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Geoinformatics for the conservation and promotion of cultural heritage in support of the UN Sustainable Development Goals

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ABSTRACT

Cultural Heritage (CH) is recognised as being of historical, social, and anthropological value and is considered as an enabler of sustainable development. As a result, it is included in the United Nations' Sustainable Development Goals (SDGs) 11 and 8. SDG 11.4 emphasises the protection and safeguarding of heritage, and SDG 8.9 aims to promote sustainable tourism that creates jobs and promotes local culture and products. This paper briefly reviews the geoinformatics technologies of photogrammetry, remote sensing, and spatial information science and their application to CH. Detailed aspects of CH-related SDGs, comprising protection and safeguarding, as well as the promotion of sustainable tourism are outlined. Contributions of geoinformatics technologies to each of these aspects are then identified and analysed. Case studies in both developing and developed countries, supported by funding directed at the UN SDGs, are presented to illustrate the challenges and opportunities of geoinformatics to enhance CH protection and to promote sustainable tourism. The potential and impact of geoinformatics for the measurement of official SDG indicators, as well as UNESCO's Culture for Development Indicators, are discussed. Based on analysis of the review and the presented case studies, it is concluded that the contribution of geoinformatics to the achievement of CH SDGs is necessary, significant and evident. Moreover, following the UNESCO initiative to introduce CH into the sustainable development agenda and related ICOMOS action plan, the concept of Sustainable Cultural Heritage is defined, reflecting the significance of CH to the United Nations' ambition to "transform our world".

1. Introduction

1.1. Cultural heritage and the UN Sustainable Development Goals

In September 2015, the United Nations (UN) adopted 17 Sustainable Development Goals (SDGs) to transform our world by 2030 (United Nations, 2015). Prior to this development, in 2013, the United Nations Educational, Scientific and Cultural Organization (UNESCO) had already declared that culture should be at the heart of sustainable development policies (UNESCO, 2013b), and cultural heritage (CH) was introduced into the Sustainable Development Agenda. Subsequently, in November 2015, the 20th General Assembly of the States Parties to the World Heritage Convention adopted a Policy on the integration of a sustainable development perspective into the processes of the World Heritage Convention (UNESCO, 2015). UNESCO thereafter launched the Culture for Sustainable Urban Development programme (UNESCO, 2016a) to emphasize the role of culture in sustainable development, and illustrate the link between the implementation of the UNESCO Culture Conventions and the achievement of the SDGs. CH is therefore now considered as a critical enabler of sustainable development, and is both directly and indirectly reflected in the SDGs.

The UNESCO World Heritage and Sustainable Development Programme[1] outlines the potential positive contributions that appropriate CH conservation and management can make to sustainable development. Firstly, a well-protected heritage property may

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[1] http://whc.unesco.org/en/sustainabledevelopment/.

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0924-2716/

contribute directly to the richness of the living environment for present and future generations. Secondly, the preservation of natural resources, including archaeological sites, is fundamental to environmental sustainability. Thirdly, heritage is an important asset for economic development, since it can help attract investments and ensure green, local, stable and respectable jobs, some of which may be related to tourism. Fourthly, heritage is essential to the spiritual wellbeing of people for its powerful symbolic, aesthetic and religious dimensions. Fifthly, well-maintained heritage is important in addressing risks related to natural and manmade disasters. Moreover, heritage related activities help people recover a sense of continuity, dignity and empowerment.

The importance of heritage for sustainable development is addressed specifically in two of UN SDGs. Under SDG 11, "Make cities inclusive, safe, resilient and sustainable", SDG 11.4 emphasises the requirement to "Strengthen efforts to protect and safeguard the world's cultural and natural heritage" so that it can continue to benefit people, as mentioned. However, economic necessity often exceeds cultural needs, especially in developing countries, and CH may be exploited to encourage tourism as a major source of income. Finding a sustainable balance between the economic exploitation of a CH site and its preservation therefore becomes a crucial challenge. For such reasons, the UN SDGs also aim to promote sustainable tourism under SDG 8.9, "By 2030, devise and implement policies to promote sustainable tourism that creates jobs and promotes local culture and products".

As defined by the UNESCO Convention concerning the protection of the world heritage (UNESCO, 1972), heritage is divided into cultural and natural heritage. Physical objects, such as monuments, architectural buildings, sculptures, paintings, and archaeological sites, are considered as CH. Natural heritage refers to sites of natural features including physical, biological, geological, and physiographical formations that of outstanding universal value from the point of view of science, conservation or aesthetics. There are also sites of mixed character, hence the world heritage list includes cultural, natural and mixed sites.[2] This paper primarily addresses the significant role of geoinformatics in CH, even though it has also been intensively used for environmental and natural heritage conservation and management.

