europeana. Besides being a self-sufficient schema in a museum framework, LIDO was proposed by the ICOM/CIDOC in 2010 as a standard for digital content aggregators. A two-step process is envisaged: mapping individual repository schemas to LIDO and mapping (once for all) the latter to the current Europeana Data Model schema (EDM). Being CIDOC-CRM compliant, LIDO adopts the event-oriented approach and guarantees a high level of interoperability. It has been tested with 3D applications. LIDO has not been conceived as a collection management system, but as a harvesting schema for the delivery of metadata.

CARARE

The CARARE metadata schema was developed for the archaeology and architecture domains and applied to 3D content in several EU projects. Version 2.0[77], developed in the framework of the 3D-ICONS project, describes in detail the artefact or monument which is being modelled in 3D, its provenance, the digital representation of the artefact or monument and its online location. It also provides technical information and quality insurance on the processes and methods utilised in the digitisation and modelling of heritage objects, information on the access, licensing and reuse of the created 3D models and any associated digital content. It enables the search, discovery and reuse of content through the mapping of metadata to aggregators and the. Europeana Data Model (EDM)

ARCO

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[75] Smithsonian metadata schema (accessed Jun. 1, 2021).
[76] LIDO (accessed Jun. 1, 2021).
[77] CARARE 2.0 (accessed Jun. 20, 2021)

Within the ARCO[78] (Augmented Representation of Cultural Objects) project, the ARCO Metadata Schema (AMS) and management tools support the development of a metadata element set for describing digitised museum artefacts, allowing museums to build virtual exhibitions available over the Internet.

CRMDIG

CRM Digital (CRMdig)[79] is an ontology and RDF Schema to encode metadata about the steps and methods of production ("provenance") of digitisation products and synthetic digital representations such as 2D, 3D or even animated models created by various technologies. Its distinct features compared to competitive models is the complete inclusion of the initial physical measurement processes and their parameters. It has been developed as a compatible extension of CIDOC CRM, which allows for querying the most relevant facts and returning complete descriptions encoded in this model by generic ISO21127 terms without need to refer to its specific properties. In contrast, competitive models cannot be queried by a more general standard and are restricted to the computational provenance only. Data encoded in the major competitive models can be transformed without loss of meaning into a CRM-Digital-form.

METS

The Metadata Encoding Transmission Standard (METS) is a data communication standard for encoding descriptive, administrative, and structural metadata regarding objects within a digital library, expressed using the XML Schema Language of the World Wide Web Consortium. An initiative of the Digital Library Federation, METS is under development by an international editorial board and is maintained in the Network Development and MARC Standards Office of the Library of Congress. Designed in conformance with the Open Archival Information System (OAIS) Reference Model, a METS document encapsulates digital objects and metadata as Information Packages for transmitting and/or exchanging digital objects to and from digital repositories, disseminating digital objects via the Web, and archiving digital objects for long-term preservation and access. The standard has been applied in documenting 3D models.

4.4. Identification of Gaps, Additional Formats, and Standards

Annex 3 of this study report presents a list of all standards in the area of CH digital documentation, archiving, presentation and preservation, resulting from our investigation and analysis.

In assessing the suitability of these standards and analysing what significant gaps in standards may remain, several discussions with expert practitioners actively involved in the area of museums, monuments and sites were conducted. At the novice level or for those with less expertise, it cannot be ignored that different and more basic types of guidance may be required to promote skills that enable widespread 3D digitisation and curation in Europe.

As discussed in previous chapters, formats evolve over time as software developers incorporate new functionality into their applications and code. This is a particular challenge related to the longevity of 3D CH digitisation projects. The formats contain data that are projected in 3D space and in a few cases together with the related embedded information for rendering. Moreover, the 3D formats cover a wide range of potential applications spanning many areas of education, research, industry and other implementations. This kind

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[78] ARCO (accessed Jun. 20, 2021)
[79] CRMDig accessed Jun. 20, 2021

of files includes the 3D geometrical information of point sets /clouds, the corresponding colour to each point and the way the points are connected together (mesh or wireframe model).

New file formats may incorporate obsolescence by removing support for older versions. It is well known that new software applications may not provide backwards compatibility with older file formats. Without format conversion tools, data may become not readable and unusable. Both open-source and commercial formats risk obsolescence: vendors sometimes use planned obsolescence to encourage customers to upgrade to new products, while open-source software communities may withdraw support for older formats, if these are no longer generally needed by their community. Obsolescence can also be an accidental outcome, which both businesses and open source communities can produce. Proprietary formats, such as TIFF, may seem durable; however, these formats will ultimately be susceptible to upgrade issues and obsolescence, if the developer goes out of business or develops a new alternative [267-284].

