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Quality specification and control of a point cloud from a TLS survey using ISO 19157 standard

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ABSTRACT

This paper presents an application of the ISO 19157 framework to the case of a point cloud (PC) representing a heritage asset whose purpose is to serve specific use cases that could be managed in a building information modeling (BIM) environment. The main contribution of this study is to clarify the relationships between the different parts of the ISO 19157 framework applied to heritage building information modeling (HBIM) products derived from terrestrial laser scanner (TLS) surveys by means of a running example. This paper presents a proposal to evaluate, control and report on the quality of the TLS survey of the Ariza Bridge (a 16th century construction). In order to achieve this objective the data quality specifications that must be met are defined by describing and identifying the requirements of five use cases of the data product: 3D visualization, location transfer, measurement, plane generation and absolute positioning. The specifications, according to ISO 19157, are formalized by selecting the data quality element to be measured, its scope, the measure used and the level of conformity necessary for the element to be accepted. In addition, the control methods for each quality element are proposed.

1. Introduction

Heritage constructions should be conserved and protected to be transferred to future human generations, particularly when they are singular ones like the Ariza Bridge (our study case). Having reliable documentation from the heritage asset helps the restoration and conservation tasks [1,2] but often no such documentation exists. To avoid losing the current heritage, reliable documentation is necessary. The documentation set is composed of historical plans, images (pictures and photographs if existing), bibliographic references, 3D surveys, etc. A device that allows an accurate 3D representation to be captured from any heritage asset is the terrestrial laser scanner (TLS), as shown in [3,4,5]. The TLS can achieve a high level of detail, describing the object's geometry [6] so that it is possible to analyze small deformations appearing in the architectural or engineering heritage asset [7,3]. We can obtain an accurate 3D model after registering a set of point clouds (PC) coming from different scan stations [1]; the PC, along with the multiple images covering a full dome of 360° x 300° from the camera inside the TLS device, facilitates the detection of features and damages [8]: the PC allows us to quantify linear, areal and volumetric magnitudes while images through textures can identify materials and pathologies such as moisture, breakages, etc.

One of the most useful aspects of PC is its ability to support Building Information Modeling (BIM) tasks and particularly the Heritage BIM (HBIM) as shown in León-Robles et al. [8], Andriasyan et al. [9], and Rodríguez-Moreno et al. [1]. The BIM product can be a building or another construction object, such as a bridge. It is not just a 3D model, its parts have a semantic and functional meaning. Although the PC allows generation of an accurate BIM it is necessary to quantify the reliability and the quality achieved for the derived BIM or HBIM [1,10,11]; following that approach, our research analyzes the surveyed data of the Ariza Bridge from a quality perspective, studying the ability of the PC 3D model to satisfy different use cases that are typical in the conservation and restoration field.

Ariza-López et al. [12] conduct a review of studies focusing on quality applied to BIM and highlight the interest and importance of the

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quality of BIM data, concludinge with the need for a better formalization of these processes and attention to cases in which quality must be controlled against reality, and not only through automatic routines (rule-based controls, e.g. clash detections). Basically they propose a statistical framework based on multiple multinomial hypothesis tests and the use of the ISO 19157:2013 framework [13] for the management of data quality issues. This ISO international standard is a useful and complete standard covering all elements of geospatial data quality under a unique and consistent approach [14], and nowadays it is under a revision process. This international standard is mainly focused on vector data, but it can be extended as shown by the papers of Ureña-Cámara et al. [15] and Ariza-López et al. [12] to metadata and BIM data respectively. In this paper we are going to apply this framework, but special attention will be paid to the aspects related to the definition of the product through its specifications and the quality control of those specifications.

The aim of this paper is to present a complete example of the application of the ISO 19157 framework to the case of a PC representing a heritage asset whose purpose is to serve specific use cases that will be managed in a BIM environment. In this way, the main contribution of this study is to clarify the relationships between the different parts of the ISO 19157 framework in their application to HBIM products derived from TLS surveys by means of a running example.

This paper is organized as follows: After this introduction, section two will present a general view of the ISO 19157 framework for data quality. Section three is centered on the process and develops methodological aspects and presents the asset we are going to work with. The fourth section details the field survey carried out. The fifth section is centered on the quality control execution, showing the results and proposing a documentation scheme. Finally, both a general discussion and a main conclusions sections are included.

2. The ISO 19157 framework for data quality

ISO 19157 focuses on the quality of geospatial data, but we believe that it can be applied to any type of data (eg BIM data). Fig. 1 shows our interpretation of the steps, components and relations established by ISO 19157 which are of interest for our purpose. This section focuses on the relationships between the components that establish a data product specification (right part of the figure), while the next section will focus on the process and its steps (left part of the figure).

ISO 19131 [16] is the international standard proposed for defining geospatial data products, as is our case. It establishes that the product specifications should be set, if possible, in a quantitative way. This implies that they could also be evaluated quantitatively from a quality perspective. For all the above, there is an interest in knowing in more detail the model proposed by ISO 19157. This standard organizes quality into six dimensions representing mainly the components of the geospatial information (spatial, thematic, temporal, logical, etc.), which are subdivided into 15 subclasses (known as “data quality elements”, DQE onwards) which define what is measured (omissions, commissions, absolute accuracy, topological consistency, etc.). To quantify various aspects related to DQEs, the international standard proposes the data quality measures (DQM). The vocation of the DQEs and the DQMs is to serve to establish the specifications of the data products, to evaluate the quality of those products and to report on the results of the quality evaluation. In order to adequately establish an aspect of quality, and subsequently to be able to control it adequately, it is first necessary to establish unambiguously the members of the population to which we refer. So the population of interest must be defined, and this is carried out by means of a scope (Sc). The scope is a filter based on time, location, classification, attributes or, in general, on any other criteria that establish a selection rule. The scope is usually defined by a type of items of interest (e.g. piers, walls, abutments, stone blocks, etc.), but it can also be defined by a set of them if they share some aspect of common interest (e.g. windows and doors and walls, when our interest is the correction of the finish colour). The joint of a Sc and a DQE is known as a data quality unit (DQU) in the jargon of ISO 19157. So the same Sc can be linked to different DQEs in order to control several perspectives of the data quality (e.g. those of all the DQEs). Also, the same DQU can be assessed by means of different DQMs and by different data quality assessment methods (DQAM). ISO 19157:2013 defines more than 70 standardized DQMs (see Annex C of ISO 19157:2013) but only a general assessment method. The last is not problematic because ISO 19157 allows the use of whatever evaluation method can be considered adequate for the assessment purpose. For example, the ISO 2859 and ISO 3951 series can be applied to the quality control of attributes and variables. For the case of the positional quality control many specific geospatial standards can

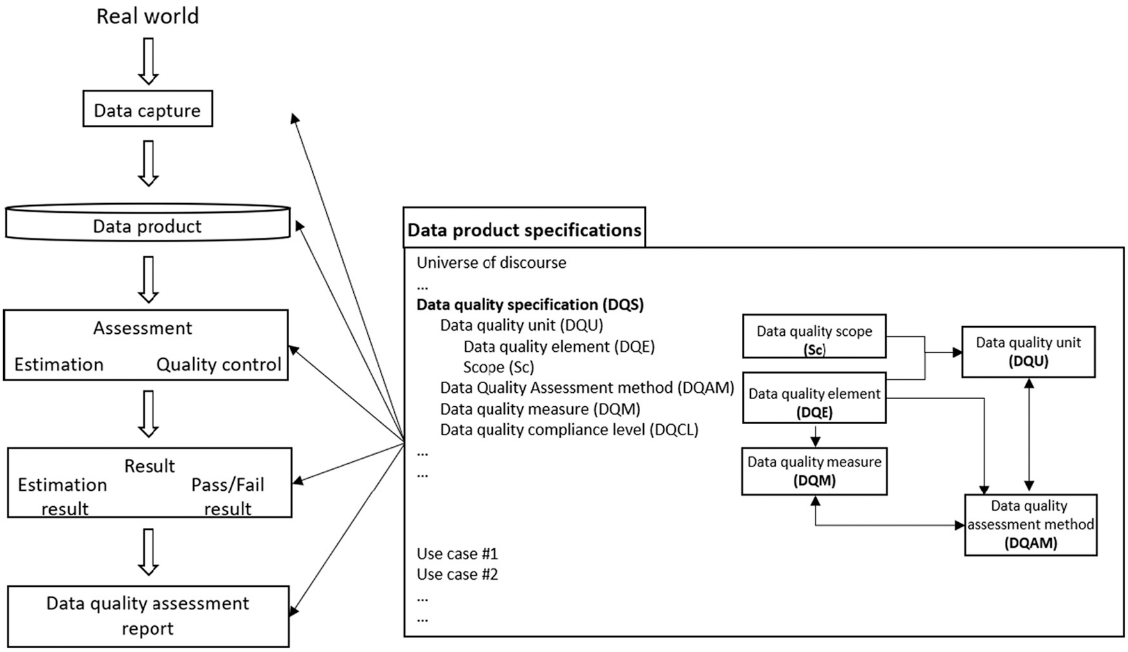

Fig. 1. Summary of key components for establishing quality specifications and controls over geospatial data.

