Quality control in the production of 3D documentation of monuments

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1. Introduction

The documentation of built heritage increasingly avails of the use of 3D scanning, which produces digital replicas in an accurate and fast way. Such digital models have a large range of uses, from the conservation and preservation of monuments to the communication of their cultural value to the public. They may also support in-depth analysis of their architectural and artistic features as well as allow the production of interpretive reconstructions of their past appearance. Such different uses have different requirements on the accuracy of the models, which must take into account and balance the cost of very detailed and accurate 3D scans with the real needs of the intended purpose and the complexity of managing a huge amount of data.

The 3D-ICONS project (3dicons-project.eu), funded by the EU to provide 3D models of European masterpieces to Europeana, the European digital library, has met very early in its development with the dilemma of producing extremely accurate digital documentation vis-à-vis the available budget and the ultimate destination of the models, a digital repository with a very broad audience accessing the 3D models through Internet connections. If on the one hand the production of high-quality models seemed a unique opportunity, on the other the limits dictated by the budget and by the project remit suggested aiming at lightweight solutions. Finally, the project partnership resolved to create both, high-quality models suitable for scientific documentation and lighter versions for public access through Europeana, of course within the limits of available resources.

In this framework, Quality Management (QM) is paramount to guarantee the reliability of a model and its suitability for technical and scientific uses. A 3D model undergoes a number of transformations: its accuracy depends on the original data acquisition, the post-processing and the simplifications occurring before it is released. These steps need to be accurately documented. The 3D-ICONS project proposes a system of special metadata, called provenance data or paradata, which collect, store and make available to potential users all the relevant information about the model generation. Being impossible an a-posteriori quality control because of the difficulty (or even impossibility) of comparing each released 3D model with predefined parameters, the project has established an a-priori control procedure which guarantees that every operation is documented and follows precise rules. This process is similar to quality management procedures adopted in the industry and in services. The resulting quality manual is a guideline for documenting good practices that together with the required paradata enable a safe use of the models.

There are various techniques used for 3D data capture: among them, 3D data scanning, photogrammetry are the most common. 3D models may also be created manually using CAD systems. In this paper we will consider only 3D scanning, but most of the general considerations apply to other techniques as well.

2. Quality Management in the 3D data acquisition

The concept of quality in digitization is related to the intended use of the digital replica. Reflecting the maturity of the field, there exist several papers and manuals concerning quality control for bi-dimensional images, for example [FADGI, 2009] and [QA Focus, 2006]. In several cases, the approach requires human inspection of the digitized item, which is made on samples only when the throughput of digitization is very large. This is, for example, the approach of BnF (French National Library). Other recommendations refer to process quality management considering that «quality is given paramount consideration at all stages of a project from initial project planning through to exit strategy. Once the workflow is underway, quality can only be lost and the workflow must be designed to capture the required quality right from the start and then safeguard it.» [QA Focus, 5, 2006]. This is a general approach to quality management as defined, for example, by ISO 9000.

Such an approach for QM considers four stages (the list is taken from [QA Focus, 5, 2006]; our terminology is slightly different):

- Strategic QM, where the methodology is defined;
- Process QM, defining how quality is assured during the digitization workflow;
- Sign-off QM, defining a-posteriori quality checks;
- Long-term QM, considering long-term preservation issues.

Here we will consider only the part concerning the digitization process, which includes data acquisition and post-processing. This stage ends when models are released for use: at this point they may be directly checked for quality, thus entering the sign-off stage.