The meaning of the term "cultural heritage" has evolved considerably in recent decades, partly due to instruments developed by UNESCO. CH no longer ends at monuments and collections of historical artefacts, which are now referred to as tangible CH, but also includes traditions or living expressions inherited from our ancestors and passed on to our descendants. This is defined as intangible cultural heritage (ICH), which includes oral traditions, performing arts, social practices, rituals, festive events, knowledge and practices concerning nature and the universe, and the knowledge and skills to produce traditional crafts (UNESCO, 2003). This paper demonstrates the application of geoinformatics to both tangible and intangible CH, and discusses the recent developments and trends in CH conservation.

The UN Statistical Commission (UNSC) created an Inter-Agency and Expert Group on SDG Indicators (IAEG-SDGs) to propose a global indicator framework (UNSC, 2015) as a guidance to measure the achievement of the SDGs. For SDG 11.4, the indicator is 'the total expenditure (public and private) per capita spent on the preservation, protection and conservation of all cultural and natural heritage'. Expenditure includes operating cost and investment spent on different types of heritage from various levels of government and types of private funding. The indicators for SDGs 8.9 are the 'tourism direct GDP as a proportion of total GDP and in growth rate' and the 'proportion of jobs in tourism industries out of total tourism jobs'.

Aside from the IAEG-SDGs, UNESCO has also proposed its own Culture for Development Indicators (CDIs) (UNESCO, 2014a), covering seven key policy dimensions and including 22 indicators, which are considered as advocacy and policy tools that assess the multidimensional role of culture in development processes. The CDIs fill a critical gap when advocating the significance of the role for culture within the SDGs. The Heritage Dimension, one of the seven policy dimensions, examines the establishment and implementation of a multidimensional framework for the protection and promotion of heritage. The core indicator is heritage sustainability, which comprises three major interrelated components, including 'registrations and inscriptions', 'protection, safeguarding and management', and 'transmission and mobilization of support'.

The world's heritage is under both natural and anthropogenic threat, which hinders the achievement of the SDGs. The International Council on Monuments and Sites (ICOMOS) analysed the threats to heritage sites from 1994 to 2004 (ICOMOS, 2005). Eight main categories of threat were identified, namely deterioration, development, extraction of resources, large-scale development projects, tourism, local on-site management deficiencies, cultural changes or deficiencies, and socio-economic-national infrastructure context. More recently, ICOMOS presented a concept note for 'Cultural heritage, the UN Sustainable Development Goals, and the New Urban Agenda' (Hosagrahar et al., 2016) addressing contemporary issues in urban heritage conservation, including urbanization, globalization and loss of identity, tourism, disasters, change in local communities, inadequate urban planning, urban ecology, and awareness of cultural rights.

In general, the threats to cultural heritage, tangible or intangible, are multidimensional and complicated. This poses great challenges to the safeguarding of CH and sustainable tourism. For example, CH sites have often been developed as tourist attractions due to the benefit of creating job opportunities and promoting local culture. However, even though tourism can promote indigenous products to the short-term benefit of local economies, it can also accelerate the deterioration of the exploited CH structures or sites. Natural disasters pose severe threats to CH. Recent earthquakes in Nepal (Dangal, 2015) and Italy (Chiabrando et al., 2016), for example, have damaged and even destroyed many important historic structures. Subtle environmental changes also affect CH in a slow but continuous manner. Climate change aspects, including atmospheric moisture variation, temperature increase, sea level rise, wind, desertification, and pollution, together with biological and geological factors are having physical, social and cultural impacts on CH (Sabbioni et al., 2009; Cassar and Pender, 2005; Hall et al., 2016; Brimblecombe, 2014). Therefore, heritage sites, in both urban and natural environments, suffer from human conflicts, development, deterioration, environmental impacts, tourist exploitation and mismanagement.

Fig. 1 summarises the role of CH in the SDGs, and the indicators from both the UN and UNESCO, as well as the threats that challenge sustainable conservation and promotion of CH. This paper will briefly discuss the use of geoinformatics in the field of CH, and focus on how it is contributing to helping achieve the CH-related SDGs.