also be applied: e.g. the NSSDA (National Standard for Spatial Data Accuracy), the EMAS (Engineering Map Accuracy Standard), etc. (see [17] for a complete guide on this subject). Finally, the quality control of a product is a statistical decision on the acceptance or rejection of a product with respect to its specifications, and for this purpose a data quality compliance level (DQCL), or conformity level, must be established. This DQCL must be expressed in the same way and using the same units as the DQM used for the DQE being considered. In this way, a quality control is well defined if a DQU (=DQE + Sc) and its corresponding DQCL (=DQM) and DQAM are properly established. These are the constituents that must be managed in order to unequivocally establish quality control when using the ISO 19157 framework. The data quality assessment results must be reported internally and externally. For this it is appropriate to use metadata, that is, data that reports on data sets. The ISO 19115 series of international standards proposes the framework for metadata related to geospatial data. ISO 19115-1:2014 [18] has a specific chapter for reporting on the quality of geospatial data. On the other hand, if necessary the quality results can also be reported using the standalone quality report proposed by ISO 19157.

3. Materials and methods

The process followed in this paper is presented in Table 1. This process consists of 5 phases; the first is the approach phase, which consists of knowing the cultural asset and the objective that is proposed for the 3D model to be generated as a result of the survey work. In this phase we also establish the use cases that clarify the use of the 3D model to be produced. The second phase is of definition, where DQAMs to be used are specified in order to assure the specifications. The third and fourth phases are of execution of the survey and quality control, respectively. Finally, we proceed to the documentation of the processes carried out (generation of metadata).

The approach and definition phases are developed in greater detail throughout the subheadings of this section. The next sections will present the implementation (survey execution and QC execution) and documentation (metadata) phases.

3.1. *Aproach phase (the asset and the product to generate)*

As indicated above, this phase aims to know the asset with which we are going to work and also the objectives that are proposed for the 3D model (product) to be generated. This section matches with the 1st phase in Table 1.

3.1.1. *Basics of the tested asset (the Ariza Bridge)*

The Ariza Bridge was designed by the architect Andrés de Vandelvira (Alcaraz 1505 - Jaén 1575), the maximum representative of the Renaissance school in Jaén (Spain). Some relevant works of Vandelvira are the Cathedral of Jaén, the Cathedral of Baeza, the Santiago Hospital in Úbeda and the City hall of Úbeda, among others. The Ariza Bridge is located in the north-east of the province of Jaén, 17 km north of Úbeda, close to the layout of the A-301 regional road. The approximate overall dimensions of the bridge are 95 m long, 17 m high, 6.3 m wide, with a main arch in the middle of 32 m. The bridge crosses the Guadalimar river in a north-south direction in an environment of olive groves and materials whose lithology corresponds to the Secondary (Triassic or Jurassic Lias) and Tertiary (Miocenic Andalusian and Tortoniense) Periods. The bridge served as the royal road between Toledo and Almería, that is, it was key in the union between the central plateau of Spain and the south-east region (the ancient Kingdom of Jaén and the Kingdom of Granada, both under the rule of Castille). The works of the current bridge did not start until 1562 and did not finish until 1583 due to economic problems. The bridge was paid for almost entirely by the city council of Úbeda. In 1847 it was reformed and the flush was rectified at the request of the muleteers and carters [19]. In the second half of the 20th century two long curved slopes were added to accommodate the bridge to the new road layout. In 1993 it was rated as a Property of Cultural Interest (category of Monument). In 1998, the Giribaile Reservoir became operational so that the waters cover the bridge when the maximum reservoir level is reached. The road through it (previously catalogued with code C-3217) was diverted and a new bridge was built. The Ariza Bridge emerges when the water level falls so that in years of drought it is fully accessible. Now it is on the red list of heritage assets (https://listarojapatrimonio.org/ficha/puente-ariza). Its state of conservation can be considered complete and reasonable.

The Ariza Bridge is a “donkey loin” bridge. It has five semicircular arches of different sizes but shows an elegant apparent symmetry. As decorative parts the bridge has the coat of arms of the city of Úbeda, moldings and four missing landmarks that were placed at each end of the protective parapets. As a peculiarity, one of its pillars has a vaulted access in the form of an L. This access, as well as its purpose, is not indicated in the original documentation; it is considered that it could have served the function of a shallow refuge for users such as cattle drivers [20]. Fig. 2 presents a photograph [21] of its state in the mid-19th century.

The bridge is built entirely with sandstone of a pleasing yellowish fine grain, and low hardness. The stone is carved in parallel, irregular and medium-sized blocks of 42 cm × 20 cm × 35 cm and the stone blocks are locked by means of sand mortar and lime (two measures of lime for three of coarse sand). According to Ruiz Fuentes [20], there were six phases of modifications until reaching the current result. These modifications involved increasing the height of the main arch as a way to avoid various problems with the location of the bridge and available materials, thus passing from an initial design consisting of an arch 25 m wide and 12.5 m high with a double 1.93 m thread to a final arch size of 32.7 m wide and 17.95 m high.

Table 1
Phases of the proposed process for a rigorous data product specification and evaluation.

Phase order	Name	Description	Article section
#1	approach	Understand the asset. Determine use cases	3.1
#2	definition	Determine the QC methods	3.2
#3	survey execution	Execution of the survey of the asset	4
#4	QC execution	Execution of the QC of the surveyed data	5
#5	documentation	Generation of metadata	5

3.1.2. *Expected product (use cases)*

We want to generate a product that we can call a “3D Digital-metric model of the Ariza Bridge” and whose general purpose we can state as “documentation of a historical heritage asset with the possibility of use in maintenance and restoration activities”. In this way, in order to define in a more precise way the intended uses of the product and the quality requirements that these entail, the use cases presented in Table 2 have been considered. Use cases are a widely-used technique for establishing the requirements in the development of software applications and many other fields [22,23]. The use cases in Table 2 are presented in cascade, so each case requires compliance with the requirements of the previous case. Thus, for example, it is considered that for a correct identification of stone blocks (use case 2) it is first necessary to have a complete model (use case 1). For each use case are indicated: a title or name; a brief description; the objective to be met; the way of use considered and the requirements of the product. Product requirements are the basis for later establishing more precise definitions of quality and its DQAMs.

The product requirements established for each use case in Table 2 are more specific and easier to evaluate, in terms of their achievement, than the general objective, which unfortunately is usually poorly defined and ambiguous. However, these requirements are not enough from the point

Fig. 2. View of the Ariza Bridge in the mid-19th century.

of view of the quality of a data product. Every product must ensure that its data quality specifications are explicit and well defined. Therefore, what is intended now is to establish those specifications that further define the product requirements indicated in the use cases. For this the geospatial data quality model proposed by ISO 19157 will be adapted and used.

For ISO 19157, a key aspect when assessing data quality is the definition of the so called universe of discourse (UoD). The UoD is a view of the real world that includes everything that is of interest. This view derives from a process of abstracting into an ideal form, which can be considered as a perfect dataset, described by the product specification or by the user requirements. The quality of a dataset is how well it represents the UoD, therefore a quality assessment is performed by comparing the dataset against the UoD. Therefore, the same dataset can be assessed against different UoDs. For the data producer, the UoD is defined by the product specification which contains the rules for constructing the dataset. For a data user, their user requirements describe a UoD which may not match the data producer's UoD. Consequently, the quality of the dataset may differ depending on which UoD it is evaluated against.

For each of the use cases in Table 2 the product requirements represent a different UoD. Given that the use cases are presented in cascade, with requirements that are assumed and accumulated from one case to the following, the corresponding UoDs can be assumed as abstractions of the real world that are more and more detailed. Table 3 presents detailed specifications which expand the product requirements of the use cases in Table 2. For each use case the UoD and one or more DQUs (DQE + Sc) have been specified. For each DQU the DQCL has been specified, which is an unambiguous definition of the minimum quality level or the maximum bad quality level. The DQCL is defined by: i) a DQM (including its name and also the identifier from Annex D of ISO 19157, if applicable); ii) its measurement unit (e.g. m, m^2, m^3); and iii) its value (e.g. 5 m^2). It is also important to note that ISO 19157 allows the definition of new DQEs and DQMs. In Table 3, the text "new proposal to ISO 19157" appears if a new DQE or DQM is included.

Not only an unambiguous definition of the data quality product specification is needed, but also an unambiguous definition of the quality control decision rule, which means a clear explanation of the way a quality control decision is taken. We consider that the following components are needed: i) a conformity level, as described previously; ii) a quality assessment result coming from a standardized quality assessment method; iii) a rule to be applied when making the decision and iv) the producer's and user' risks level, if needed. Some of these are present in Table 3, but the evaluation method for each specification will be presented in section 2.2.