Open standards initiatives, including IFC[80], STEP[81], IGES[82] and E57 (see Annex 3) have been introduced in an attempt to mitigate the challenge of project archiving and coherent model exchange which exist. Open-source formats can be seen as technologically neutral, however, they can also be seen as vulnerable to the development communities that support them [182-232]. Even when 3D models can be output into an open standard, the result can incur loss since "native" 3D CAD file formats cannot be interpreted accurately in any but the original version of the original software product used to create the model" [269, Smith, 2009].

In general, there is a lack of interoperability among the variety of pre-processing systems used to calculate, create and process 3D point clouds and meshes. Therefore, the software and hardware available for processing acquired 3D data can influence the complexity of the system. It can also have a direct impact on the quality and long term preservation of the end results. In order to replicate the exact scene or model, it is often necessary to preserve a lot of additional information (metadata) related to the different parameters described in this study (environment, equipment, operators, etc.).

At the moment of writing this report, several international organisations such as CEN, ISO, Web3D[83] and IIIF[84] are actively involved in 3D standardisation. CEN is for example actively engaged in the standardisation of 2D and BIM: standardisation in the field of structured semantic life-cycle information for the built environment. For example committee CEN 422[85] will develop a structured set of standards, specifications and reports which specify methodologies to define, describe, exchange, monitor, record and securely handle asset data, semantics and processes with links to geospatial and other external data. The corresponding Working Groups (WGs) are: CEN/TC 442/WG 1- WG7.

Other specific European standardisation activity in the field of conservation of CH was essential to acquire a common scientific approach to the problems relevant to the preservation and conservation of the cultural property. Therefore, the scope of a second important CEN Technical Committee (TC 346) was to establish standards in the field of the processes, practices, methodologies and documentation of conservation of tangible CH to support its preservation, protection and maintenance and to enhance its significance. This includes standardisation on the characterisation of deterioration processes and

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[80] Industry Foundation Classes IFC (accessed Jun 1, 2021)
[81] Standard for the Exchange of Product Data STEP (accessed Jun 1, 2021)
[82] Initial Graphics Exchange Specification IGES (accessed Jun 1, 2021)
[83] Web3D (accessed Jul. 30, 2021)
[84] IIIF: International Image Interoperability Framework (accessed Jul. 30, 2021)
[85] CEN 422 (accessed Jun, 6, 2021)

environmental conditions for CH and the products and technologies used for the planning and execution of conservation, restoration, repair and maintenance.

The International Standards Organisation (ISO) is an independent, non-governmental organisation, the members of which are the standards organisations of the 165 member countries. It is the world's largest developer of voluntary international standards, and it facilitates world trade by providing common standards among nations. In the last two decades, ISO has started intensive work through multidisciplinary experts to develop standards focusing in the area of CH. An example is the work carried-out by the technical committee ISO/TC 42 on Photography standards which has a joint working group (ISO/TC42/JWG 26) focusing on the digitisation of CH Materials (see also 2.5) and formed to standardise tools and techniques for maintaining consistency when digitising CH materials[86].

Another important achievent in the area of ISO standardisation in CH is the Conceptual Reference Model (CRM), which is a theoretical and practical tool for information integration in the field of CH and it can help researchers, administrators and the public to explore complex questions with regards to our past across diverse and dispersed datasets. The standard was created from a group of multidisciplinary experts in cooperation with the scientific committee on documentation (CIDOC) of the international Museums association (ICOM). In 2006, it has been recognized as an official ISO standard and it was renewed in 2014 (ISO 21127:2006 or 2014).

A further entity actively involved in standardistion is the IIIF 3D Community Group[87] which has been cataloguing user stories[88] and user needs, exploring various 3D workflows[89], and launched a 3D platform viewer comparison project[90] (VCP) with major 3D developers and researchers considering common challenges and potential solutions to key areas (e.g. annotations). Some of the key questions have been around the conceptual framework needed to address the use cases for digital dioramas, including by adding depth to the current 2D IIIF canvas model, and by embedding one or more canvases within a 3D scene (e.g. multiple paintings or texts or music associated with a cathedral, temple or palace placed again on the walls or interior of a suitable model). With growing user and institutional demands, technical developments, and examples of advanced research collection and integration of virtual resources (e.g. morphosource.org, exhibit.so, hubs.mozilla.com), there is a pressing need for a technical specification to ensure interoperability and longer term sustainability.