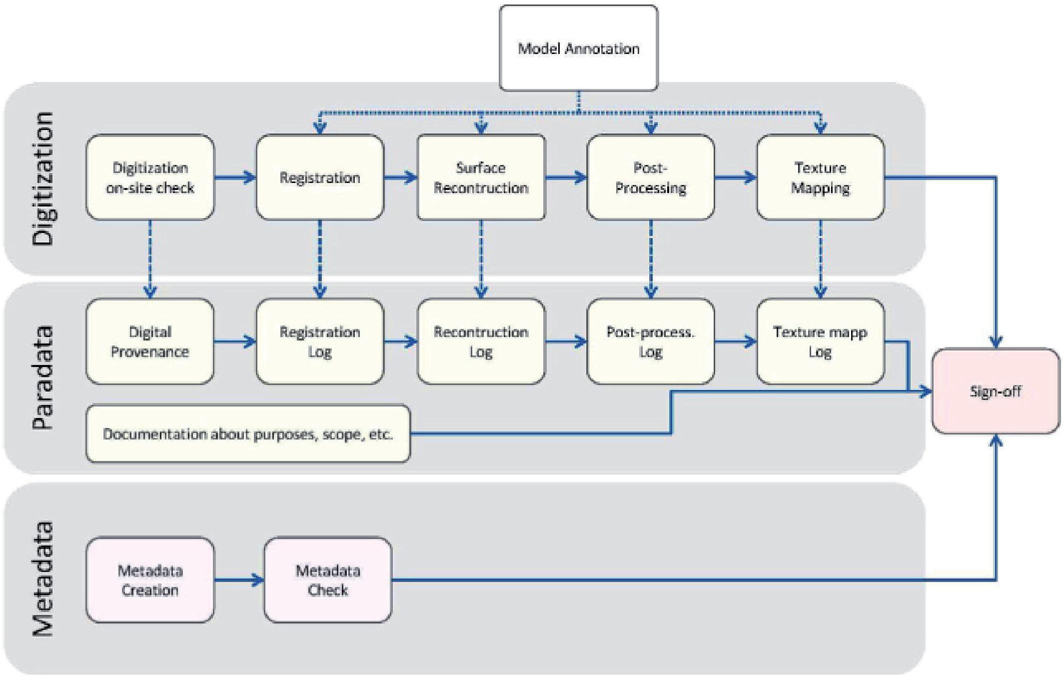
Typically any process-based QM relies on proper documentation. The templates used to document the different actions and the instructions for their compilation form the so-called Quality Manual or Handbook (QH). The documents produced are on paper or in a digital format.

In our case, QM documentation concerns data creation or transformation, producing other data and metadata: therefore, the documentation may be stored together with the data/metadata it concerns, although it describes the process and not the data, as is the case of metadata. For example, when taking a photo it is a common practice to note information about the camera, the lenses, etc., besides noting the photo subject. Such information used to be stored separately, on paper in the old times of analogic photos. Capture and storage of process metadata is now made automatically and stored together with the data in the EXIF heading of the TIFF format, which may also include metadata such as time and place of the shot collected via the camera's internal clock and GPS. In the present paper we will briefly analyse the 3D data capture and post-processing process, discuss how the technical data about the process may be acquired and give an example, the 3D-ICONS metadata schema, which has adopted this approach. Technical data about the process are usually called the digital provenance of the outcome. Other supporting information, e.g. the reason for data acquisition, are called paradata, a term introduced in the digital cultural heritage domain by the London Charter [Beacham, Denard and Niccolucci, 2006; Bentkowska-Kafel and Denard, 2012]. We will also follow the convention recently proposed [Niccolucci and Felicetti, 2013] of calling paradata all these data together, including under this name also the technical paradata, i.e. the digital provenance ones.

3. The 3D data scanning acquisition process

In the last decade the development of Terrestrial Laser Scanner (TLS) reached a high level of performance in terms of point density, measurement precision, time of acquisition and colour capture. Developed for industrial design, TLS is today adopted in other disciplines like Architecture and Cultural Heritage. Using TLS technology to document a scene is not a trivial task; indeed it requires a deep knowledge of the equipment and of the process based on topographical principles. Despite the automated characteristics of current technology, use is not limited to “push a button and wait for results”. Guides on good practice for the collection and archiving of point cloud datasets in heritage applications have been published by English Heritage [Bryan, Blake and Bedford, 2009; Barber, Mills and Andrews, 2011] and by ADS [Payne, 2010].
The main steps of the production of a 3D model are data capture, data processing, and data optimization.
Before starting a scanning campaign, it is crucial to define the resolution, suited to the needs of the project. Choosing the right resolution means saving time during the acquisition, and reducing the time spent on the processing of the data and the noise [Lerma, Van Genechten, Heine and Quintero, 2008]. Clearly the resolution depends also on the equipment and its settings, which must be noted for future reference. Recording this information about every scanner in use by an organization may be made once for all, and then just recalled for the equipment used for a specific activity. An accurate network of reference points is also very important when documenting a monument. Each scanner position and orientation angles must be defined according to a local or global site coordinate system. The quality of the overall point cloud obtained from the composition of the single scans (an operation called registration) is strictly related to the accuracy of the scan positions and the target recording. On the other hand, if the scan position is unknown it is possible to use three Ground Control Points (GCP), allowing the so-called indirect registration [Lerma, Van Genechten, Heine and Quintero, 2008]. In any case, all this information must be recorded. After the registration of all the point clouds, the next step is the creation of a continuous surface. The Poisson Surface Reconstruction and the Delaunay Triangulation are two of the most common algorithms used to create triangulated meshes from point clouds. Data post-processing involves several steps, according to the aim of the digital acquisition: point cloud cleaning, resampling, mesh creation and hole filling. Reverse engineering software offers several tools for mesh optimization, mesh cleaning and resampling, which is particularly suited for 3D model visualization on the web. Reducing the number of triangles creates a lower resolution model, e.g. to facilitate the navigation of the 3D data. Texture mapping is the final step of the pipeline in order to obtain a photorealistic 3D model. The colour can be ap-