3.2. *Definition phase: the data quality assessment methods (DQAMs)*

To fully define a specification that is established by a measure the assessment or method must be indicated. If this is not done, each may apply slightly different or very different DQAMs, so the desired quality of the product is not really ensured. ISO 19157 does not speak of standardized DQAMs (in the sense that it develops for measurements), but we consider this to be a critical aspect in the definition of a product. Table 4 presents the relation between the use cases and the proposed DQAMs. This section matches with the 2nd phase in Table 1.

As a complement to this section, each of the DQAMs needed to assess the product specifications is presented in a summary form in a table in Appendix A. The content of each table from this appendix follows this scheme:

- Name. Name given to the method.
- Identifier. Value uniquely identifying the method in our organization.
- ISO Type. Indication of the ISO 19157 method type: direct external or direct internal.
- Result type. Indication of the result type: estimation for a quantity determination (e.g. RMSE = 5 m) or a quality control for a pass/fail result.
- Purpose. Brief text with the purpose of the quality assessment method.
- General Description. General and brief description of the method, with the identification of source(s), if existent.
- Detailed description. Detailed description of the method, including, at least:
  - o Population. Definition of the population in accordance with the scope of the DQU considered in the specifications.
  - o Inspection. Explanation of the full inspection or sampling approach. In the latter also including:

Table 2
Use cases considered for the definition of the data product.

Use case #1	3D visualization
Description	The 3D model must allow visualizations of the real world asset with different zoom levels and from different points of view in order to show a general view.
Objective	General inspection and knowledge of the asset and communication purposes.
Way of use	The visualization of the 3D model occurs in a software tool allowing the change of points of views, perspectives and zoom levels.
Product requirements	Seamless pattern. Completeness (general view).
Use case #2	Location transfer
Description	The 3D model must allow the evaluation of how to organize a possible location transfer of the asset.
Objective	Identify each of the stone blocks that make up the bridge and their positions, in order to organize the work of disassembly on site and assembly in another location.
Way of use	Visual identification and numeration of all stone blocks and minor details in each corresponding position.
Product requirements	Completeness (identification of stone blocks).
Use case #3	Measurement
Description	The 3D digital-metric model must allow the extraction of measurements as on the actual asset.
Objective	The obtaining of measurements of the asset for use in analysis, maintenance and restoration activities.
Way of use	Visual measurement on the 3D digital-metric model included in a software tool that allows extracting measures of angles, distances and surfaces (e.g. areas affected by pathologies).
Product requirements	Relative positional accuracy to the order of centimeters.
Use case #4	Plane generation
Description	The product must allow the generation of planes of several surfaces of the bridge.
Objective	Obtain a simplified mathematic model that represents major construction surfaces of the bridge (wall, wing wall, pier, spandrel, roadway, etc.).
Way of use	Statistical adjustment of surfaces to PCs.
Product requirements	High density of the PC. Planes defined from the PC with a low error in orientation.
Use case #5	Absolute positioning
Description	The 3D digital-metric model must have a high absolute positional accuracy.
Objective	Accurate positioning and orientation of the model in a large scale map.
Way of use	The model can be integrated into a large scale map. Therefore, coordinates from well-defined points in the model have a high absolute positional accuracy.
Product requirements	Absolute positional accuracy to the order of centimeters.

Table 3
Data quality specifications from data product requirements in Table 2.

Use case #1: 3D visualization			
Requirements	Data quality specifications		
Seamless pattern	UoD:		3D model of the bridge, made up from a PC and a set of photographs for texture. All the components that make up the bridge's visible structure are present (walls, piers, etc.) without any occluded area.
Completeness (general view)	DQU	DQE:	Omission
		Sc:	The whole textured 3D model of the surface of the bridge.
	Description:		No missing components, totally or partially, when comparing the model with the UoD.
	DQCL	DQM:	Rate of missing items (ID = 7, ISO 19157)
		Value:	$\leq 5\%$
Use case #2: Location transfer			
Requirements	Data quality specifications		
Completeness (stone blocks)	UoD:		The same as case #1, but each visible (outer) block of the bridge can be identified.
	DQU	DQE:	Omission
		Sc:	The whole textured 3D model of the surface of the bridge.
	Description:		No missing blocks, totally or partially, when comparing the model with the UoD.
	DQCL	DQM:	Rate of missing items (ID = 7, ISO 19157)
		Value:	$\leq 5\%$
Use case #3: Measurement			
Requirements	Data quality specifications		
Relative positional accuracy	UoD:		The same as case #2, but linear measures from coordinates of the PC present an error with bias below 0.01 m and standard deviation below 0.02 m.
	DQU	DQE:	Relative positional accuracy.
		Sc:	The whole PC of the surface of the bridge.
	Description:		Low bias in the error of distance measures when comparing the model with reality.
	DQCL	DQM:	Bias of positions (1D) (ID = 128, ISO 19157)
		Value:	≤ 0.01 m
	DQU	DQE:	Relative positional accuracy.
		Sc:	The whole PC of the surface of the bridge.
	Description:		Low standard deviation in the error of distance measures when comparing the model with reality.
	DQCL	DQM:	Standard linear error (ID = 34, ISO 19157)
		Value:	≤ 0.02 m
Use case #4: Plane generation			
Requirements	Data quality specifications		
Density of the PC	UoD:		The same as case #3, but the PC has a density higher than 1 point/cm^2 and the mean error in orientation of the calculated planes is below 2°.
Plane accuracy	DQU	DQE:	Density of information (new proposal for ISO 19157).
		Sc:	The whole PC of the surface of the bridge.
	Description:		Minimum local density of the PC, higher than a given threshold.
	DQCL	DQM:	Points per square meter (new proposal for ISO 19157).
		Value:	$\geq$ 10,000 points/m^2 ($\geq$ 1 point/cm^2)
	DQU	DQE:	Geometric accuracy (new proposal for ISO 19157).
		Sc:	Subsets (patches) of the PC corresponding to planes in the surface of the bridge.
	Description:		Low mean error in the orientation of planes in the surface of the bridge, when comparing the model with reality.

(continued on next page)

  - Sample Scheme. Identification and explanation of the sampling scheme.
  - Sample Size. Sample size value or its calculation formula.
  - Sample collection. Explanation of sample collection procedures and rules (if needed).
- Resources. Explanation of the resources needed to apply the method, for example:
  - Instrumental. Instruments that are needed for the assessment development.
  - Human. Special requirements (if existent) for the operators.
  - Reference. If needed, it is the source, tangible (i.e. reality) or intangible (i.e. some type of data) that constitutes the reference against which to compare
- Measures. Identification and explanation of the measures to be used, in accordance with the specifications considered.

Table 3 (*continued*)

Use case #1: 3D visualization			
Requirements	Data quality specifications		
	DQCL	DQM:	Mean angle error between normal vectors to planes (new proposal for ISO 19157)
		Value:	$\leq 2^\circ$
Use case #5: Absolute positioning			
Requirements	Data quality specifications		
Absolute positional accuracy	UoD:		The same as case #4, but a coordinate transformation has been applied in order to locate, rotate and scale the 3D model in an absolute coordinate system. The final radius of the error sphere is checked to ensure that is below 0.05 m.
	DQU	DQE:	Absolute positional accuracy.
		Sc:	The whole PC of the surface of the bridge.
	Description:		The radius of the error sphere is below 0.05 m (probability of 61%).
	DQCL	DQM:	Mean Radial Spherical Error (uncertainty-related data quality basic measures, ISO 19157)
		Value:	≤ 0.05 m

DQCL, Data Quality Conformity Level, DQE = Data Quality Element, UoD: Universe of Discourse.

Table 4
DQAMs for each use case.

Use case	DQAM
#1	Quality control of omissions of components in a 3D model skin
#2	Quality control of omissions of stone blocks in a 3D model skin.
#3	Quality control of the relative positional accuracy of a 3D model skin.
#4	Quality control of the information density of a 3D model skin.
#4	Quality control of the geometric accuracy of a 3D model skin.
#5	Quality control of the absolute positional accuracy of a 3D model skin.

- Processes. A step by step explanation of the steps of the evaluation method.
- Result. A brief guideline on the result.

Appendix A includes six DQAMs. These methods are diverse: some of them are full inspection and others sample based methods; some of them are based on human evaluation and others on instrument measurements. With this variety of methods we want to demonstrate that the proposed framework is adequate for any case.