The plan for the IIIF 3D Technical Specification Group is to continue a collaborative approach to clarifying and specifying interoperable frameworks for 3D data, including common ways to:

- annotate 3D media of various types into a shared canvas space, with commentary,
- combine 3D media with images and AV content within a shared space,
- specify the presentation (placement, orientation, and contextualisation) of 3D media.

The group will continue its work with other standards bodies and 3D image viewer developers, to collaboratively address the many challenges around this rapidly evolving and expanding area. The combined and widespread expertise from the many 3D specialists will continue to guide the work of the IIIF 3D Technical Specification Group, as it outlines sustainable options for the interworking of existing open standards (e.g. VRML/X3D,

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[86] CH Materials (accessed Jun, 6, 2021)
[87] IIIF 3D Community Group (accessed Jun, 6, 2021)
[88] User stories and user needs (accessed Jun, 6, 2021)
[89] 3D workflows (accessed Jun. 6, 2021)
[90] A Viewer comparison project (accessed Jun. 6, 2021)

WebXR), established foundations (e.g. WebGL, Three.js, react-three-fiber), and emerging proposals (e.g. <model> tag), to provide recommendations for expansions to and modifications of IIIF APIs to better interoperate with the evolving digital ecosystem of online 3D content.

These 3D developments will complement the ongoing updates and continued widespread adoption of the IIIF technical specifications for 2D and Audio/Video (A/V) data, which has been enabling greater access to widespread resources – of even greater significance for teaching and learning and research during the pandemic – as well as providing for richer presentations, close inspection and shareable annotation of media.

IIIF specifications also enable the recombination of long-separated parts of an original whole (e.g. missing sections or leaves in a digitised medieval manuscript, viewed with missing pieces contained in another digitised collection). IIIF adoption continues to enable effective sharing and support for the preservation of CH resources, whether as individual items or as combinations of media from one or more collections, locally and globally.

These technical developments for the community relies on regular meetings and input from the community. Planning for the IIIF 3D technical specification includes recorded monthly meetings, complementing the more general Community presentations and discussions, and involving group problem-solving with regular input from and interactions with representation from 3D researchers and media and viewer developers, including from Cambridge, Duke, Edinburgh, UC San Diego universities, Deutsches Museum, IIIF Consortium, Mnemoscene, MorphoSource, MPEG consortium, Sketchfab, Smithsonian, Visual Computing Lab (CNR-ISTI, Italy) and Web3D Consortium. IIIF regularly collaborates with 3D-related projects and other international organisations such as CEN, ISO and IEEE, ensuring the interconnection with more communities, to further develop 3D standards which will be the most widely usable and adopted across current and future proposals and projects.

4.5. Convergence and Training

The use of photorealistic 3D models is becoming increasingly common in the CH sector. The combination of image integrated laser scan data and/or photogrammetric imagery with advanced visualisation software is capable of providing visually outstanding renderings, simulations and animations especially for the areas of engineering, creative industry, tourism and education. At times, 3D images are indistinguishable from photographs. This brings up a number of relevant gap-related issues.

3D models can be developed using a variety of sources, from terrestrial laser scan data to hand measurements. As a model is being developed, it is unlikely that every surface has been based on objective scan or photogrammetric data. Whereas a talented modeller may be able to develop a 3D CH asset model independent of its actual environment, it is more of a challenge to connect the model to its real context with precise positioning data, other survey information and all related intangible information and data.

The process of using digital technologies to create in the domain of CH 3D data acquisition, new - or to modify existing - business processes, “culture”, and customer experiences to meet changing business and market requirements is defined as a Digital Transformation. In this current and challenging transition period for Europe in this domain, professional and vocational training for those in work, together with continuous development of new curricula, syllabi and courses at undergraduate and postgraduate level are a vital requirement. Innovation in education and training for CH data acquistion will enhance awareness of and openness to digital initiatives.

In tandem with this study, there a strong demand emerging to carry out a pan-European initiative in cooperation with international bodies in the field of DCH, which is in line with the recommendations of the Council of Europe's Strategy 21[91] in the areas of Knowledge and Education for CH, together with those of ICOM, ICOMOS and, UNESCO's Education 2030 Framework for Action.

