4D Reconstruction of Cultural Heritage Sites

Pablo Rodríguez-Gonzálvez a,b, Angel Luis Muñoz-Nieto a, Susana del Pozo a, Luis Javier Sanchez-Aparicio a, Diego Gonzalez-Aguilera a, Jon Mills c, Karolina Fieber c, Ian Haynes d, Gabriele Guidi e, Laura Micoli e and Sara Gonizzi Barsanti e

a TIDOP Research group, High School of Ávila, University of Salamanca, Avila, Spain; (pablorgsf, almuni, s.p.aguilera, luisj, daguilera}@usal.es
b Department of Mining Technology, Topography and Structures, Universidad de León, Ponferrada, Spain; p.rodriguez@unileon.es
c School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne, UK; (jon.mills, karolina.fieber}@ncl.ac.uk
d School History, Classics and Archaeology, Newcastle University, Newcastle upon Tyne, UK; ian.haynes@ncl.ac.uk
e Departament of Mechanical Engineering, Politecnico di Milano, Milan, Italy; (gabriele.guidi, laura.micoli, sara.gonizzi}@polimi.it

Abstract: Multi-temporal three-dimensional (3D) reconstructions are fundamental for the preservation and maintenance of all forms of tangible Cultural Heritage (CH) and often provide the basis for decisions related to interventions and promotion. Introducing the fourth dimension of time into 3D geometric modelling of real-world data allows the creation of a multi-temporal representation of a site to plan maintenance and promotion. This chapter aims to provide a comprehensive approach for CH time-varying representations, to integrate heterogeneous information derived from a range of sources to help inform understanding of temporal aspects of change across different working scales and environments. Two landscape-scale study cases, Hadrian’s Wall (UK) and Milan Roman Circus (Italy), are presented based on a methodological approach for CH time-varying representations proposed by the JPI-CH European Project Cultural Heritage Through Time (CHT²). CHT² aims to provide a new set of tools and working methods to support the study of the evolution of CH sites.

Keywords: 4D modelling; cultural heritage; data fusion; historical data; knowledge representation

1. Introduction

Cultural Heritage (CH) encompasses both tangible assets (e.g., monuments, archaeological remains, artefacts, etc.) and intangible ones (e.g., traditions, social practices, rituals, etc.). This article focuses on tangible heritage and the creation of
graphic representations that can significantly aid monitoring, management, routine maintenance, study and promotion of a CH site. In such a way, knowledge about heritage objects can be transmitted to future generations.

There is an increasing commitment to preserve and restore CH, thereby fostering its better management, study or promotion. CH is a rich legacy for the current generation who have an undeniable responsibility to preserve it. Tangible heritage becomes extremely important as a cultural, social and economic resource in modern societies. It is therefore necessary to continuously develop techniques in order to achieve a better understanding of its evolution through time and improve maintenance approaches. Research, conservation and restoration of CH assets are complex tasks that are being addressed from a multidisciplinary perspective: archaeologists, architects, art historians, surveyors, tourist promoters and advertising agents, amongst others. Since the footprint of time sometimes imposes terrible consequences on CH, it often becomes necessary to not only recover the memory of original features of historical buildings, urban and landscape environments, but also understand its likely evolution. In this way, heritage legacy can be safeguarded for present and future generations, preventing future damage and aiding understanding of the current remains as an evolution of its original state.

Due to the advancement in technology, research and innovation improvements are increasingly noticeable, not only in data acquisition, but also in the ability to include multiple complementary fields. Digital methods and techniques can link historical documentation data and disseminate them for a better understanding and perception of their evolution through time. With the aim of studying the current state and geometry of CH elements, numerous different geospatial technologies can be used, from airborne to ground level, such as Airborne Laser Scanning (ALS), Mobile LiDAR Systems (MLS) and Terrestrial Laser Scanning (TLS), aerial and terrestrial photogrammetry, Global Navigation Satellite Systems (GNSS), etc. Historical datasets are extremely heterogeneous in terms of chronology, shape, style and structure, appearing as texts, paintings, engravings, old photographs, maps, etc., and in analogue or digital formats. Therefore, it is necessary to establish schemes to order and clarify the current status regarding multi-source data acquisition and fusion for CH management at its different scales. It is also necessary to consider different data sources and their nature (e.g., metric or non-metric), as well as the final aim of four-dimensional (4D) reconstruction and visualization.