An important aspect that we want to highlight is that when human operators intervene, we always consider a set of conditions for improving the accuracy of the result. In this study the framework indicated by [24] has been taken as the basis, which proposes: (i) using a group of selected operators; (ii) designing a specific training procedure for the group of operators in each specific DQAM; (iii) calibrating the work of the group of operators with controlled data; (iv) supplying the group with appropriate written documentation of the product specifications and the quality control process; (v) helping the group with appropriate service support during the quality-control work and socializing the problems and the solutions and, finally, (vi) deriving the result from a multiple assignation process to the operators of the group. This is achieved by averaging the set of individual numerical results (for quantitative values), determining the majority or achieving agreements within the set (for qualitative values).

4. The survey execution

This section matches with the 3rd phase in Table 1.

4.1. Surveying equipment

Two scanners (Leica C10 and Leica BLK360) and a total station (Leica TS-06) were used in the scanning of the bridge. The characteristics of the instruments used are as follows:

- Total station Leica TS-06: 1" angular precision, 2 mm ± 2 ppm range precision and quadruple axis compensator.
- Scanner Leica C10: Accuracy of single measurement at 10 m, 6 mm in position and 4 mm in range; 12″ in horizontal and vertical angle. Single 17° x 17° image: 1920 × 1920 pixels (4 megapixels) Full 360° x 270° dome: 260 images; Levelling capability including dual axis compensator that will be used to obtain the entire survey level.
- Scanner BLK360: Accuracy of single measurement at 10 m, 6 mm in position and 4 mm in range. 40″ in horizontal and vertical angle. HDR image capability. 15 Mpx 3-camera system, 150Mpx full dome capture.

The parameter settings for each scan are presented in Table 5: a) field of view, expressed as composition of the horizontal and vertical angular range, covered by the scanner; b) scanning resolution, that indicates the number of points captured per unit of flat surface which is perpendicular to the scan, and c) imaging, including image size and whether the scanner uses HDR (High Dyamic Range) or not.

4.2. Bridge scanning

We started from arbitrary local coordinates of a survey point on the deck of the bridge (Pte) and an arbitrary orientation direction, from where six survey points (P1, P2, …, P6) were measured with the total station (red circles in Fig. 3). P1 to P4 were located on the south bank of the Guadalimar river while P5 and P6 were located on the north bank. In relation to the bridge P1, P2 and P5 were located on the upstream side while P3, P4 and P6 were located on the downstream side.

The only 2 stations where the C10 scanner was stationed for the survey were Pte and P1, whose scans we will call respectively Pte_{C10} and P1_{C10}. The rest of the survey was carried out with the BLK360 scanner whose first station was located at station P1 (P1_{BLK}) so that scans Pte_{C10}, P1_{C10} and P1_{BLK} could be accurately registered. After this registration the P1_{BLK} scan, which is not initially levelled due to the lack of level of the BLK360 scanner, will be levelled.

The remaining BLK360 scans were taken from arbitrary positions (yellow triangles in Fig. 3) that were chosen in situ, trying to guarantee a good coverage of the bridge (important for use cases #1 and #2) and a high density of points (important for use case #4). The process is semi-automatically controlled by the Leica Cyclone 360 software, which can be divided into two phases: 1) rough manual registration, using the viewing capabilities of Cyclone 360 over the PC (Fig. 4), and 2) registration optimization when the software tries to find the best fit between the scan to be registered and all previously registered scans:

1. Manual registration by visualization between two individual scans is as follows: the plant view is matched using rotations (Fig. 4a) and then translations (Fig. 4b); From the elevation view, the tilted scan is corrected (Fig. 4c) and then moved until both scans roughly overlap (Fig. 4d); finally, the registration is automatically optimized,

Table 5
Scan setting.

Scanner	Field of view	Scanning	Imaging	
		Resolution	Size for full dome	HDR
C10	360° x 270°	1 cm at 10 m	1920 × 1920 pixels × 260 images	No
BLK360	360° x 300°	1 cm at 10 m	150Mpx	Yes

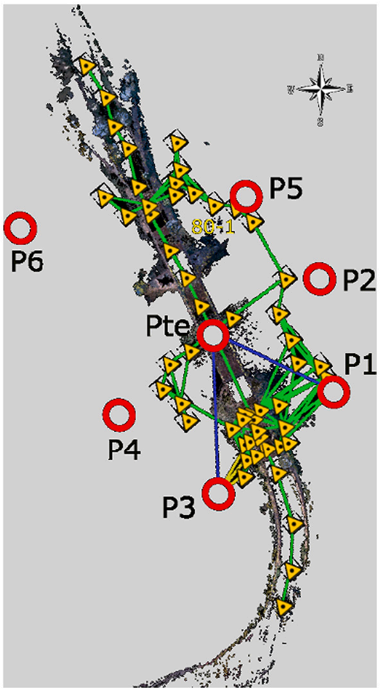

Fig. 3. All survey points used for the survey execution. Red circles (Pte and P1 - P6) constitute a network in a local coordinate system. Yellow triangles show the arbitrary location of the BLK360 scanner for the scanning of the bridge. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

obtaining the mean adjustment error (Fig. 4e) together with the percentage of common coverage of both scans.

2. As a result of the registration optimization, Cyclone 360 displays a series of links between the scans (green lines between the yellow triangles in Fig. 3). The set of links $l_{Si\text{-}j}$ starting from a scan *Si* and matched to scans *Sj* (*j* = 0,1,..,n) indicates how many *Sj* scans directly influence the *Si* scan registration adjustment. The link colour has a qualitative meaning, good (green), medium (yellow) and bad (red), which serves to give a quick idea of the quality of the record. A bundle adjustment is performed by the software minimizing the errors between all the linked scan stations.

The final result (bundle adjustment), after the last scan registered has been computed, shows the links that took part in the network adjustment (Fig. 5a). A summary referring to the quality parameters of the global adjustment is computed (Fig. 5b), whose meaning is as follows:

- Bundle error: Total error obtained after adjusting the whole network.
- Overlap: Mean value of PC percentage common to two scans related by a link.
- Strength: This parameter value would be 100% if all the points used to register a scan were uniformly distributed along all the 3D space directions.
- Cloud-to-Cloud: Mean error considering all the errors for each pair of linked scan stations.

The most informative error in our study is the bundle error. Its value is 0.006 m, which could be considered suitable for the purposes of this type of survey. It is also important to note that this bundle error value points to the fulfilment of the data quality specifications of use case #3 in Table 3 (bias of positions of positions ≤0.01 m and standard linear error ≤ 0.02 m), which has to be confirmed with the quality control execution.

Fig. 5c shows an orthoimage from the PC (upstream) in order to facilitate understanding of the PC of the Ariza Bridge which results from

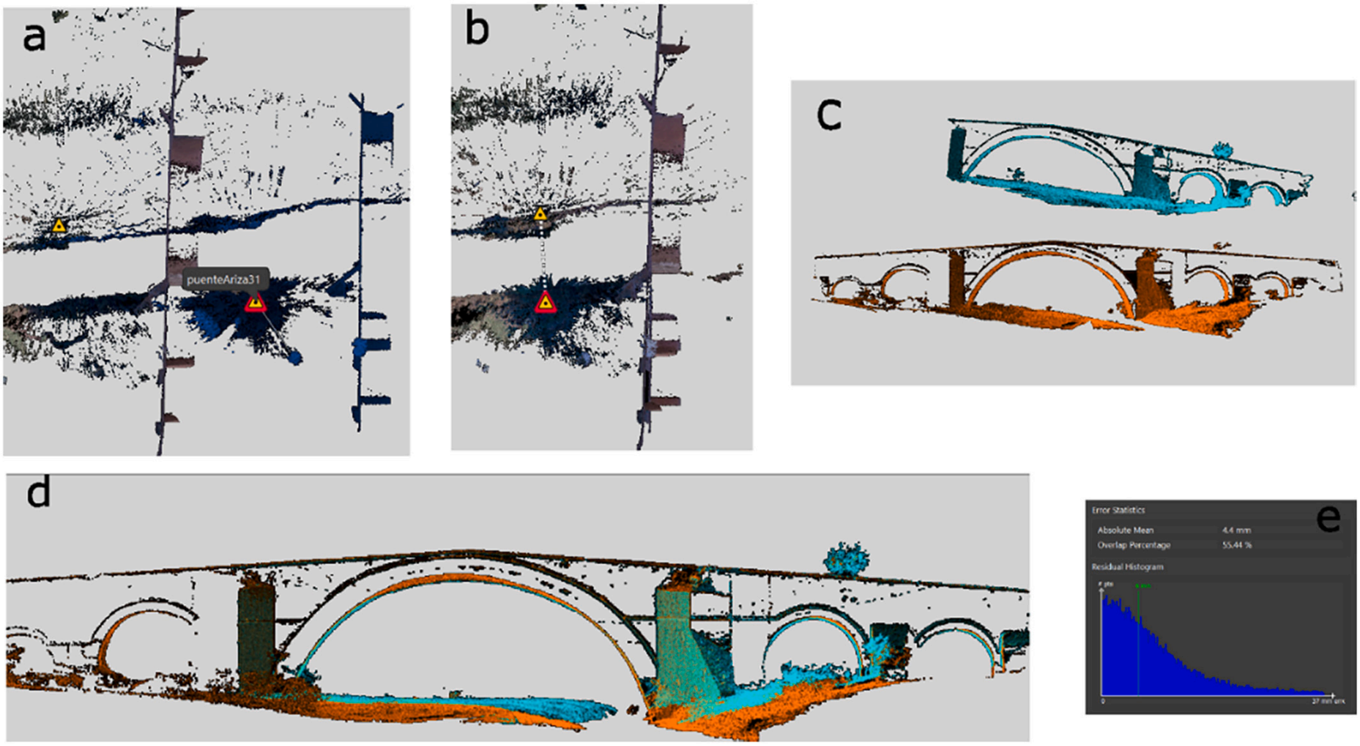

Fig. 4. Manual registration by visualization between 2 individual scans: plant view matching after applying rotation (a) and after applying translations (b); elevation view tilt correction (c) and roughly overlapping (d); results of the mean adjustment error after the optimization of the registration (e).