The current revolution of developments in the sector of ICT in CH does not correspond to an effective human capacity of DCH researchers and experts to work in the area of CH digitisation projects, tools and devices. In general, relatively few people have the know-how and ability to master digital 3D data acquistion tools, repositories, long-term preservation and platforms for example, to promote mass digitisation and documentation in the conservation of heritage, increase high quality of 3D CH replicas, etc. It is necessary to balance the continuous technological development with social needs so that ICT becomes a fully effective resource for heritage development and awareness.

Training offers in new data acquisitions technologies and standards/norms, accompanied by meaningful certification and accreditation, should be stimulated. These should be addressed to the different target groups involved in CH and their position in the 'digital workflow of CH data acquisition', broken down into different steps or stages and distinguished between technology skills, curatorial issues, decision and long-term preservation. Interdisciplinary approaches are necessary to address all the needs and skills required for the specific field sector of 3D data acquistion in DCH. Such trainings should lead to a recognised international or European certification and accreditation that will ensure a multidisciplinary profile. In general, theoretical and technical parts should be taken into consideration together, in order to create a complete vocational training programme.

Universities, institutes, chambers and research infrastructures (such as DARIAH and CLARIN) conducting multidisciplinary technical education and interdisciplinary digital humanities training should introduce and teach the relevance of cultural background information for the understanding of 3D CH digital creation of tangible objects and their digital curation. Advanced high tech hardware, software and multidisciplinary professional and non professional user needs convergence are now quickly bringing these fields together. To support this process, focused education, training and awareness on the use of international standards are required. To assure the skills and capacities of the next generation of surveyors, digital curators, museologists and archaeologists, the question 'who needs to be trained, for what purpose and at what level' should be directly addressed, not least within the programmes managed by the European Commission but also by ICOMOS, ISPRS[92], ICOM, NEMO and UNESCO.

5. Forecast Impact of Future Technological Advances

Over the last 30 years, digital technologies have become the primary means of collecting, conserving and disseminating European and international CH. Advances in technical fields such as applications of multiple sensor, scale, spectral and temporal considerations ('all in one' or 'black box' solutions) linked to the developments in artificial intelligence (AI), analytics, blockchain, cloud computing, ontologies, Internet of Things[93] (IoT), aerial and terrestrial LiDAR and machine learning are developments that have revolutionised the construction industry. With the continuing emergence and deployment of AR/VR/MR

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[91] Council of Europe's Strategy 21 (accessed June. 23 2021)

[92] ISPRS (accessed 2. July 2021)

[93] Internet of Things (accessed Jun. 23, 2021).

(Extended Reality- XR) and the use of UAVs, technology will play an indispensable role in the management, conservation, and protection of CH. Consequently, the development of these systems will have a direct impact on the CH sector. Industry 4.0 continues to drive digital transformation and adoption of new novel technologies and processes across different domains. It is often challenging for CH professionals to and keep up with abreast of the onslaught of new terminology that comes with it.

5.1. Extended Reality (XR)

XR (including VR, AR and MR) is an area of technology with high growth prospects. According to IDC research [110] investment in virtual reality (VR) and augmented reality (AR) will have increased 21-fold over the next four years, reaching EURO 15.5 billion by 2022. A recent report by Vynz Research[94], foresees a global market worth USD 161.1 billion in revenue by 2025 and cites as major players, the folllowing: Alphabet Inc., Oculus VR, LLC, Microsoft Corporation, Qualcomm Technologies Inc., Intel Corporation, Himax Technologies Inc., Samsung Electronics Co. Ltd., PTC Inc., and Sony Corporation.

5.2. The Metaverse

The term ‘metaverse’ has been around since the nineties, recently gaining media attention due to large companies such as Facebook. The metaverse involves bridging the gap between real life and the internet using XR. Users potentially wear devices that can allow them to interact with augmented objects and information on top of their ‘real’ environment, adding a new dimension to reality while giving the internet existence in the real world. For the metaverse to function, it will be highly dependent on augmented reality, internet connectivity, and user data. Augmented reality is any technology that overlays a digital environment on a physical environment that users can interact with. It is therefore heavily dependent on wearable display technologies capable of combining live video with digital elements. In many ways, the metaverse can be thought of as an online “game” that augments itself in real-life and allows players to interact with each other both physically and digitally. A significant aspect is that the augmented world seen by users is shared amongst everyone connected, along with data and augmented objects.

Relevant CH 3D applications are already being developed, such as the one depicted below where a hologram avatar priest guides users (see also Figure 40) in exploring the 3D digitised church and frescoes at Asinou (see also Annex 2). In the approach of a monument holistic digitisation, the priest and the liturgy have been fully scanned too.