1.2. Geoinformatics technologies in cultural heritage

Geoinformatics technologies, including photogrammetry, laser scanning, remote sensing, web-mapping, and geospatial data science, have long played an important role in CH documentation and preservation (Remondino and Rizzi, 2010; Pieraccini et al., 2001; Barber et al., 2006; Levoy et al., 2000). In this section, the

[2] http://whc.unesco.org/en/list/.

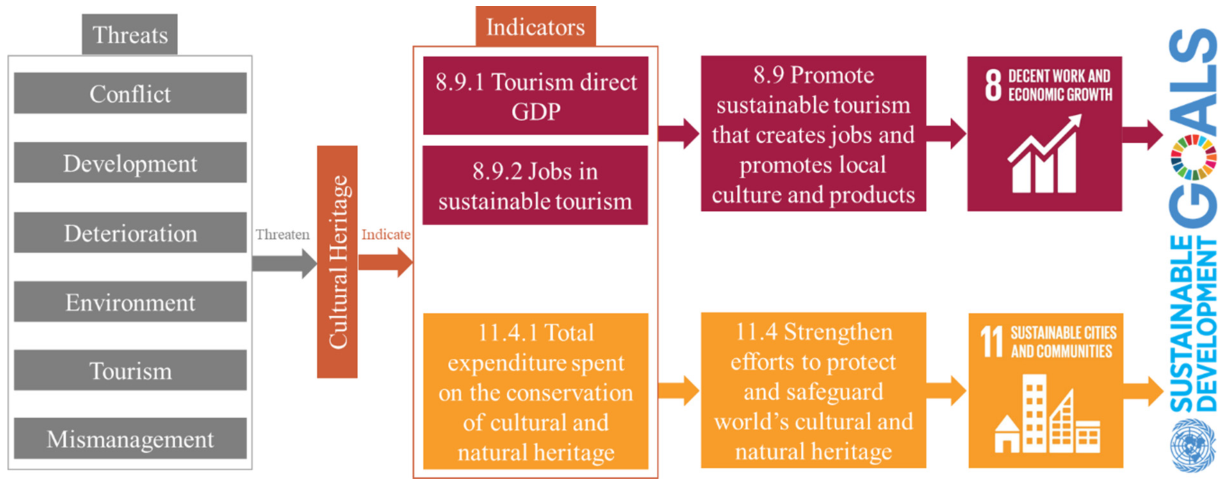

Fig. 1. The role of Cultural Heritage in contributing to the UN's SDGs.

various geoinformatics technologies and their applications in CH are introduced.

Photogrammetry, as a technology of extracting information from a series of images, has long been used to record, measure, and model heritage structures (El-Hakim et al., 2003; Kersten and Lindstaedt, 2012; Pollefeys et al., 2001; Remondino and Menna, 2008; Reu et al., 2013; Santagati et al., 2013; Dhonju et al., 2017a). Remondino and El-Hakim (2006) reviewed image-based modelling (IBM) methods among which modern photogrammetry, enhanced by structure-from-motion (SfM) and dense image matching from Computer Vision, can fully automatically reconstruct 3D models from both calibrated and un-calibrated images or video (Brutto and Meli, 2012). Even though the model accuracy depends on various factors (such as the image network, resolution, number of image, calibration), highly accurate geometric models can be achieved (Koutsoudis et al., 2014). Generated 3D models are 3D surfaces with photorealistic textures, and are hence ideal for visualisation and animation purposes. In addition, digital cameras are now ubiquitous, affordable, portable, and easy-to-use. This means that non-experts can also take advantage of this technique with minimum training (Boochs et al., 2007), and photogrammetry is therefore no longer limited by the users' knowledge or location and thus can be easily adopted worldwide. Depending on the specific application, photogrammetry has been applied to the recording and modelling of both small scale artefacts (Kersten and Lindstaedt, 2012) and large scale archaeological sites (Reu et al., 2013). Unmanned aerial vehicles (UAVs) have become a popular imaging platform for medium to large-scale 3D ground mapping (Nex and Remondino, 2014; Remondino et al., 2011). However, as a passive sensing technology, photogrammetry has its limitations such as light dependence, lack of scale, and the requirement for image texture (Dhonju et al., 2017a).