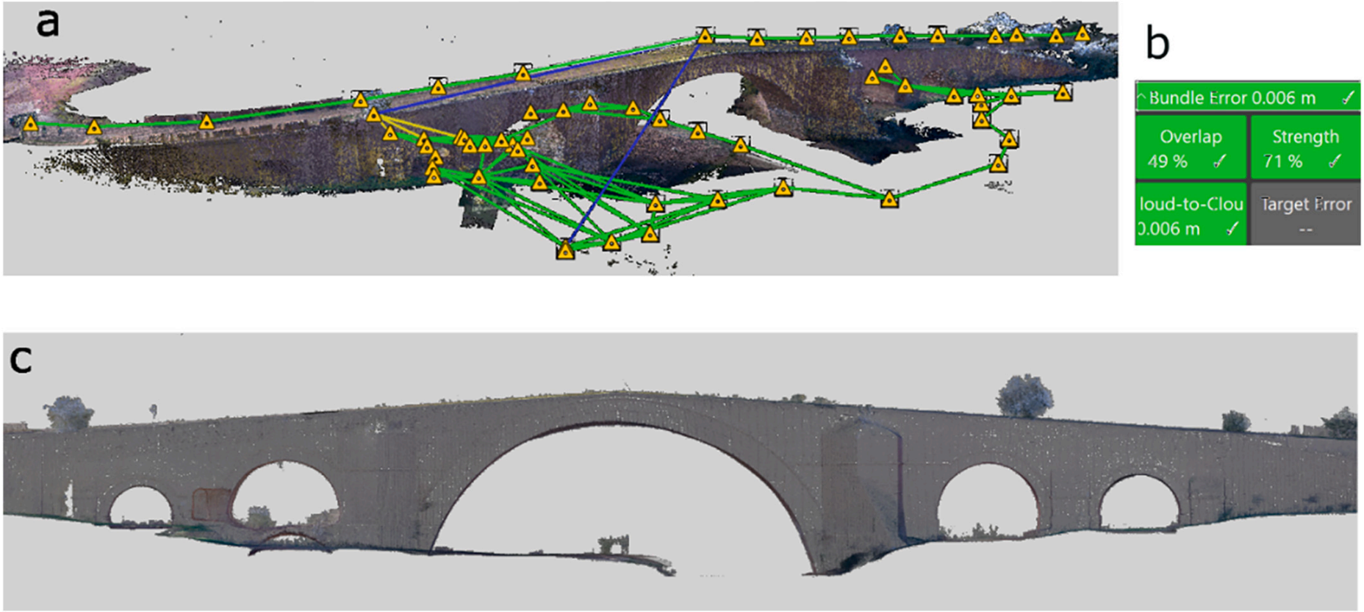

Fig. 5. Bundle adjustment result: a) links between scans, b) quality parameter values, c) PC orthoimage.

the bundle adjustment.

4.3. Positional quality control from the registered survey

In order to perform the registration quality control and estimate its uncertainty, the local coordinates of four targets placed on the bridge (upstream) were analyzed (Fig. 6). With this objective the bridge was scanned from P5, which is close to the targets, using a second therefore independent Leica C10 scanner. The differences between the local coordinates were obtained as follows:

- Using Cyclone 360, the local coordinates from the target center were obtained from the BLK360 PC. The most perpendicular and nearest scan to the targets, labelled as 80–1 in Fig. 6, was used to obtain these coordinates.
- The same process was applied to the independent scanning performed from P5 with the C10 scanner.
- The local coordinates ́differences from the 4 targets were calculated, obtaining an average difference in 3D positioning of 0.025 m. Table 6 shows more detailed information. Data from the C10 scanner appears as "reference" while data from BLK360 appears as "survey".

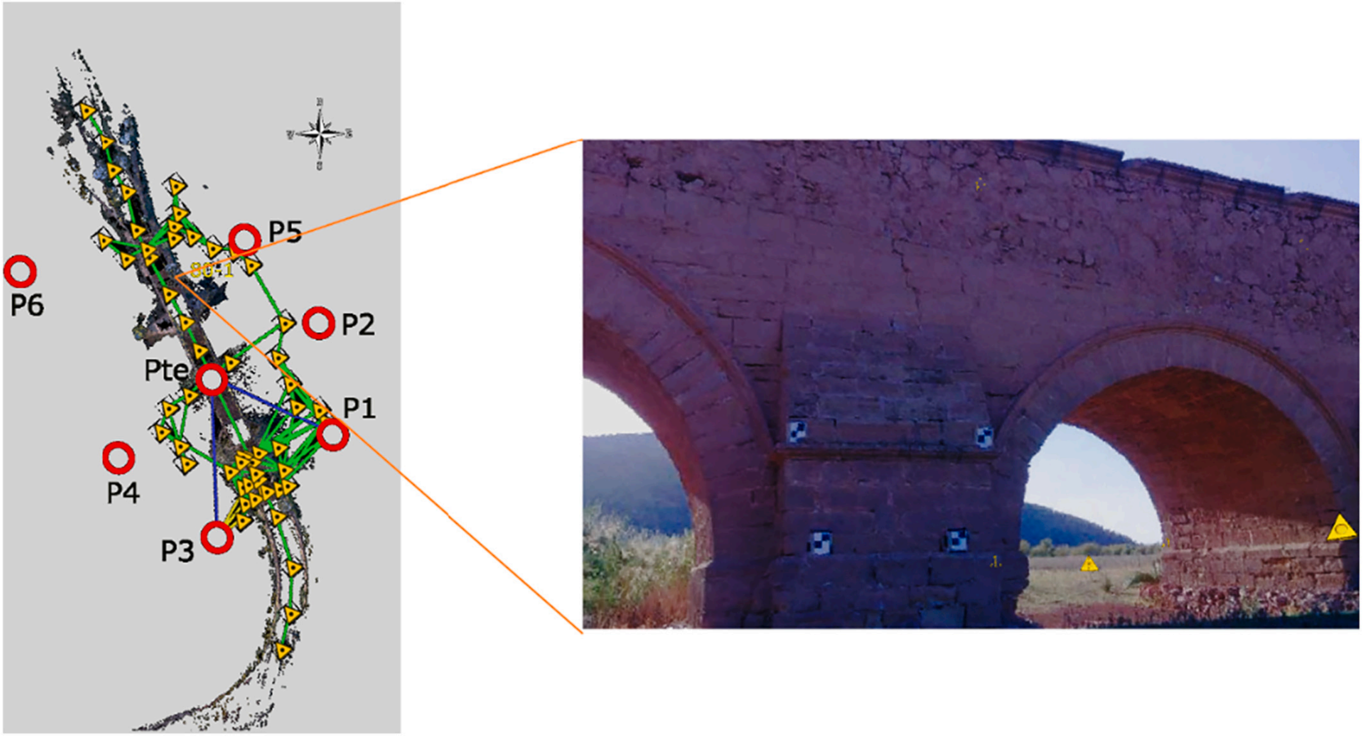

Fig. 6. Positional quality control from the registered survey using targets.

Table 6
Differences in the local coordinates of the targets. Reference coordinates are derived from the scanning performed with the independent Leica C10 scanner. Survey coordinates are derived from the registered survey performed with the Leica BLK360 scanner. μ and σ are the mean value and the standard deviation, respectively.