1.1. Related Works

4D analysis based on real-world data captured on-site has been carried out mainly at urban levels due to the general availability of historical aerial imagery that allows the analysis of urban transformation and 4D modelling (Patias et al., 2011; Adami, 2015). The automatic processing of historical aerial imagery is not a trivial
task, since it involves the recovery of unknown parameters (Redecker, 2008), which could yield geometric errors (Nocerino et al., 2012), and therefore mislead subsequent 4D analysis. Besides reality-based models, in recent years reconstructive models have also assumed an interesting role, for the possibility to visualize architecture that no longer exists. This is achieved through an analytical process based on the integrated knowledge of historical sources and real three-dimensional (3D) data. Crowdsourced imagery is also now offering ways to create 3D models of different epochs from web-retrieved images of lost or altered CH assets (Kyriakaki et al., 2014) (Stathopoulou et al., 2015). For more than two decades, researchers have discussed the use of virtual reconstructions of environments that no longer exist as an instrument for the interactive interpretation of archaeological ruins or heavily stratified archaeological sites (Stanco and Tanasi, 2011), for the presentation of generic cultural sites (Rua and Alvito, 2011) and even for new archaeological discoveries (Frischer et al., 2008).

Several 4D projects have integrated 3D data capture of a contemporary scene with 3D data of the same site reconstructed from paintings representing rigorous perspective views (El-Hakim et al., 2008), or from plans giving the horizontal footprint of a building and drawings for reconstructing elevations (Russo and Guidi, 2011). Photogrammetry and TLS provide similar products in terms of accuracy, the point clouds being complementary (Bastonero et al., 2014). However, there are some inherent problems in TLS and digital image integration, such as accuracy preservation when different geometric resolutions are involved (Ramos and Remondino, 2015). An example of such multi-source data combination to generate a 3D metric reconstruction of an urban environment is given in Balsa-Barreiro and Fristch (2015), where the 4D component was added by historical image wrapping. Moreover, 3D data has been derived from written sources that describe different historical stages of a building (Micoli et al., 2013; Kresten et al., 2014), or using the size of actual excavated decorations and the knowledge of specific rituals for adding geometrical constraints to the reconstruction of a religious building (Guidi et al., 2014).

1.2. Paper Aims

The main focus of the research reported in this paper is to bring together heterogeneous information and expertise to offer a better understanding of 4D (3D + time) digital products of CH assets. This workflow and recommendations are framed into the Cultural Heritage Through Time (CHT²) project (CHT² 2017) (Rodríguez-Gonzálvez, et al., 2017a). CHT² not only aims at achieving the full integration of the temporal dimension and its management and visualization for evaluating CH elements through time, but also at creating a protocol to produce and optimize 3D/4D digital models of CH sites useful for architectural studies and analysis and research purposes (Rodríguez-Gonzálvez, et al., 2017b).
2. Theoretical Background and Methodological Approach

The analysis of CH elements or sites from a 4D perspective depends on both the working scale and the historical data available for each particular case study. Both the definition of working scale (Section 2.1) and the time varying representations (Section 2.2) are therefore reviewed in the following subsections.

2.1. Working Scale Definition

For large CH sites, at landscape scale, the optimal solution is invariably derived from multi-source data sensor integration (Guidi et al., 2009), where the different methods and techniques balance their own drawbacks to reach an efficient solution (Gonizzi Barsanti et al., 2012). An example of the spatio-temporal analysis of a rural landscape scale is provided by Modica et al. (2011) where several geomatics technologies were employed, one of the most efficient being remote sensing (Ratcliffe et al., 2004). For CH elements of reduced dimensions at architectural scale, such as buildings or archaeological remains, the reconstruction of temporal evolution is carried out on the basis of metric/non-metric data, such as historical drawings (Nocerino et al., 2014).

Multi-source data fusion is one of the main challenges in 4D reconstruction and visualization of CH. This implies providing a solution for the combination of mixed data sources (both metric and non-metric) with the aim of creating time-varying representations. For this purpose, the suitability of the different sources of metric data should be systemized according to the CH object size and its complexity. For a better understanding of the approach proposed by this paper to perform 4D CH analysis, it is helpful to group CH assets according to their characteristics. One of the most common classifications of CH studies (Kraak and Ormeling, 2011) is based on categorization according to the size of the element under study or scale range at the following levels: artefact, architectural, urban and rural landscapes (Table 1). This classification may seem unsophisticated, but the addition of other variables would complicate the classification and would result in confusion when describing the approach.