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[94] Vynz Research (accessed Jun. 22, 2021).

Figure 40. Metaverse presentation of the real Priest as an avatar at UNESCO WHL Asinou Church, Cyprus (Copyrights EU FP7 MSCA ITN project ITN-DCH)

5.3. 5G and the Continued Advancement of Mobile Technologies

Since late 2018, over 25 countries have deployed 5G wireless networking systems. These systems are presently installed in major cities worldwide. By 2024, an estimated 1.5 billion mobile users will be using these networks, accounting for 40% of current worldwide activity. 5G networks will significantly improve connectivity between Internet of Things (IoT) devices, as well as feature lower latency, enhanced capacity, and increased bandwidth compared with 4G networks.[95]

From a heritage site management perspective, 5G will enable more robust connectivity between site and management offices, institutions, government agencies, and citizens. The increased connection speed and low data latency will allow better monitoring systems, for example sensing structural changes to a historic structure. The sensors will be able to monitor vast areas at a relatively low cost. The significant increase in connectivity and smartphone technology advancements (such as better cameras and processors) will allow smoother AR and VR experiences and provide a richer visitor experience for CH. Moreover, the availability of the technology on a consumer device could be an enabling medium for heritage building information modelling (HBIM) and digital twin efforts in construction and heritage facility management.

5.4. LiDAR

Interest in developing mechanical lidar scanning devices, tiny-chip solid-state lidar units, and the emerging frequency-modulated coherent wave lidar (FMCW[96]) is increasing due to the rising number of autonomous vehicles. Dramatic improvements in the technology have led to higher pulse repetition rates (PRRs) and miniaturisation. Furthermore, as illustrated by the number of start-up companies to serve the autonomous market, research and development in the technology will have a direct and indirect impact on the CH digitisation sector.

3D LiDAR technology is now available on the Apple iPhone 12[97] and iPad Pro, indicating this technology's arrival in the public domain. Other smartphones use a single light pulse to measure depth, whereas the iPhone sends out waves of infrared light pulses similar to a terrestrial laser scanner. Similarly to the proliferation of photogrammetric apps, the availability of this kind of technology on a consumer device is likely to encourage the interest of software developers. Moreover, the availability of the technology on a relatively inexpensive consumer device could be a tool for Building information modelling (BIM) and digital twins.[98] Increased interest in mobile consumer LiDAR will encourage further software development, promote innovation, and potentially reduce the costs of professional systems. There is also potential for the integration of mobile systems into a more advanced heterogeneous ecosystem, which will directly benefit the CH sector.

5.5. JPEG XL

The JPEG XL (ISO/IEC 18181 – see also Annex 3) is a general-purpose image compression codec by the Joint Photographic Experts Group (JPEG) committee. The raster graphics file format is free and open-source. JPEG XL generally has better compression than JPEG, PNG and GIF and is designed to supersede them. The new file format brings both high fidelity — which represents the ability to render an image accurately with minimal

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[95] The Future of 5G: Comparing 3 Generations of Wireless Technology (accessed Jun. 22, 2021).
[96] FMCW (accessed Jun. 22, 2021).
[97] Apple iPhone 12 Lidar (accessed Jun. 22, 2021).
[98] The Future of Lidar is Critical to the Future of Our World (accessed Jun. 22, 2021).

information loss — as well as universality. JPEG XL has added support for 360-degree images, image bursts, large panoramas and mosaics and printing.

Since it may eventually replace the current JPEG, PNG, and GIF format files, it is likely to be of interest to the CH community. Migrating to this file format will reduce archive and storage costs and subsequently also global data use, because servers can store a single JPEG XL file to serve both JPEG and JPEG XL clients, according to the JPEG committee.[99]

5.6. BIM, HBIM, HHBIM and the Digital Twin

The contemporary application of Building Information Modelling (BIM) has existed since the 1970s. It is a collaborative way of working that facilitates the design, delivery and maintenance of buildings throughout their entire lifecycle. Heritage Building Information Modelling (HBIM) typically centres on digitising existing heritage monuments, driven by the increasing technological advancements in 3D data capture, such as photogrammetry, laser scanning and reconstruction [182-233].

A key to understanding the future of BIM and HBIM is to consider the building as a database of interlinked data structures and related information (an ontology for architects, civil engineers and others). CAD, scan data, drawings, and specifications are simply different manifestations of the database.[100] The accumulation of data linked to a virtual representation of a monument or its components makes in an HBIM system makes it easier to understand and manage project information, as well as indicate how construction and maintenance will develop over time.[101] 3D models with enriched embedded metadata (BIM) are a more effective solution but difficult to achieve, because they still require massive manual intervention from the engineers in charge of the 2D and 3D modelling of the objects.