Target	Reference			Survey			Difference		
	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)	X (m)	Y (m)	Z (m)
T_1	1012.49	5032.473	91.638	1012.469	5032.494	91.635	0.021	−0.021	0.003
T_2	1013.188	5035.096	91.615	1013.151	5035.101	91.612	0.037	−0.005	0.003
T_3	1012.543	5032.842	90.143	1012.524	5032.844	90.134	0.019	−0.002	0.009
T_4	1013.052	5034.708	90.137	1013.034	5034.708	90.133	0.018	0.000	0.004
μ							0.0237	−0.007	0.0047
σ							0.0089	0.0095	0.0028

From the coordinate differences presented in Table 6 the following can be concluded:

- The bias in X, Y and Z is represented by the mean values (μ), with a maximum of 0.024 m in the coordinate X. A 3D bias value can be obtained if the root mean squared error, which corresponds to a value of 0.025 m, is computed.
- The uncertainty in X, Y, Z is represented by the standard deviation (σ) values, with a maximum of 0.010 m in the coordinate Y. A 3D uncertainty value can be obtained if the mean is computed, which corresponds to a value of 0.007 m.

It must be taken into account that part of the bias and uncertainty may be due to the error of the coordinates of P5, which was measured from Pte with the total station. Also, the setting up of the independent scanner C10 in P5 can have an important influence. Nevertheless, the reported error in the setting up was (0.001, 0.001, 0.003) m.

4.4. GNSS measurement and coordinate transformation

Use case #5 needs the absolute positioning of the data. Therefore the official ETRS89 UTM 30 N coordinates and the orthometric[1] altitude were also observed using a GNSS instrument at all seven survey points (Pte and P1-P6). We used a Leica GPS1200 and real-time NTRIP differential corrections from the Andalusian Positioning Network (RAP, Red Andaluza de Posicionamiento). These absolute coordinates were then employed to calculate the transformation parameters that allow georeferencing of the entire survey with absolute coordinates. An affine two-dimensional transformation was calculated for planimetry. The average of the altitude differences between the local Z coordinate and the H orthometric altitude was calculated for altimetry. The residuals of the transformations are presented in Table 7, also showing the standard deviation in each of the three components and the root sum squared (RSS) of these deviations. This RSS value can be interpreted as the radius of an error sphere with a probability of 61% (see the uncertainty-related data quality basic measure named MRSE in ISO 19157).

Table 7
Residuals X, Y, H of the transformation from the local coordinate system to the official coordinate system.

Survey point	Residuals (m)		
	X	Y	H
Pte	0.0067	0.0052	−0.0051
P1	0.0072	−0.0003	0.0008
P2	−0.0016	0.0084	0.0088
P3	−0.0029	−0.0050	−0.0181
P4	−0.0069	0.0005	0.0088
P5	−0.0080	−0.0108	−0.0071
P6	0.0055	0.0020	0.0118
Standard deviation	0.0064	0.0064	0.0108
RSS	0.014		

5. Quality control execution, results and documentation

This section matches with phases 4 and 5 in Table 1. As explained in section 2.2, Appendix A includes a set of six DQAMs which have been detailed in order to assess whether the product data quality specifications from Table 3 are achieved. In Table 8 we summarize the quality control execution, relating the methods applied from Appendix A to the data quality specifications from Table 3. In each row of the table are detailed: the ID of the DQAM in Appendix A, the ISO 19157 method type (direct internal or direct external), the result type (control or evaluation), the number of the use case, the DQE and the DQCL, this last conformed by the measure to be computed and the value allowed to achieve conformity.

After performing the quality control presented in Table 8, the results should be reported. Table 9 shows the metadata of the Ariza Bridge 3D model quality assessment, including for each use case the measure ID, the measure result, the conformity result (yes/no) and a metaquality[2] comment. This last aspect helps us to understand the quality of the assessment process.

Both Table 8 and Table 9 together with Appendix A, and also with

Table 8
Summary of the quality control execution.

DQAM ID	Method type	Result type	Use case	DQE	DQCL	
					DQM ID[1]	Value
1	external	control	#1	Omission	7	≤ 5%
2	external	control	#2	Omission	7	≤ 5%
3	external	control	#3	Relative positional accuracy	128 34	≤ 0.01 m ≤ 0.02 m
4	internal	control	#4	Density of information	dens01[2]	≥ 10,000 pts./m²
5	external	control	#4	Geometric accuracy	geom01[3]	≤ 2°
6	external	control	#5	Absolute positional accuracy	MRSE	≤ 0.05 m

[1] ID is the measure identifier in Annex C from ISO 19157.
[2] dens01 is a new proposal for ISO 19157: Points per square meter.
[3] geom01 is a new proposal for ISO 19157: Mean error in normal vectors to planes.

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[1] Geoid undulation calculated with PAG (Programa de Aplicaciones Geodésicas) from the Insituto Geográfico Nacional (Spain), which uses the EGM2008 – REDNAP geoid model.

[2] Metaquality is the information about the reliability of data quality results (ISO 19157, Annex E). It may be described using the following elements: confidence, representativity and homogeneity.

Table 9
Results after the quality control execution.

Use case	DQM ID	Result		Metaquality comments
		Value	Conformity	
#1	7	20%	No	Confidence: Three operators have participated.
#2	7	8%	No	Confidence: Original scans were inspected if required. Confidence: Three operators have participated.
#3	128	−0.006 m	Yes	Confidence: Three operators have participated.
	34	0.018	Yes	Representativity: sample size higher than required: $n = 32$
#4	dens01	38,505 pts./m^2	Yes	Representativity: Three planes have been considered.
	geom01	0.97°	Yes	
#5	MRSE	0.034 m	Yes	Confidence: Seven survey points were used for an affine transformation (planimetry) and a height displacement (altimetry).

Table 2 (use cases) conform to our proposal of a standalone quality report as suggested by ISO 19157. It should be remembered that this standard does not suggest any template for reports. It only defines a report as a free text document providing fully detailed information about data quality evaluations, results and measures used. For more clarity regarding the proposed report, Table 10 summarizes its structure.

6. Discussion

This discussion will focus on the main contributions made, which cover especially conceptual components but also the survey execution and the results.

6.1. The conceptual perspective

From a conceptual perspective, this paper proposes the adoption of the ISO 19157 data quality model and use cases to establish product specifications. The adoption of this model for a product based on a PC is something new, although it has already been applied to the BIM case [12]. In this study the use of PCs has been linked to the case of HBIM projects, but PCs are also highly applicable in the case of "as built" BIM projects, all of which opens a wide field of application to our proposal. However, the ISO 19157 data quality model is especially oriented to the case of vector data, so its application to the case of a PC presents a challenge. In this sense, completion is the DQE that requires some explanation (use cases #1 and #2). Although its definition is simple, its evaluation is complex in our example, given that in the PC model there are no objects. In this case, the application of the previously indicated framework [24], which involves the participation of trained and calibrated experts, has allowed us to resolve this issue between data models with agility and accuracy.

Another relevant contribution of this study is the proposal of use cases as a basis for establishing quality specifications. The use cases are not part of the ISO 19157 model but, as has been shown, they help clarify the specific quality objectives that the data product must satisfy. Although the use cases are presented in a simple way, as a colloquial text, their writing has been the result of a complex and quite lengthy discussion process between the parties involved (users, quality experts, surveyors). Understanding what is a use case is not easy for a non-expert; therefore, given the lack of experience and previous documentation related to this aspect the realization of the use cases required a group process of iterative approaches. Along these lines, the use cases presented can serve directly in cases similar to the one presented here, or as guidelines for writing style. An added value of the proposed use cases is their sequential nesting. That is, there is a logical structure of usage requirements. This structure is of notable interest because properly developed, it could be the basis of a product classification system based on the capabilities of use that it offers.

Table 10
Structure of the proposed standalone quality report.

Section	Content	Example
I. Use cases	Description, objectives, way of use, product requirements.	Table 2
II. Quality control execution	For each use case: DQEs, DQAMs, DQMs and DQCLs.	Table 8
III. Results	For each use case: quantitative and/or compliance results.	Table 9
IV. Assessment methods	For each DQAM: detailed description.	Appendix A

The quality specifications that have been established are a direct application of the ISO 19157 data quality model. The greatest contribution that this paper makes is the use of the jargon of ISO 19157, the complete formalization of each requirement (UoD, DQU, Sc, etc.), and the linking of the specifications to the use cases, which offers a didactic example of the process of adopting the ISO 19157 model. Once the use cases have been established the determination of the components that make up each of these specifications and the required quality levels is not straightforward. This contribution is very technical but still requires the participation of users, many of whom do not have specific knowledge on data quality. These specifications are responsible for the suitability for use of the data product obtained, which is why they are critical. The determination of the different UoD, DQE, Sc, DQM and DQCL values has required great discussion among the participants. UoDs are often not obvious, and even less so when working with images. On numerous occasions ISO 19157 proposes several measures (DQM) for the same DQE, so the most appropriate one must be chosen for the use case, which may also be conditioned by the work method and resources. The proposed values for DQCL have been based on the researchers' own experience, since there are no international standards that establish these thresholds.