<table>
<thead>
<tr>
<th>CH Category</th>
<th>Scale Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artefact</td>
<td>From 1:1 to 1:5</td>
</tr>
<tr>
<td>Architectural</td>
<td>From 1:10 to 1:100</td>
</tr>
<tr>
<td>Urban landscape</td>
<td>From 1:100 to 1:1 000</td>
</tr>
<tr>
<td>Rural landscape</td>
<td>From 1:100 to 1:5 000</td>
</tr>
</tbody>
</table>

Table 1. Typical scale ranges for each of the cultural heritage (CH) categories commonly established (adapted from Kraak and Ormeling, 2011).
Here, the different categories of CH assets are specified in order to assist inventory compilers and users in determining the appropriate procedures to be followed. Leaving aside “artefact” scale (although commonly considered in the field of CH, it has not been included within the range of scales studied in this paper), three main categories of CH assets have been established: “rural landscape”, “urban landscape” and “architectural” scales. The term “rural landscape” is applied to those cases where an extensive rural area exists. If the study case has a similar extension area to rural landscape cases, but instead of a rural environment it exists in urban space, the term “urban landscape” is adopted. Finally, “architectural” scale refers to those cases where the object in question focuses on a larger scale than in the two previous cases and where the Z axis is predominant (buildings, monuments, sculpture statues, etc.).

2.2. Time-Varying Representations

CH reconstruction can cover a large variety of situations, depending on the type of temporal analysis that is required (Figure 1).

Figure 1. Three cases of time-dependent 3D analysis covered within the framework of the analysis of our legacy through time.

With reference to Figure 1, it is possible to identify three types of 4D models that can be produced for any CH asset:

a. Reconstruction of the diachronic evolution of a structure or environment that does not exist any longer, possibly with the exclusion of a few archaeological remains. This is generally associated with lost heritage, where partial traces arrived in the current age and will require the combination of surveyed data and philological analysis to reconstruct;
b. Reconstruction of the diachronic evolution of a structure or environment based on the historical analysis of data acquired on physically accessible assets at the current or a previous time (the blue highlighted area in Figure 1);
c. Prediction of the diachronic evolution of a structure or environment into the future based on the historical analysis of data acquired on physically accessible assets at different times.

Although all cases involve diachronic representation, the first and second cases (a and b) differ in how 3D data can be collected, implying different concepts of 3D data integration:

1. In case a, the creation of time-varying documents or representations is based on the use of mixed sources, both metric and non-metric. For example, 3D reconstruction of a Roman building at different stages according to both the 3D scanning of its remains and historical sources;
2. In cases b and c, the creation of the time-varying representations is based on rigorous metric 2D or 3D data, derived from a wide variety of sensors in physically accessible scenarios at different stages. For example, 3D models acquired at different times of a collapsing building surveyed during its deterioration.

2.3. Multi-Source Data Integration

As commented previously, the methodological procedure required to analyze CH elements or sites from a 4D perspective depends on both the working scale and the historical data available for each particular case study. Figure 2 shows the processing tasks of the workflow approached from a spatial dimension perspective (2D or 3D data format). However, the data collection step, which includes both historical and current data, is described from a different point of view based on the its main source of data. Thus, as detailed in the following point, data collection has been classified into (i) geometrical, (ii) thematic, (iii) historical/cultural, and (iv) non-conventional sources.

A total of four main phases were considered, comprising data collection, processing, fusion, and analysis of results. For an in-depth description of the different phases, please refer to CHT² methodology definition (CHT², 2017).
Due to the variability of data sources, and in order to provide a more compact summary than is shown in Figure 2, all available information sources can be classified from a quantitative and qualitative point of view and with regard to its geometrical character (Rodríguez-Gonzálvez, et al., 2017a). In the case of the rural landscape, geometrical data is provided mainly by active or passive airborne techniques. On the one hand, aerial photogrammetry can be considered as the main source due to its longest temporal span dating back to the mid-19th Century up until the present day. On the other hand, although relatively new, ALS may provide more robust measures of a rural landscape as it can penetrate vegetation cover, thereby providing more detailed information about terrain. In addition, it is possible to obtain information from satellite imagery, which can provide information at different spectral wavelengths whilst covering vast territories.

Moreover, the use of miniature Unmanned Aerial Vehicles (UAVs) since the beginning of the 21st Century provides flexibility (mission planning, height and frequency of flights) and high resolution data. For its part, the common attribute of historical and cultural sources is the subjectivity of the information with no rigorous geometrical representation (graphical information such as map, drawing or paintings) or even any kind of associated geometry (literature, texts, etc.).