plied directly on the point cloud creating the so-called 'point per vertex' where an RGB value is assigned to each point. Cutting-Edge TLS are equipped with an internal or an external camera, allowing colour capture directly registered on the point cloud with no additional intervention by the operator. Alternatively, images taken separately are mapped on the meshed surface. The digitization workflow, adapted from the one presented in [QA Focus, 2006] for 2D digitization, is shown in the diagram below.



4. Paradata automatic generation and mapping/conversion towards a standard format

The 3D-COFORM project (www.3d-coform.eu) has defined a procedure for the management of metadata and paradata for 3D objects to comply with all the different scenarios sketched above, with the main aim to capture the semantic information created at any stage. This extension of the CIDOC-CRM, called CRMdig [Doerr and Teodorakis, 2011] is specifically designed to describe machine-generated and human-created provenance information for 3D objects, the processes which led to their creation and the mutual relationships between physical and digital objects, actors, places and time spans. CRMdig is event-based and comprises classes and properties specifically designed for the representation of provenance events, including Data Acquisition, Capturing and Calibration events, and a set of specific properties to state meaningful relations among them. 3D-COFORM has also developed a toolset to exploit the model and to demonstrate the various ways of producing semantic information, open and accessible, ready to be shared with other data encoded in CRMdig and in other CIDOC-CRM related formats. The RDF syntax, used for the encoding, allows the publication on the web in Linked Open Data format.

4.1. Acquisition

3D scanners, as well as digital cameras, give the possibility to capture a certain amount of the information concerning the various aspects of the acquisi-

tion process performed, and to record it in various formats (usually free text, CSV or XML files). Paradata can be created from these files with simple processes of conversion, i.e. by mapping the various “sections” of the original files, on the corresponding entities of the selected reference ontology. But some considerations should be done when dealing with this kind of tools.
First of all, unlike to what happens with digital cameras, which usually record the acquisition information in the EXIF header of the generated image files during the acquisition process, laser scanners try to never “invade” the object acquired. The information, when recorded, is usually written in a set of log files, typically structured text files, user readable with specific software. On the other hand, if EXIF can be considered a standard for recording digital image information, no standard is used for the encoding of laser scanner acquisition information (i.e. tool calibration, people and places involved and so on) at present time. Putting this data into a standard format is crucial, in our opinion, for interoperability, reuse and exchange of this valuable information. While digital cameras are usually standalone instruments, 3D scanners require the use of a computer where part of the software used for the operation runs and saves information (and the 3D objects themselves) in some local folder. This feature on the one hand makes it very easy to identify and use log files for the purpose of paradata generation, which are generated after an operator’s request for processing. On the other hand, since log files vary in type according to producers and scanner models, an “ad hoc” study and implementation is needed to retrieve and reuse this kind of information.
The separation between tools and software should allow, in the future, the release of interfaces and plugins able to record the provenance information directly into a standard format, to make it immediately available for scientific purposes and shareable in the community. But the proprietary nature of the software supplied with the laser scanners, the scarcity of APIs provided by the producers, and the difficulties in developing external (open) interfaces, certainly poses serious problems for standardisation at this stage.
The only way to get paradata from log files generated by the proprietary software is the implementation of various mapping frameworks, each specific to a scanner, able to implement efficient conversions towards a (more) standard format. Finally, when the automation of this process is not possible (e.g. because the “black box” proprietary software does not allow any information recording), the only solution is the manual creation of the provenance information related with a given 3D acquisition. For this purpose, a specific set of tools is absolutely necessary. The good news is that this can be done once for all for each scanner model in use with an organization, and perhaps be stored in publicly accessible repositories, leaving the operator only the task of recording capture-specific parameters. Within 3D-COFORM [3D-COFORM], several solutions have been tested to handle this kind of problems. A mapping and conversion tool has been released in order to transpose the content of the log files into valid CRMdig RDF triples. Specific interfaces (subsequently incorporated into the Ingestion Tool) have been developed for the manual definition of provenance information when provided by the proprietary software. All the tools allow users to build levels of standard metadata during the acqui-

sition process, even when information is missing.