Despite the above, another important aspect that should be specified for a quality assessment is the DQAMs to be applied. It should be noted that the determination of the use cases, the specifications and the DQCL values does not guarantee achieving the desired quality levels. It is clear that the DQAM will condition not only the results but their metaquality (confidence, representativity, homogeneity). For all the above, the content of Appendix A should also be highlighted here. This appendix specifies the evaluation methods, and its inclusion offers transparency to the process. Precisely the lack in ISO 19157 of a treatment of the DQAMs equivalent to the measures is a criticizable aspect of the model proposed in ISO 19157. This standard includes a list of standardized DQMs, but the DQAMs are not treated in the same way. We consider that this is an important failing, and Appendix A shows that it is possible to develop a list of standardized DQAMs despite the limited space of a scientific publication. They have been described in a summary form in a fairly simple way, but with a detailed and well-organized exposition.

6.2. About the survey execution

From the perspective of the survey execution, the design of the survey had two objectives: to achieve a survey with high absolute and relative positional accuracy of the bridge, and to be able to carry out the corresponding quality controls of the result. Accuracy in absolute positioning would be achieved by means of a radial survey with a total station from a single station, measuring points surrounding the bridge and subsequently making a transformation based on the coordinates obtained through GNSS.

The small values of residuals obtained when computing the transformation with GNSS data (Table 6) implies that there are neither systematic nor gross errors in the radial survey. Relative accuracy was achieved by cloud-to-cloud recording of close, high-overlap scans. However, due to the fact that the work area was very open (unlike in urban environments) difficulties were detected in the field itself in carrying out the automatic registration of contiguous scan stations, which made it necessary to reduce the separation between them. This problem was accentuated in the area of the bridge roadway. Taking these considerations into account, the DQM values were in accordance with the specifications imposed on the product.

It has been observed that the light conditions of the area and the distance from the scanner to the scanned object greatly influence the ability to identify details on the 360° images captured by it. This greatly affects the quality assessment of the completion DQE (use cases #1 and #2). This implies that the scanner operator should plan the scan stations taking into account the atmospheric conditions and the position of the sun with respect to the object in order to avoid large differences in contrast. It should also ensure that all parts of the object have been scanned, at least once at a minimum distance so that the details required in the specifications can be observed.

6.3. *About the results*

From the perspective of the results, the product is not compliant with all of the quality specifications (DQCL values) proposed by the researchers. The numbers of omissions in use cases #1 and #2 have exceeded the limit. The remaining use cases, #3, #4 and #5, do not present any problem. Speaking simply, this means that the 3D model can be adequately located in the space, that it is suitable for obtaining any measure required (distances, angles, surfaces), but it fails if a complete transfer of the asset is intended (<5% of blocks missing) or for a full visual inspection of each of the all the components of the bridge structure (<5% of missing components, totally or in part). Since the requirements were assumed to be accumulated from one use case to the next, the uncompliance related with use cases #1 and #2 might appear as contradictory to the compliance related with use cases #3, #4 and #5. This reinforces the need for, as mentioned above, a classification scheme for this type of data product, based on the capabilities, or incapabilities, of use. The compliance of use cases #1 and #2 could be achieved easily if several scans were added in a complementary field campaign; nevertheless, the important thing is to include in our proposal what ISO 19157 calls a standalone report. Given that this report is free to elaborate, we have proposed a simple structure (Table 10), but with enough detail for experts and non-experts. This way any user could obtain knowledge about the use cases, the DQCL established for them, the DQAMs applied and the DQM results (values and conformity). This information, if included in any heritage dataset repository, would be of high value, providing confidence to any data user, who could anticipate whether any application from this dataset is viable or not.

7. Conclusions

The greatest contribution of this study to the field of HBIM projects or those who work with PCs is to exemplify how the perspective of data quality should be approached in a rigorous manner. This means adequately handling concepts such as use case, discourse universe, data quality unit, data quality element, quality measure, etc., and the relationships established between them.

A relevant conclusion of this study is that the ISO 19157 data quality model can be applied in an adapted, but also rigorous way to the case of a PC that represents a cultural and heritage asset whose digital model can later be incorporated into a (H)BIM work methodology. However, given the lack of similar previous experiences, as well as specific guidelines, determining the use cases and specifications is a costly task that requires group processes and several iterations.

Planning the TLS survey is essential to achieving the level of compliance defined in the specifications of the different use cases, particularly in measurement and plane generation. The cloud-to-cloud recording method has proved to be suitable for obtaining the required accuracy in absolute and relative positioning. In relation to the real case application of the proposal to the Ariza Bridge presented here, not all requirements of the different use cases have been fulfilled. However, incompliance in the 3D visualization and location transfer use cases can be overcome through supplemental scan stations where the deficiency is noted.

Finally, one aspect that we want to highlight in this conclusion is that of metadata. The example developed and the application of ISO 19157 have allowed us to propose a standalone quality report to inform about the results. It offers very rich information on the quality of the data product created (the PC) with a perspective of fitness for use that can be addressed with current (H)BIM methodologies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

This appendix extends section 2.2, and includes the standardized specification of the defined Data Quality Assessment Methods (DQAMs) to apply in this study. The DQAMs are presented in summary form in order to fit their space to a scientific publication.

Table A1
Method for the quality control of omissions of components in a 3D model skin.

Name	Quality control of omissions of components in a 3D model skin
ID	1.
ISO type	Direct external.
Result type	Control.
Purpose	To detect the omission of components that conform the visible structure or skin of the asset represented by a 3D model.
General description	The method consists of visually evaluating, with a suitable tool, the 3D model and verifying that there is no omission of any component of the structure of the asset in its digital representation.
Detailed description	• Population. It is made up of all the components of the visible structure of the asset. Each component is in turn composed of a subset of 3D points for geometry and a subset of image pixels for texture. • Inspection. This is a visual based full inspection method where operators revise the entire skin of the 3D model.

(*continued on next page*)

Table A1 (*continued*)

Name	Quality control of omissions of components in a 3D model skin
Resources	• Instrumental. Hardware and software with capabilities for fast rendering of 3D models and annotation. • Human. At least two operators with experience in the visual evaluation of 3D models. • Reference. Reality is the reference.
Measure(s)	Count of error cases. An error is an instance of the population that is missing in the digital representation. An component is considered to be missing if it is not fully covered by both the point cloud and the texture image.
Process	• Analysis in situ of the structure of the skin of the asset. Identification and counting of the components that conform the structure (population of interest). • Establishment of a virtual itinerary in the 3D model for the visual verification of all the members of the population. • Execution of the visual evaluation of the 3D model with annotation of each error (each operator independently) when comparing with the reference. • Consensus between operators' results and the final count of the cases. • Comparison of the final count with the quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a full inspection, the acceptance or rejection of the product is performed directly by comparing the result to the DQCL. Metaquality: As an inspection developed independently by more than one operator and after a consensus, the result of this assessment can be considered of high accuracy.

Table A2
Method for the quality control of omissions of stone blocks in a 3D model skin.

Name	Quality control of omissions of stone blocks in a 3D model skin.
ID	2.
ISO type	Direct external.
Result type	Control.
Purpose	To assess the inability to properly detect individual stone blocks in the model (image) due to poor visualization.
General description	The method consists of visually evaluating, with a suitable tool, a sample of stone blocks of the 3D model and verifying the proper identification of each individual stone blocks by its perimeter.
Detailed description	• Population. It is made up of all stone blocks that conform the skin of the asset. Each item of the population is composed of a subset of 3D points for geometry and a subset of image pixels for texture which represent the 3D model of the visible surface of a stone block. • Inspection. This is a visual-based sample inspection method where operators revise a random sample of cases. • Sample scheme. A random sampling is applied. The sample is generated on the 3D model surface or on a 2D development of all the outer surfaces of the 3D model. • Sample size.[a] It is determined using a binomial infinite population approach, and the following formulae: $n > \frac{\left(z_\alpha\sqrt{\pi_0(1-\pi_0)}+z_\beta\sqrt{\pi_1(1-\pi_1)}\right)^2}{\delta^2}$ Where: n is the calculated sample size α is the significance of the test or Type I error (usually 5%) β is the type II error (usually 10%) (power of the test = 1- β) π_0 is the supposed probability (actual quality level) δ is the maximum detectable distance from π_0 π_1 is defined as $\pi_1 = \pi_0 + \delta$ Z is the statistics from a typified normal distribution. • Sample collection. Some guidelines and rules are provided to enable operators to carry out the sample collection.
Resources	• Instrumental. Hardware and software with capabilities for fast rendering of 3D models and annotation. • Human. At least two operators with experience in stone blocks visual analysis. • Reference. Could be reality or a photographic source of greater accuracy and detail.
Measure(s)	Count of error cases. An error is an instance of the population that is missing in the digital representation. A stone block is considered to be missing if its edges are not clearly identified or if the edges are clear but do not coincide with the real ones.
Process	• From the point cloud, random selection of a sample of points. • Selection of the sample of stone blocks. Each random point should clearly belong to a stone block, in which case this stone block is selected. If not, another random point, and corresponding block, should be introduced in the sample. • Execution of the visual evaluation of each stone block of the sample, with annotation of each error (each operator independently) when comparing with the reference. • Consensus between operators' results and final count of the cases. • Comparison of the final count with the quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a sample-based control, the acceptance or rejection of the product is performed by comparing the result obtained to DQCL, with a risk of the decision being determined by the statistical considerations (α, β, δ, etc.). Metaquality: As an inspection developed independently by more than one operator and after a consensus, the result of this assessment can be considered of high accuracy.