As a result of national research and innovation projects in Italy, researchers at the Politecnico di Milano in cooperation the DHRLab at the Cyprus University of Technology, have worked on a new methodology for a modified HBIM system which includes information about the 3D CH asset, the digital data produced (2D, 3D, audiovisual and storytelling) and technical specifications about the project and the equipment itself. This data structure (Paradata), taken together with the corresponding object's metadata leads to a holistic documentation of the 3D CH asset and is defined as Holistic Heritage BIM (HHBIM[102]) providing information such as the purpose of digitisation, conditions relating to data collection and processing, equipment and methods used, the process of digitisation, the actors involved, the production tecnologies and the storytelling (memory).

A Digital Twin[103] is essentially a virtual replica of a physical component or entity and the dynamics of that component or entity [250]. This live twin gathers data and uses physics-based simulations to create a data rich living, breathing 1:1 model that behaves in the same way as its real-world counterpart. This means a digital twin can have many useful applications ranging from initial concept and reconstruction, through to continuous monitoring, fault detection and protection planning, and in high risk scenarios such as climate change. Digital Twins (dynamic) are seen as most relevant for monitoring and maintenance of CH sites and objects, HBIM (static) for reverse engineering and conservation.

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[99] Overview of JPEG XL (accessed Jun. 22, 2021).
[100] The Future of BIM (accessed Jun. 22, 2021).
[101] Exploring the Future of Building Information Modelling (accessed Jun. 22, 2021).
[102] Holistic Heritage BIM - HHBIM (accessed Jun. 19, 2021)
[103] From BIM to digital twins and digital twin for restoration (accessed May 28, 2021)

5.7. Cloud Computing

Cloud computing technology is already causing significant change across business communication and industry. The architecture, engineering, and construction sectors are also integrating cloud-based BIM into their workflow. A cloud-based repository is becoming a necessity as digitisation projects continue to grow with increasingly faster and smarter laser scanning systems, integration of photogrammetric imagery, high-resolution still images, renderings and animations,. The immediate benefit for CH is that their scan data becomes securely shareable with administrators, clients, scholars, experts and contractors anywhere in the world. Critically, valuable point data from the CH site, associated (H)HBIM and project information is held on secure servers. This allows CH sites to rent computing equipment, software, and systems on an as-needed basis over the Internet, reducing the costs associated with traditional IT infrastructure. Increasingly, a cloud-based platform for semantic enrichment and visual analysis of 3D models is necessary in the CH sector.

Cloud infrastructures will need to act as one-stop solutions and to provide the required ICT support for hosting high quality content and graphical interfaces suitable for all kinds of users together with:

- archival/retrieval resources (linking different parts of a 3D object to the main structure);
- tools for visual data analysis, data annotation and for the modification, validation and import/export of paradata and metadata;
- expert functionalities for the import and export of 3D models in all available 2D and 3D formats and related IPR issues;
- the possibility to embed in the 3D model structure other related information, such as multimedia linked data (audio, video, text, image).

A future breakthrough could be the direct integration of licensed HBIM infrastructures and other needed 3D software packages in a common Cloud space, within the European Data Space for Culture, giving EU CH stakeholders the possibility to work with their objects and collections 24/7 from anywhere on smart devices.

5.8. Open Data

The Open Data Programme provides regional satellite data and, at times, aerial LiDAR to all potential users for free and without a licence[104]. Several cities, counties, and states have used this 2D and 3D information to improve urban planning, better community management, and encourage more effective communication with citizens. In addition, this initiative has resulted in widespread utilisation at times directly beneficial to local heritage properties and sites. The Open Data Policy focuses on specific policies and strategies to foster open data at a national level. The dimension also analyses governance structures that allow private and third sector organisations and implementation measures that enable available data initiatives at the national, regional, and local levels.[105] Countries like the Republic of Ireland and the Netherlands have established country mapping efforts, and Switzerland has gone to 3D in its topographic maps.[106] The EuroGeographics Council has developed the EuroGlobalMap, a 1:1 million scale topographic dataset covering 55 countries and territories in the European region.[107]

5.9. Artificial Intelligence/Machine Learning

Apart from the obvious advances in robotics (accurate kinematics, dynamics, and contact properties) as well as autonomy and simulatability, it is likely that machine learning (ML)