Laser scanning, in its various forms, generates dense clouds of 3D points describing the target's geometry. Laser scanning became rapidly popular in the surveying industry due to its direct and accurate 3D measurement characteristics and ease of use. Data acquisition can be efficient and planned regardless of light conditions because of active sensing, which can be critical for underground measurement, for example. Another characteristic of laser scanning being able to penetrate vegetation is in its ability to capture objects behind or below foliage. Therefore, among other active sensing technologies, laser scanning is commonly used in heritage recording, modelling, and deformation or structural monitoring (Barber et al., 2006; Muñoz-Nieto et al., 2008; Jaafar et al., 2017; Castellazzi et al., 2015). Guidi et al. (2007) evaluated the performance of low-cost active sensors for heritage documentation, in which two widely used laser scanners were compared. Barber et al. (2006) described the application of laser scanning for architectural conservation. Images are often taken simultaneously and then superimposed onto the laser scanning data for colourization.

Obviously both IBM and range-based modelling (RBM, as from laser scanning) have their pros and cons. Böhler and Marbs (2004) compared laser scanning and photogrammetry for heritage recording. Guidi et al. (2003) proposed to fuse range measurements and photogrammetry to improve the metric accuracy of 3D models, which became a common ground for reconstruction of 3D structures, including heritage modelling (Remondino, 2011; El-Hakim et al., 2004; Guarnieri et al., 2004; Yastikli, 2007). Guarnieri et al. (2004) discussed the use of both digital photogrammetry and laser scanning for heritage surveying. El-Hakim et al. (2004) proposed to use integrated techniques for large-scale detailed heritage site reconstruction. Yastikli (2007) used both photogrammetry and laser scanning for heritage documentation, as did Remondino (2011) and Guidi et al. (2008). Guarnieri et al. (2013) used both technologies for the monitoring and structural assessment of complex structures. Radar technology, such as ground-based synthetic aperture radar (GBSAR), has also been combined with Terrestrial Laser Scanning (TLS) for monitoring heritage structures (Tarchi et al., 2000; Montuori et al., 2014; Tapete et al., 2013).

The combination of ground-based geoinformatics technologies will satisfy small-to-medium scale heritage documentation and monitoring, however for large-scale archaeological site this can be labour intensive and time consuming, especially for sites that are unsuitable for in-situ surveying, such as areas of conflict. In such environments, spaceborne or airborne remote sensing provides an ideal alternative. Wiseman and El-Baz (2007) illustrated how spaceborne and airborne remote sensing techniques were used for archaeological exploration. High-resolution multispectral imaging and synthetic aperture radar (SAR) were specifically discussed, as well as the integration with geographic information systems (GIS) for analysis and management. Satellite remote sensing has been used for archaeology since the late 1900s, as reviewed by Parcak (2009). Lasaponara and Masini (2011) also reviewed optical satellite remote sensing in archaeology from imagery interpretation to data processing for CH documentation and management. Satellite remote sensing in archaeology from past, present and future perspectives was discussed by Lasaponara and Masini (2012), in which optical satellite sensors were listed and active remote sensors were presented. Space-borne SAR has been

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increasingly used in landscape archaeology and CH applications (Tapete and Cigna, 2017a; Tapete and Cigna, 2017b; Chen et al., 2017). Very recently, Verhoeven (2017) reviewed and assessed passive airborne optical imaging technologies for the characterisation and monitoring of landscape archaeology. Giardino (2011) reviewed the history of NASA remote sensing contributions to archaeology. Since the 1970s, orbiting and sub-orbit platforms have provided multispectral and hyperspectral imagery, beside active sensing data, for the discovery, characterization and analysis of heritage sites worldwide. Agapiou et al. (2015) discussed CH management and monitoring using remote sensing data and GIS to understand the conservation circumstances of heritage monuments in relation to hazardous environments. Recently, Agapiou (2017) discussed remote sensing big-data for heritage applications. Petabyte-scale satellite data are available from Google's Earth Engine platform, which is a massive spatial information system that has potential for global scale heritage monitoring and management.

GIS, or more broadly speaking, spatial information science, has long been used for heritage spatial database management to achieve improved planning and preservation (Jigyasu, 2013; Kawan, 2012). UNESCO and UNITAR (the UN Institute for Training and Research) have teamed up to protect cultural and natural heritage sites using the latest geospatial technologies. In addition, the crowd-sourcing application, UN-ASIGN Crowd[3] has been developed to facilitate the collection of photos and assessment. Indeed, through the ubiquity of smartphones and the internet, crowdsourcing and citizen science are becoming widespread by the combination of GIS and advanced web-mapping, and have been successfully applied for heritage documentation (Vincent et al., 2015; Shakya et al., 2013; Tiwari, 2013; Dhonju et al., 2017b).