[a] In this study, the adopted sample size is $n = 102$ (α = 5%, β = 10%, δ = 0.1).

Table A3
Method for the quality control of the relative positional accuracy of a 3D model skin.

Name	Quality control of the relative positional accuracy of a 3D model skin.
ID	3.
ISO type	Direct external.
Result type	Control.
Purpose	To assess the relative positional accuracy between well-defined and easily-identifiable features on the skin of the asset.
General description	The method consists of a dimensional measurement-based evaluation with a suitable tool. A sample of pairs of well-defined and easily-identifiable features is generated and evaluated. The EMAS method is applied (see [25] for details).
Detailed description	• Population. It is made up of all well-defined and easily-identifiable features that are present in the skin of the asset. • Inspection. This is a sample-based inspection method where operators measure distances between random pairs of features. • Sample scheme. A random sampling is applied. The sample is generated at the 3D model surface or on a 2D development of all the outer surfaces of the 3D model. • Sample size: 20 pairs of well-defined and easily-identifiable features. The features of each pair should belong to the same plane of the asset. • Sample collection. Some guidelines and rules are provided to enable operators to carry out the measurements.
Resources	• Instrumental. Hardware and software with capabilities for fast rendering of 3D models, measuring and annotation. • Human. At least two operators with experience in positional accuracy assessments. • Reference. Reality is the reference.
Measure(s)	Mean and standard deviation of error in distance. Between each pair of features of the sample, the distance is measured both in the model and in reality. The discrepancy between both measurement results is used in the analysis.
Process	• From the point cloud, random selection of a sample of points ($n = 20$). • Verification of the suitability of each sample. In the surroundings of each point of the sample, a pair of features of the asset should be selected for measurement. The pair of features has to satisfy the following conditions: (1) be well-defined and easily-identifiable features, both in the model and in reality; (2) belong to the same plane of the asset. If the above is not possible, another random point should be selected from the population. Measurement of distances between each pair of features. Each pair should be measured by each operator more than once, both in the model and in reality (reference). The discrepancy value between the model and the reference is obtained for each pair of features. • From the set of discrepancy values, final computation of mean error and standard deviation of the error. • Comparison of both the mean error and standard deviation with the corresponding quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a sample-based control, the acceptance or rejection of the product is performed by comparing the result obtained to DQCL, with a risk of the decision being determined by the statistical considerations (α, β). Metaquality: As an inspection developed independently by more than one operator and after an average procedure, the result of this assessment can be considered of high accuracy.

Table A4
Method for the quality control of the information density of a 3D model skin.

Name	Quality control of the information density of a 3D model skin.
ID	4.
ISO type	Direct internal.
Result type	Control.
Purpose	To assess whether the density of points in the product is higher than or equal to the specification.
General description	The method consists of determining which area of the model has the lowest point density and checking if its density value is higher than or equal to the specification.
Detailed description	• Population. It is made up of all points of the point cloud that define the 3D digital model of the asset. • Inspection. This is a full inspection method executed automatically.
Resources	• Instrumental. Hardware and software with capabilities for fast density calculations.
Measure(s)	Point density. The density of the point cloud is computed. Total area of the 3D model skin and total count of the number of points in the skin are considered for the computation.
Process	• An appropriate software tool (e.g. script) is used. • Comparison of both minimum density values with the corresponding quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a full inspection, the acceptance or rejection of the product is performed directly by comparing the result obtained to the DQCL.

Table A5
Method for quality control of the geometric accuracy of a 3D model skin.

Name	Quality control of the geometric accuracy of a 3D model skin.
ID	5.
ISO type	Direct external.
Result type	Control.
Purpose	To assess the uncertainty of subsets (patches) of the point cloud in relation to well-defined planes.
General description	The method consists of an angle-measurement-based evaluation with a suitable tool. A sample of normal vectors to flat and well-defined planes is evaluated with a more accurate source.
Detailed description	• Population. It is made up of all flat and well-defined planes that are present in the asset. Each item of the population is composed of a subset (patch) of points which represent the 3D model of a visible flat plane of the asset (only the geometry, not the image texture). • Inspection. This is a sample-based inspection method. • Sample scheme. Determined by judgmental criteria. • Sample size. Determined by judgmental criteria.

(*continued on next page*)

Table A5 (*continued*)

Name	Quality control of the geometric accuracy of a 3D model skin.
Resources	• Sample collection. Some guidelines and rules are provided to help operators to carry out the measurements (e.g. for TLS observations, plane sample conformation, statistical analysis, etc.). • Instrumental. Hardware and software with capabilities for fast rendering of 3D models, and extracting samples of the cloud. High accuracy TLS devices for field survey. Continuously Operating Reference Stations (CORS) for differential computations and corrections. Statistical software for the plane adjustment and statistical analysis. • Reference. A more accurate 3D model of each patch of the sample. It can be obtained from a suitable and independent high accuracy TLS survey of the planes of the asset which have been used to determine the patches of sample.
Measure(s)	Mean angle error between normal vectors. For each patch of the sample an adjustment to a plane is computed and its normal vector derived, both in the 3D model and in the reference. The discrepancy between both vectors is used in the analysis.
Process	• From the point cloud, selection of a sample of patches. For each patch, extraction of points from the 3D model, adjustment of the corresponding plane and computation of the normal vector. • For each patch, extraction of points from the reference (i.e. the independent high accuracy TLS survey), adjustment of the corresponding plane and computation of the normal vector. • For each patch, computation of the angle error. It is obtained from the difference in the orientation between both normal vectors. • From the set of angle errors, final computation of the mean value. • Comparison of the mean error with the corresponding quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a sample-based control, the acceptance or rejection of the product is performed by comparing the result obtained to DQCL, with a risk of the decision being determined by the statistical considerations (α, β, δ, etc.).

Table A6

Method for the quality control of the absolute positional accuracy of a 3D model skin.

Name	Quality control of the absolute positional accuracy of a 3D model skin.
ID	6.
ISO type	Direct external.
Result type	Control.
Purpose	To assess the absolute positional accuracy of the 3D model.
General description	The method consists of the computation of a 3D (or 2D + 1D) coordinate transformation to georeference the 3D model in an absolute reference system (location and orientation). The residuals of the transformation are assessed. It is mandatory that the 3D model has been previously assessed as compliant in relation to relative positional accuracy requirements. Both the residuals and the relative positional accuracy results are taken into account in order to obtain a final absolute positional accuracy result.
Detailed description	• Population. It is made up of all the points used for the coordinate transformation. • Inspection. This is a full inspection method where operators analyze the residuals of the coordinate transformation
Resources	• Instrumental. Any software with capabilities for least squares adjustment. • Human. One operator with knowledge of coordinate systems management.
Measure(s)	Mean radial spherical error (MRSE) is calculated (see ISO 19157). It is obtained from the composition (propagation of uncertainties) from an MRSE derived from the relative positional accuracy assessment and an MRSE obtained from the residuals of a coordinate transformation.
Process	• Precondition #1: the 3D model is compliant in relation to relative positional accuracy requirements after applying the DQAM #3, annotating the standard deviation value (sd_{rel}). • Computation of the relative 3D MRSE as $MRSE_{rel} = sd_{rel} \times 3^{1/2}$ • Precondition #2: a coordinate transformation has been computed in order to locate, orientate and scale the 3D model in an absolute coordinate system. The transformation can be 3D (i.e. a Helmert transformation) or 2D (i.e. an affine transformation) for coordinates X, Y and 1D (i.e. an altitude displacement) for coordinate Z. The transformation is computed from a set of survey points with known coordinates both in a local and in an absolute coordinate system. The number of survey points must be higher than the minimum required for the computation. The residual values (X, Y, Z) of a least squares adjustment are available. • Computation of the standard deviation value of the residuals for each component of the coordinate transformation: sd_{resx}, sd_{resy}, sd_{resz} • Computation of the MRSE of the residuals as $MRSE_{res} = (sd^2_{resx} + sd^2_{resy} + sd^2_{resz})^{1/2}$. • Computation of the absolute 3D MRSE as $MRSE = (MRSE^2_{rel} + MRSE^2_{res})^{1/2.}$ • Comparison of the MRSE value with the corresponding quality level for conformity (DQCL).
Result	Reported as a yes/no value in relation to DQCL. As a full inspection, the acceptance or rejection of the product is performed directly by comparing the result obtained to the DQCL.

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