The urban landscape scale offers the possibility of using a greater variety of sensors to perform data acquisition to document the current state of CH assets, and with the option of mounting instruments on both terrestrial and aerial platforms. It is possible to obtain information from ALS and TLS, as well as from more innovative systems such as MLS. MLS should be highlighted within the active techniques for urban landscape scales due to its exclusivity of use for the working
scales selected in Section 2.1 (Rodríguez-Gonzálvez, et al., 2017b). However, the temporal range of available historical data is limited. Meanwhile, and with greater temporal significance, it is possible to collect a variety of images (single, stereo or multi-image networks) from both aerial and terrestrial platforms for subsequent off-line processing. As in the rural landscape scale, the common attribute here is the subjectivity of the information with no rigorous geometrical representation. Compared with rural landscapes, besides historical documents, drawings and paintings, it is noteworthy that in urban environments it is more probable to find engravings as graphical information.

3. Case Studies

The methodology and recommendations to collect actual and historical data, and its fusion to achieve an historic reconstruction is tested at landscape scales, according to two different CHT² case studies and two different perspectives: Hadrian’s Wall (Fieber et al., 2017) and Milan Roman Circus (Micoli et al., 2017). In the first case, a 3D approach was employed due to the available historical sources, while in the second study, the nature of available historical information favored a 2D analysis on the basis of geographical information systems.

3.1. Rural Landscape: Case of Hadrian’s Wall

Around AD 122, the Roman Emperor Hadrian ordered a wall to be built, dividing Britain in two. It stretches over 117 km (80 Roman miles) from Bowness on the River Solway on the north-west coast of England to Wallsend on the River Tyne in the north-east. Hadrian’s frontier system is complemented by a sophisticated system of outposts and coastal watch stations, thereby offering a remarkable glimpse of ancient society. The Wall today (Hadrian’s Wall, 2017) is a designated UNESCO World Heritage Site and its surrounding landscape is very different to that of Roman times. Although significant portions are still visible, the remaining fabric and landscape of the Wall are subject to various modern-day stresses, for example tourism, urban development and natural hazards. Due to the length of the Wall, three different sites that characterize natural hazard phenomena were selected as study cases to apply the strategies developed in Section 2:

- **Beckfoot Roman Fort**: The fort (Bibra), civilian settlement and cemetery at Beckfoot (Historic England, 2017a), located to the south-west of the main Wall, is preserved as a cropmark. Analysis of aerial photographs reveals clear details of building outlines (Figure 3a) and partial excavation indicates extensive survival of building and defensive wall foundations. The Beckfoot site has been subject to significant coastal erosion, with archaeology buried under sand dunes being frequently exposed by coastal processes.
- **Birdoswald Roman Fort**: Birdoswald (Historic England, 2017b) is one of the best preserved of the 16 forts built as part of the Hadrian’s Wall frontier system. The monument includes the Roman Fort (Figure 3b) and the section of Hadrian’s Wall and vallum between the River Irthing to the east and the field boundaries east of Harrow Scar milecastle 50 to the west. The excavated area of the fort is open to visitors but is at critical risk to landslides instigated by fluvial erosion from the River Irthing running along the south of the site.

- **Corbridge Roman Station**: The Roman town of Corbridge (Historic England, 2017c) marks the site of the most northerly urban settlement in the Roman Empire. The streets of the town have been excavated and are open to the public. The landscape is subject to fluvial flood hazard from the River Tyne to the south (Figure 3c).

![Figure 3.](image)

(a) Beckfoot Fort outlines seen from the air, with a beach and sand dune complex in the foreground, viewed from the west c.1949 (Ref: NY/0848/A).
(b) Birdoswald Fort c. 1947 (Ref: NY/6166/A).
(c) Corbridge Roman Town seen from the air, viewed from the northeast c. 1945 (NY/9864/A). All images are from University of Newcastle upon Tyne Air Photograph Collection, copyright Cambridge University.

In the first instance, an extensive archive search was conducted in order to identify existing materials, with particular focus on historic aerial photographs, including the Historic England Archive and Newcastle University’s archives. Although more data were available, three epochs of aerial photograph datasets were initially selected for each of the sites: one from the 1940s, one from the 1980s or 1990s and one modern dataset acquired in 2016.

The archival photography was subsequently digitized at high resolution (600 dpi for the earliest datasets, 2000 dpi for 1980s/90s) by the Historic England Archive (note that digitisation was not performed using a photogrammetric scanner, and the resultant imagery is therefore likely subject to distortions; see, for example, Thomas et al., 1995). Archival aerial photography was complemented by other data provided by English Heritage and Newcastle University, including historic topographic maps, topographic and geophysical surveys and drawings.
Furthermore, LiDAR point cloud data were obtained for all three sites from the Environment Agency’s repositories (Environment Agency, 2017) and an additional LiDAR survey of Birdoswald acquired in 2008, being in possession of Newcastle University (Miller et al., 2012), was added to the time series (Figure 4).