4.2. Processing

A detailed analysis of log files produced by various post-processing software is the subject of a previous paper by some of authors of the present paper [Niccolucci and Felicetti, 2013]. The results are summarized here for the sake of completeness.

Most of the post-processing software does not record the various steps carried out during the editing phase. Other software, however, provides functions to record every change made to the model in order to be able not only to “undo” a certain operation or to go “back in the history” of actions (in a way similar to what happens with the “History” feature provided by Photoshop), but also to have a complete log of all the steps performed with the software to reach a certain modelling stage.

To demonstrate how paradata creation could be straightforward during the post processing stage, the tool MeshLab (one of the most popular open source 3D processing tools available) was integrated, within the 3D-COFORM framework, with a module able of creating complete logs of actions in XML format. The use of a structured format for the description of the performed actions makes extremely simple to perform further mappings and conversions operations towards CIDOC-CRM compatible formats (e.g. CRMdig /RDF).

Other software provides minimal information on the actions performed, in most cases only what is necessary to implement the common “undo/redo” features. This information, when available, can still be of value. It can be captured in various ways, e.g. with specific functions to save the log text files containing the “commands history”, and then modelled in CIDOC-CRM/CRMdig as a set of events.

Unfortunately, most proprietary software, while keeping track of all the transactions performed, does not allow exporting the related information in any readable/reusable format. This prevents the acquisition of the provenance information, which in this case is totally lost.

4.3. Annotations

Annotation is a particular form of post-processing, which does not necessarily imply any modification of the 3D model. Usually, an annotation is just an enrichment of a 3D model by means of a set of metadata that is tied on top of it with specific relations, in order to create an additional layer of information. Most of the existing tools designed to annotate 3D models are very trivial and provide very basic functionalities, often limited to the possibility of attaching just some labels or similar free-text notes on specific parts of the model.

The 3D-COFORM project has released a robust and complex annotation framework, supporting much more complex and diverse annotation scenarios. The annotation model defines the notion of “Area” (a location of any shape or size considered “of interest” in a 3D model) and takes advantage of specific entities of CRMdig (such as “Annotation Event” “Annotation Object”) to define more structured and meaningful assertions than text-only annotations, e.g. the relation between the 3D digital object and the real world object it was created from. Notwithstanding the complexity of the framework, the original 3D models are never affected by any of the performed annotation operations.

4.4. Ingestion

Ingestion is the last phase, on the border between capture/processing and sign-off, and takes place when creating libraries of digital objects efficiently structured. Metadata are finalized and the digital object is stored for future use. As for annotations and for some cases of acquisition, this is usually a manual process requiring specific interfaces to guide the user through all the stages of data collection and archiving.
The 3D-COFORM ingestion tool provides an excellent example of a tool for gathering these metadata, generated through all the previous steps and stored in the system, including the ability to specify Actors involved in the processes, the Places where the processes happened, the devices used and so on, following the CRMdig model. This activity usually occurs at the same time of data (3D models) ingestion in the repository, although it is conceptually separated from it.

5. Dealing with paradata: the 3D-ICONS schema

In a large-scale project of digital objects creation, as those providing content to Europeana, the variety and diversity of the processes involved require an effective way to manage data and their descriptions. Digital resources cannot be interpreted and correctly reused without the knowledge about the meaning of the data and the ways and the conditions of their creation. Also when aiming at a very wide audience with no specific purpose in mind, storing the life-cycle of the 3D object by collecting information from the generation phase of the model to the final use and keeping track of the instrument settings (calibration, tolerances, errors), the status and the conditions of the physical object and any possible reason that influenced or determined the creation of the model will support data reliability. Paradata make explicit the methodological premises and the research targets of the digitization, so that alternative hypothesis and factual evidences to support the motivations and the reasoning at the basis of the implementation of 3D content can be easily expressed. The London Charter defined some principles [Beacham, Denard and Niccolucci, 2006; Bentkowska-Kafel and Denard, 2012] for the use of computer-based visualisation methods in relation to intellectual integrity, reliability, documentation, sustainability and access, particularly in order to promote technical rigour in digital heritage visualisation, and ensure that computer-based visualisation processes and outcomes can be properly evaluated by users. The Charter does not implement a metadata schema or prescribe specific aims or methods; it rather establishes broad principles for the use of computer-based visualisation, upon which the intellectual integrity of such methods and outcomes depend. In the framework of the objectives of 3D-ICONS (3dicons-project.eu), particularly relevant is the principle 4.6 on the Documentation Process. The London Charter establishes that “Documentation of the evaluative, analytical, deductive, interpretative and creative decisions made in the course of computer-based visualisation should be disseminated in such a way that