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[104] Path to the Digital Decade: Open Data Portals Policy (accessed Jun. 22, 2021).
[105] Path to the Digital Decade: Open Data *Policy* (accessed Jun. 22, 2021).
[106] Future trends in geospatial information management: the five to ten year vision (accessed Jun. 22, 2021).
[107] Open Data and European Location Services, Digital Single Market (accessed Jun. 22, 2021).

models will underpin the automation of more DCH data mining tasks (predictive as well as prescriptive) tasks, based on supervised, unsupervised or reinforcement learning. The automatic (AI) integration of 3D laser scan data into a BIM CAD application (Scan-to-BIM) will inevitably become more accurate, effective, and practical, often extending data collection to cover multiple complexity parameters at a time.

Automation will ideally replace the tedious (and potentially error-prone) manual drawing over point data, much like natural language processing (NLP) applications will take over the semantic (on top of syntactic) parsing of knowledge, when mining through lengthy textual databases, e-archives, or other web DCH content. AI systems can automatically classify consistent objects and features within point clouds, interconnect them with cross-validated terms and concepts (updated glossaries and thesauri) and infer associations and links arising from summarising, discriminating, and analysing high-dimensional data across different levels of granularity (e.g., GIS Copernicus data to support geospatial analytics) and authenticity.

AI-based systems are expected to further support the design, optimisation and implementation of the end-to-end digitisation process, often merging several steps and/or skipping them entirely, by offering seamless integration with cloud technologies, and compatibility with role-based, parallel processing platforms offered as-a-service - for example, instantly recognising and tagging streetlights, doors, fixtures or identifying walls, columns, and roofs within the point clouds data sets (features ready to be integrated in different Levels of Detail (LOD) in HBIM systems or in 3D repositories and visualisation platforms).

Moreover, AI could support the automatic enrichment of para/metadata and help to increase the quality of 3D data sets. Through the continued advancement of such data-intensive methods, systems could eventually become ‘smart’ enough to understand the virtual environment. This would enable constructed models to project novel and meaningful predictions and to supporting critical event processing; in other words to allow for (near-) real-time responses empowered by streaming and perpetual analytics and immediate notification capabilities, for example, where a museum object is moved or missing or to monitor potential structural issues in a monument.

5.10. Blockchain Technologies

Considering the pressing issues of authenticity and provenance in DH, especially for objects or artefacts of significant cultural, historical, archaeological or technological value, constant upgrades on the traditional network security protocols for digital information/data protection are highly important. The decentralisation induced by distributed-ledger (blockchain) technologies can efficiently support controlled stewardship, ownership, and exhibition management, combining contemporary system design with wireless sensors and smart grids to ensure traceability and avoid tampering. Newly introduced encryption algorithms pertaining to the organisation, retrieval, and management of DCH information are expected to revolutionise digital resource conversion, storage and transmission, thus redefining DCH information security in terms of data confidentiality, integrity and availability.

Blockchain technologies are already showing promise concerning digital heritage preservation and public access synergies intended in the 1970 UNESCO resolution. Increasingly many collaborative networks of stakeholders are expected to adopt these novel approaches in registries, to reconfigure their display and payment rights, provided these are jointly governed by (inter-)national policies, market deployment and end-user (social) support. To ensure sustainable operation, it is important for policymakers and users alike to understand blockchain system architectures and realise their transformative potential, together with any legal or ethical concerns, in order to increase collective awareness, engagement and participation.

6. Conclusions

This study pays special attention to the fact that 3D digitisation of movable and immovable CH can be an exceptionally complex process, with numerous factors limiting the eventual quality of the 3D CH asset. Parameters such as budget, available time, object location and conditions, accuracy and precision, expertise become significant in setting both the production effort and output standard. At the time of finishing this report, there is a lack of internationaly recognised standards or guidelines for planning, organising, setting up, managing, implementing, using paradata or metadata or evaluating CH 3D data acquisition results and projects. Some exception exists at national level such as in the UK (English Heritage and Historic Environment Scotland) and in the USA (FADGI).

With smart acquisition technologies and software reaching new levels of efficiency, data capacity and processing time and accessibility in terms of cost, it becomes even more crucial to grasp the fundamentals of data capture and processing methodologies. With photorealistic renderings now commonplace, this implies revisiting 2D/3D scanning and processing procedures and further understanding the physics and hard reality behind the hardware, to effectively build upon efficient and cost-attractive technologies as they become more mainstream.