![Figure 4. Airborne laser scan of Birdoswald Roman Fort and surroundings (2008).](image)

The 2016 photography was provided by Historic England in digital format for both the Birdoswald and Corbridge sites. Due to the fact that such photography did not exist for Beckfoot at the time of the archive search, an UAV survey was performed in order to complete the time series for that site. The Beckfoot UAV survey was conducted using a Quest300 fixed-wing UAV (QuestUAV Ltd., Amble, UK). This UAV can carry a maximum 5 kg of payload with approximately 15-minute flight time (Peppa et al. 2016). Two gimballed Panasonic DMC-LX5 digital cameras (Panasonic UK Ltd.) were mounted on-board the UAV at the time of survey. One Panasonic camera was a standard camera sensitive to visible light (RGB), whilst the second was modified to be sensitive to near infrared (NIR) wavelengths (three NIR bands). The camera’s main specifications are shown in Table 2. The flight height of 91 m and with nominal pixel size of 2 μm enabled a 4 cm ground sampling distance for the acquired images.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Sensor Size [mm]</th>
<th>Sensor Size [pixels]</th>
<th>Focal Length [mm]</th>
<th>Average GSD [mm]</th>
<th>Images</th>
<th>Approx. Area [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMC-LX5</td>
<td>8.07 × 5.56</td>
<td>3648 × 2736</td>
<td>5</td>
<td>~40</td>
<td>546</td>
<td>1.0 × 0.5</td>
</tr>
</tbody>
</table>
With a maximum of 15-minute flight time, and operating within Civil Aviation Authority restrictions relating to the use of UAVs, the immediate Beckfoot survey area was divided into two overlapping parts (north and south) and surveyed under two separate sorties. The camera was set up with a fixed shutter speed of 1/800 s to decrease image blurring, a fixed aperture of f/2 and ISO 100. The exposure interval was set to 2 seconds and the side overlap to 80%. A total of 27 circular control point targets of 0.40 m in diameter were evenly distributed over the site (except for the north-east corner where no access to the fields was granted) and were surveyed in GNSS rapid static mode (five-minute observations), which delivered 3D accuracy at mm-level relative to the GNSS base station. The GNSS base station was established on one of the fields and observed in GNSS static mode for approximately four hours, delivering 1 cm planimetric and 2 cm vertical absolute accuracy. Moreover, Ground Reflectance Calibration Targets were also placed on site at the time of survey to enable calibration of RGB and NIR imagery.

Both archival and current-day photography were processed to generate 3D point clouds. Since archival imagery was not scanned on a photogrammetric scanner and the camera calibration information was unavailable, the structure-from-motion (SfM) pipeline was adopted in order to obtain digital surface and terrain models for each site and to facilitate multi-temporal landscape comparisons. Agisoft Photoscan software was used for this task. Point clouds for each individual epoch were geocoded using selected terrain features, considered to have remained stable over the years, or measured Ground Control Points (GCPs) in the case of the Beckfoot 2016 survey data. As can be seen from the internal Photoscan quality assessment of the absolute orientation results, presented in Table 3, the initial orientations of the archival imagery were generally found to be worse than for current-day datasets (particular evident in Table 3 as illustrated for the Beckfoot site since the 2016 epoch comprised the UAV survey). This can be attributed to a number of factors, including the degradation of the image quality over time, the lack of camera calibration data, quality of A/D conversion, sub-optimal network configurations for SfM processing, availability of fewer ground control points, and so on. Moreover, the dense image matching routines used in the SfM pipeline often performed poorly on archival datasets. This can be seen, for example, in the 1946 Corbridge dataset where data voids are clearly visible in the model (Figure 5a). Such data voids are particularly apparent in the middle of open fields where high quality image texture is lacking.
Figure 5. (a) 1946 dense point cloud of Corbridge landscape and (b) Visualisation of 2016 Corbridge landscape generated in Geovisionary. Both cases were generated from archive photographs supplied by Historic England/English Heritage.

Table 3. Photoscan quality assessment of absolute orientation for three epochs of data at Beckfoot.