the relationship between research sources, implicit knowledge, explicit reasoning, and visualisation-based outcomes can be understood" [London Charter]. Since one of the main 3D-ICONS goals was to develop a metadata schema capable of capturing all the semantics present in understanding and interpretation of data objects, the first year of the project addressed updating the CARARE schema by adding classes or entities and properties to make the original schema compliant to the 3D-ICONS requirements. In CARARE the Information Resource designed to hold metadata about an event is Activity. In the description of the various digitization processes it is important to distinguish between different types of events. The schema proposes the extension of the definition of Event Type:
• EventType - general classification of the type of event or activity which took place, e.g. survey, archaeological excavation, digitization, rebuilding. Use of a controlled vocabulary is recommended.
• Methods - the methods used in this specific activity, e.g. open area excavation, sample survey, augering, boring, stratigraphic, restoration, conservation, etc. A controlled vocabulary is recommended.
Other information that should be provided according to the principles of the London Charter aim at defining the objective of the 3D data capture. The changes proposed by 3D-ICONS consist of two new attributes:
• had_general_purpose (source = CIDOC-CRM) - this is a free text description of the general goal or purpose of an Activity, e.g. practicing, preparing, monitoring, researching, designing, testing etc.
• had_specific_purpose (source = CIDOC-CRM) - a free text note describing the specific goal or purpose of this activity, e.g. carrying out 3D data acquisition, restoration of a part of a building, completing a survey, constructing a building, etc.
To register digital machines and software used for the digitization process and formal derivation two separate elements have been defined:
• Techniques - the techniques used in this activity. Use of a controlled vocabulary is recommended.
• Materials - the materials used during the event. Use of a controlled vocabulary is recommended.
In order to define the digitization process adopted to create the 3D final model, the schema adds some relation to explain the relations between the Heritage Asset, Digital Resource and the Activity related to the digitization processes. The properties reuse those from CIDOC-CRM and in particular from CRMdig. The relations proposed are:
• was_digitized_by - this is the relation between a Heritage Asset and an Activity in which it was digitized. (It is a specialization of was_present:at). Give the id number of the target record or a URI.
• has_created (source = CRMdig) - this is the relation between an Activity and a digital resource or digital file it created; it includes raw data files, processed data files and final models published online.
• consists_of (source = CRMdig) - this is a repeating group of elements which allows the specific activity (or activities) that took place during the overall Event to be described.

• created_derivative - this is the relation which defines the reuse of a Digital Resource to create derivatives, e.g. during the different processing phases of digitization. It is a specialization of Is Derivative Of. Give the id number of the target record or a URI.

Thanks to the publication [Object Template] of object templates of EDM, the mapping of CARARE 2.0 resulted in a simplification [3D-ICONS D6.1]. The last OWL version of EDM has been aligned to CIDOC-CRM Core Classes and some properties of CIDOC-CRM have been reused in EDM allowing a more simple integration of CARARE 2.0 into EDM. The extension of the previous CARARE schema, covering new concepts, assures a simple mapping among different existing standard. Hopefully CARARE 2.0 will foster the adoption by Europeana providers of a clearer approach to describing the features of the cultural object, the techniques and the methodologies chosen for the digitization and the motivation behind the creation of the digital object. Complete knowledge of the digital resource will allow for a more efficient reuse of the archive and increase the usability of the resources available on-line. Furthermore it will be easier to compare models, their complexity, any eventual innovation in their creation and their reliability.

6. Conclusions and further work

The present paper deals with quality issues in the use of 3D, a topic that in the scientific debate has been often mixed up with other concepts. For example, a common misconception confuses scanning accuracy, precision or a large number of 'triangles' with model quality. In fact, the former are not a necessary condition for the latter, and sometimes they are not even sufficient. In our approach, quality means 'well documented': what could be considered a "poor" model from a strictly technical point of view may result in being of better quality than an undocumented high-resolution one. A good model is, in sum, one on which the user may rely on, knowing the circumstances of its creation and the limits of its intended use. As proposed e.g. in [Niccolucci and D'Andrea 2006] and more completely with CRMdig, the CIDOC-CRM is powerful enough to provide semantics for cultural 3D objects incorporating quality documentation. We consider the approach proposed in the present paper as a starting point for the full development of quality management documentation for digital cultural objects and 3D-ICONS as its first implementation, demonstrating its feasibility in a large-scale project. This project introduces the principle of the necessity of paradata in every repository of cultural objects. The complexity of 3D has made this exigency not deferrable any more.

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