This study demonstrates that complexity and quality are fundamental considerations in determining the necessary effort for a 3D digitisation project to achieve the required value of the output.

The complexity of 3D data acquisition projects can be determined after assessing factors such as stakeholder requirements, project specifications, personnel qualifications, object type and location, environmental conditions, equipment, real object conditions, and pre-processing software. These factors have been defined in a more precise manner in this study. Determination of quality may comprise the degree of detail, precision, and resolution of the geometric accuracy of the 3D shape and the fidelity of capturing colour/texture.

Along this path, the study has arrived at a sequence of important findings listed below:

- At the time of the end of this study, there is no generally accepted EU framework for specifying the level of detail and the accuracy requirements for geometric recordings of CH tangible assets: every object is geometrically documented based on the accuracy and cost specifications supplied by the owner or stakeholder.
- The words ‘complex’ and ‘complicated’ are frequently used in the CH domain without a clear distinction. A definition of complexity in 3D digitisation should apply to both movable and immovable objects, refer to geometric, surface/texture and material complexity and be scale/application-variant. However, complexity does not reside in the geometry of a 3D model or the final number of points and vertices. Instead, it relates to the stakeholder requirements, its location, state of condition and other factors described in section 3.
- An indication of complexity can only occur after the 3D digitisation of a CH object, but in practice, this would be a fruitless exercise. Therefore, it makes sense to reverse this thinking and start from the technical specifications which are dictated by the purpose of the 3D digitisation activity in question.
- Accordingly, there is a need to shift attention from “Object Complexity” to “Model Complexity”. This means that the focus is not the complexity of the actual object (which is connected only to the data capture phase) but the complexity of the produced model, which is connected to the entire process of data acquisition and processing.
- A 3D digital data acquisition project should be regarded as a process, with specific stages and interacting parameters that have to be carefully assessed and planned. The documentation of the process (a set of technical information that describes its

characteristics – the creation of paradata) as well as all needed subprocesses, is extremely important for the long-term preservation of the digital documentation. Technical issues to be highlighted include: quality assessment, repeatability, non-linearity, geometry vs. colourimetry, multimodality, scalability, registration, reliability, and interoperability.

- A proposed Data Acquisition Process Management System (DAPMS) provides for the first time, a fundamental infrastructure to define and manage different processes in the area of 3D digitilisation of tangible CH objects.
- Indicators and proposed parameters for complexity and quality (radial pie charts) are proposed for adoption in any future standardisation work.

Seamless integration with state-of-the-art technology archetypes grounded on smart systems relying on Machine Learning[108], blockchain[109] platforms, edge computing[110] and Internet of Things[93] (IoT), will surely result in considerable improvements with regards to capturing and processing of 2D/3D data. AI algorithms for the automatic registration/merging of different point clouds generated from a variety of sensors, together with greater computational power directly linked with high-bandwidth (5G) Internet connections on free-of-charge cloud infrastructures, could provide for more robust and resilient decentralised models. This can empower new services, such as working with larger data volumes and bigger 3D models of higher grade, at higher speeds. Such approaches will allow better monitoring of the end-to-end 3D digitisation process in real-time, while ensuring that any decisions on quality sufficiently factor in task-specific complexity on a case-by-case basis.

The potential of applying advanced technologies in CH 3D is firmly acknowledged by the European Commission in its recommendation on a *Common European data space for cultural heritage*[111] where it states*: '…the uptake of such advanced technologies has a significant impact on European recovery and growth following the COVID-19 pandemic, and Member States should support it by taking appropriate measures'*.

Adopting the integrated approaches proposed in this study could also constitute a critical turning point in the implementation of the EU Digital Day 2019 Declaration of cooperation on advancing digitisation of cultural heritage[112], by verifiably increasing the quality of 3D CH data acquisition project results in the fastest way possible, leading to new possibilities for the standardisation and long term 3D para-/, meta-/ data preservation and - not least - achieving the digitisation targets proposed for the newly envisaged data space[113].

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[108] Machine learning (accessed Jun. 15, 2021).
[109] Blockchain (accessed Jun. 15, 2021).
[110] Edge computing (accessed Jun. 15, 2021).
[111] Common European data space for cultural heritage (accessed Nov, 2021)
[112] Declaration of Cooperation on Cultural Heritage (accessed Jun. 17, 2021).
[113] To digitise 40% of all cultural heritage at risk in 3D by 2025 and 100% by 2030, 20% of the most visited sites by 2025 and 50% by 2030.

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