<table>
<thead>
<tr>
<th>Year</th>
<th>X Rmse [m]</th>
<th>Y Rmse [m]</th>
<th>Z Rmse [m]</th>
<th>3D Rmse [m]</th>
<th>No. of GCPs Used in Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1948 B/W</td>
<td>1.425</td>
<td>1.512</td>
<td>1.755</td>
<td>2.720</td>
<td>16</td>
</tr>
<tr>
<td>1991 B/W</td>
<td>0.731</td>
<td>1.177</td>
<td>2.741</td>
<td>3.071</td>
<td>15</td>
</tr>
<tr>
<td>2016 RGB</td>
<td>0.016</td>
<td>0.015</td>
<td>0.020</td>
<td>0.029</td>
<td>27</td>
</tr>
</tbody>
</table>

As a result of the sub-optimal archival dataset orientation results, alignments were refined using various data fusion approaches, including both in-house surface matching algorithms (Miller et al., 2008) and ICP (Besl and McKay, 1992) routines in the OPALS software (Pfeifer et al., 2014), to ensure rigorous registration from epoch to epoch, thereby generating spatially consistent 3D time series for subsequent 4D CH analysis. Whilst the gently undulating landscapes of the Beckfoot and Corbridge sites lack relief and therefore do not readily lend themselves to such data fusion approaches, the application of surface matching was found to improve the registration of multiple epochs in the majority of cases. An example is illustrated in Figure 6, where the improvement in the co-registration of the 1946, 1984 and 2016 epochs for the Corbridge site is visually evident (the section is taken through an area believed to be stable, i.e., unchanged through time). It is noteworthy that the processing of the 1984 Corbridge dataset was particularly problematic, the DEM displaying artefacts characteristic of SfM and dense image matching application such as apparent “doming” (see, e.g., James and Robson, 2014) and data voids in areas of low image texture. As a result, some residual errors are still apparent even after application of the ICP algorithm. Finally, data were collated in ArcGIS (ESRI Inc.) and Geovisionary 3 (Virtalis) software to enable visualisations (e.g., Figure 5b) and 4D CH analysis.
3.2. Urban Landscape: Case of Milan Roman Circus

The case study covers a south-west area of the city centre of Milan (Italy) that corresponds to the Roman Circus. On this zone, it is possible to see several traces of the different historical periods from ancient times until the densely urbanized structure of the present day. According to archaeological finds, Milan has been inhabited since the 5th Century BC in the area corresponding to the current Via Meravigli, Via Valpetrosa, Piazza del Duomo. In this zone, some protohistoric tracks converge, with traces of the following Roman roads still recognizable in the city plan.

In 2nd to 1st Centuries BC, excavation works and levelling were undertaken, in order to adapt the ground to the Roman urban model. At that time, the first urban planning was conceived, probably maintaining the road network. In 286 AD, with the tetrarchy subdivision, Milan became the capital of the Western Roman Empire, under the Emperor Maximian. During the imperial period, up to 402 AD, the area was modified by the construction of major buildings such as the Imperial Palace, the Circus and the defensive walls (Mirabella Roberti, 1984). The Circus was the open-air venue for chariot and horse races, or rather the place dedicated to the celebration of the Emperor’s greatness and for this reason it was generally located near the Imperial Palace (Humphrey, 1986). Milan’s Circus was also adjacent to the defensive walls with which it shared the western part. Although the Circus of Milan was one of the most important of the empire, today only few traces are still visible: a tower of the city walls, a tower of the Carceres reused as a bell tower of the Monastero Maggiore after 1500, and some sections of the walls or foundations in the private properties nearby, sometimes hidden in their interiors or in the basements (De Capitani D’arzago, 1939).

Historical sources report the existence of the Circus until Longbard’s era. From that period, as with other monuments in Milan, the materials of the Roman structures were re-used in the construction of other buildings. Many questions are
still open about the building’s elevation and its relation to the surrounding area: the imperial palace and the town’s fortification walls.

The area of the Circus includes the Church of San Maurizio; during the 1800s, its main cloister and the buildings connected to the opening of two new roads (Via Luini and Via Anasperto) were destroyed. Moreover, further serious damage occurred during the World War II bombings of August 1943. Nowadays, only small portions of the monument remain visible and a lot of historical documentation was lost in a fire during World War II. Since the 1960s, the area of the complex has been occupied by the Archeological Museum of the Municipality of Milan (Civico Museo Archeologico di Milano) and residential buildings (Capponi, 1998). Small remains of the Circus are still visible in the basements of modern buildings in that area.

The information gathering process involved different sources to be integrated in order to hypothesize a reconstruction of the area:

- **Historical**: involves both non-graphic (mainly bibliographic resources) and graphical ones (drawings and historical painting, maps, and photographs).
- **Current**: 3D survey.

The first kind of source taken into account is the *bibliographic resources* to document the history of the city and the monument. In particular, historical texts were considered, from which it is possible to infer useful information about life, state of the monument and reports of archaeological excavations past and present. Especially important for the study of the monument was the text of the archaeologist De Capitani D’Arzago, who thoroughly studied the Roman Circus of Milan in the late 1930s, confirming the existence, location and essential size of it thanks to the discovery of the parallel walls, some portion of the foundations and a large part of the curve. His planimetric reconstruction of the monument is shown in Figure 7.

Another step was a collection of maps, drawings and images concerning the various topics covered in the research. *Drawings and historical paintings* are fundamental to gather information no longer available today. When possible, data for individual monuments are searched. If these are not available, as in the case of the studied area, historical representations of elements of the same typology and age are searched.

This kind of approach is useful to have typological indications and to validate the reconstructive hypotheses proposed by scholars. Unfortunately, in the case of Milan, only poor graphical representations of the monuments involved were available, with reference to their active period. With regard to more recent times, all the drawings of survey campaigns carried out in the area have been collated.
Figure 7. Plan of Milan Circus according to archaeological studies conducted by De Capitani D’Arzago, 1939. Legend: full red pattern: foundations of visible walls or put into light; obliquely red dashed line pattern: identified masonry foundations; red dashed lines pattern: supposed masonry foundations.

In the post-war period, many buildings destroyed by bombing were rebuilt. In this phase, the excavations for the foundations of modern buildings have, in some cases, revealed archaeological findings that were used as the basement for the analyzed building itself. In other cases, for example in correspondence of new roads or other unbuilt areas, such findings were simply covered underground. In the latter cases, the survey drawings made during excavations, as for the example shown in Figure 8.a, were fundamental to derive information about archaeological remains no longer accessible today.

A deep iconographic research was then carried out, collecting also different maps from various periods that highlight the urban structure of the area. About 60 city maps representing different historical periods from the Renaissance to the present day have been identified at the Civica Raccolta delle Stampe Achille Bertarelli and analyzed to study the evolution of the urban area.

Another type of data are photographs taken mainly during the post-WW2 excavations. Images of artefacts and structures inside the urban area, taken from different perspectives and sometimes referring to two or more different periods of their life, provide valuable support for the 3D reconstruction process. Specifically, a search of the photographic archive at the Superintendence’s office was made with regard to the area of interest. About one thousand images were found and about 100 of them were selected for inclusion in the study. This selection regards artefacts visible during construction projects (e.g., the metro, new skyscrapers) or inspections of the Superintendent. These images provide valuable documentary heritage because many artefacts are no longer visible, embedded in the foundations of modern buildings (Figure 8b).
Figure 8. (a) Drawing of an archaeological excavation carried out at Via Circo 14 in 1949 and (b) Elevated view of the remains of the three pillars of the Circus foundations, Via Circo in 1959. Both images are courtesy of Soprintendenza Archeologia della Provincia di Milano.

Another stage of the work relates to the 3D survey of all the remains still visible in order to have a starting point for the reconstruction (Table 4). Please note that the full image resolution was not employed in the 3D photogrammetric reconstruction due to memory limitations. Currently, the survey works of the visible portions of the monument have been performed only inside the archaeological museum in Milan. The results, shown in Figure 9, consist of the 3D digitization of one of the towers of the “Carceres” of the Circus, nowadays used as the bell tower of the church dedicated to San Maurizio, and the so-called “polygonal tower”, belonging to the city walls when the Circus was in activity.

Table 4. 3D sensors and survey specifications used for the Roman Circus of Milan.

<table>
<thead>
<tr>
<th>Building</th>
<th>Building Size [w, d, h] [m]</th>
<th>Measurement Principle</th>
<th>Sensor</th>
<th>Images</th>
<th>GSD [mm]</th>
<th>Average 3D Resolution [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower of the Carceres</td>
<td>8.6 × 7.8 × 25.8</td>
<td>Phase-shift laser scanning</td>
<td>Faro Focus 3D</td>
<td>26</td>
<td>-</td>
<td>~50</td>
</tr>
<tr>
<td>Polygonal tower of the city walls</td>
<td>11.3 × 11.3 × 19.8</td>
<td>Photogrammetry</td>
<td>Canon 5D Mk II</td>
<td>187</td>
<td>2.5 to 16</td>
<td>~35</td>
</tr>
</tbody>
</table>

Due to the wide extent of the site, the presence of remains, and their state of conservation, the opportunity to perform a 3D survey is being assessed with the Superintendent. All the remains identified by the archaeologists will be deemed
relevant to the Circus and useful to its digital reconstruction. Depending on the conditions of operation, such 3D digitization will be made with terrestrial photogrammetry or laser triangulation, depending on the available conditions such as lighting, working space, etc., according to the CHT2 methodology.

The monument portions detected, suitably georeferenced, will serve to validate the archaeological excavations of the past and will provide the main constraints with which to create the 3D reconstruction. In addition to the validation of historical plans, the 3D portions are fundamental as elements of proportion, in relation to the examples of the same type of monument highlighted by other sources, to define the trend elevation of the building, typically the most critical parameter in the reconstruction of any ancient building that no longer exists.

![Figure 9. 3D point clouds: (a) tower of Carceres, (b) polygonal tower of city walls adjacent to the Circus, still visible in the garden of the Civico Museo Archeologico di Milano.](image)

Integrating such different data as those available for the reconstruction of the Roman Circus of Milan needed to start from a metric framework, adding all the various information in a controlled destination environment. In addition, the same environment should include functions for georeferencing each part. For this reason, QGIS was used as such a destination environment, using the georeferenced survey data of the municipality of Milan as the starting point. The reorientation of the raster image representing the scanned archaeological map was made with a Helmert transformation that performs simple scaling and rotation, similar to the process carried out in the reconstruction of the San Giovanni in Conca Basilica (Guidi and Russo, 2009; Russo and Guidi, 2011). With the same approach, the footprints of the two towers shown in Figure 9 have been georeferenced.
This starting material has been imported in the Rhinoceros CAD system where the contours of the Circus and the key elements of the surroundings have been redrawn according to the previous and most recent surveys. The presence of such 3D surveys, in addition to the “architectural grammar”, typical of analogous buildings designed and built in the same period, provide crucial information regarding the elevation of the whole structure, the number of seats possibly present inside the hippodrome, the consequential best estimate of access points for letting the crowd enter and exit the structure, the positioning of the Emperor’s special seats, from which he could see the most crucial points of the whole Circus for supervising the various operations before and after races (Mirabella Roberti, 1984; Humphrey, 1986).

This 3D reconstruction hypothesis is therefore built up by adding layers of information to the starting raw reconstruction, according to the best match of archaeological evidence. This produces a loop between the phases of modelling and archaeological checking, that guarantee—as already proved in previous projects (Guidi et al., 2014)—a productive interdisciplinary exchange between the various professionals involved, ranging from surveyors, 3D modellers and archaeologists.

Although, at present, such reconstruction is being created for the time period when the Circus was fully functioning as the most important structure for horse races in the city (2nd to 3rd Century AD), another two periods will be considered: the pre-Maximian era (pre-2nd Century AD), and the current time, that will help in understanding the relationship between this important piece of Milan’s CH, and its current structure.

4. Conclusions and Future Perspectives

Representing the relationship between time and space provides a powerful mechanism to visualize and communicate CH. It can be useful not only to study and analyze the past, but also to foresee possible risks in the future. The aim is to provide a comprehensive overview for conducting studies of CH assets over time for different working scales and environments. It serves as an initial guide for organizing all tasks, from collecting historical documentation, acquiring current data, processing to visualizing results. It is oriented to perform studies through time, including the monitoring of CH assets that may or may not still exist but whose temporal evolution has left remains on the current landscape.

The developed methodology for integrating multifarious data has been applied to two different case studies at the landscape scale: rural and urban. The rural study, due to the nature of CH assets, necessitates the use not only of geospatial technologies such as aerial photogrammetry, but also geophysical approaches such as ground penetrating radar. Moreover, current data acquisition is aimed not only at providing 4D reconstructions that inform cultural
dissemination, but also for the preservation of the present remains in the face of coastal and fluvial evolution of the landscape. To this end, the 4D models produced will help inform appropriate numerical models to predict landscape evolution in the future. In the urban case, the geo-referencing of the hidden assets plays a relevant role in obtaining precise measurements of the shape and length of the structures. By merging data related to the current state of the monument with the vast archival material collected, a rearrangement of the historical representations will be made, for example the normalization of historical plans into a uniform scale. From such an integrated base of information, a 4D reconstruction will be carried out together with archaeologists, in order to better identify the true reconstruction of the ancient building and any changes that affected the area from their origin until the present time.

Meanwhile, due to the wider scope of the topic addressed, the presented methodology is open to augmentation. This is especially the case in those methodology stages that contain greater ambiguity and variability in order to accommodate the requirements of each specific case study and data to be collected. Moreover, application at other working scales, such as the architectural level, is also possible.

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