All of these geoinformatics technologies are actively contributing to one or more aspects of heritage conservation. Closely related techniques, such as Computer Aided Design (CAD) and Virtual Reality (VR), are also being harnessed for heritage protection and promotion and are underpinned by the outputs from these geoinformatics technologies.

2. Contribution of geoinformatics to Cultural Heritage related SDGs

This section addresses in detail the contributions of geoinformatics to two main CH elements corresponding to the SDGs: protection and safeguarding of CH (SDG 11.4) in Section 2.1, and promotion of sustainable tourism (SDG 8.9) in Section 2.2. The detailed aspects of these two elements, which are analysed in each of the subsections, are illustrated in Fig. 2.

2.1. Safeguarding and protection of Cultural Heritage (SDG 11.4)

According to UNESCO's conventions (UNESCO, 1972, 2003), appropriate scientific and technical measures necessary for the identification, protection, conservation, presentation and rehabilitation have to be taken for the protection of the world's cultural and natural heritage. This section introduces the different aspects of CH safeguarding, for example, measurement, documentation, modelling and monitoring, and discusses the role of geoinformatics technologies in each of these aspects.

2.1.1. Identification and 2D localisation

Identification of CH is a fundamental first step for sustainable safeguarding and protection. This involves assessment of CH worth based on different criteria such as historic, physical, social, architectural and archaeological value. The location of a heritage site or structure is normally the first step to be identified. Even though most CH is known to authorities or local people, much still remains hidden or undiscovered.

Geoinformatics technologies have successfully been utilised to reveal previously unrecognised archaeological heritage. For example, an increasing number of heritage structures in the Nile Valley have recently been discovered using satellite imagery, including 17 new pyramids (Parcak et al., 2016). Parcak and Tuttle (2016) also discovered new monumental structures in Jordan using Google Earth, WorldView and UAV imagery. Moreover, aerial photogrammetry can be used for both archaeological site exploration and mapping. Buried archaeological remains indicated by 'cropmarks' seen from aerial images were mapped and presented by Historic England.[4] Evans (2016) used ALS for exploring long-term socio-ecological dynamics in Cambodia. Sittler and Schellberg (2006) also used ALS in assessing CH hidden under forest canopies. Possibilities and limits in detecting and assessing structural elements of archaeological CH were discussed (Sittler et al., 2007).

Determining the precise location of a structure is also crucial for the analysis of monuments and landscapes over time. Geoinformatics techniques have been used for precisely georeferencing ruins lying beneath ground level, with respect of the current city fabric of Milan. This was a crucial step for determining the accurate shape of the Roman Circus, which heavily influenced the current shape of the city (Guidi et al., 2017). Historical perspective images have proved very useful to provide 2D localisation and measurement of building façades or even to generate pseudo-3D reconstructions based on rectified images of entire structures. García-Gago et al. (2014) derived 2D information by means of a single image-based modelling approach. In particular, a bottom-up approach, which exploited the perspective of the image, the existence of the three vanishing points and the usual geometric constraints (i.e., planarity, orthogonality, and parallelism) was applied for the 2D localisation and measurement of a destroyed historic building from archival imagery.

2.1.2. 3D digitisation and documentation

Countless heritage monuments or relics have been destroyed as a result of human conflict. Technologies now allow us to document and reconstruct these CH objects in 3D with detailed information so that they can be at least preserved digitally and restored or reproduced for subsequent generations. Digitisation of CH will help the documentation, information sharing, presentation and restoration of CH while minimising the risk of potential damage. Pieraccini et al. (2001) addressed the necessity of 3D CH digitization from four perspectives, namely, digital archive, high fidelity physical replica, digital restoration and monitoring. 3D reconstruction techniques, such as laser triangulation, photogrammetry, structured light, time-of-flight laser scanning, were examined for heritage digitisation. Two case studies, the 'Porta del Paradiso' by Lorenzo Ghiberti and a child bust by Andrea della Robbia, were presented. The applicability and effectiveness of photogrammetry and laser scanning for heritage digitisation were proven. Pavlidis et al. (2007) reviewed non-contact methods for 3D digitization of cultural objects and monuments, including laser scanning, shape from structured light, photogrammetry and videogrammetry. Both photogrammetry and laser scanning are still commonly used for digitisation and 3D modelling for heritage management, protection, reproduction for exhibition. More examples of 3D CH modelling using geoinformatics technologies, especially

[3] https://www.unitar.org/unosat/un-asign-crowd-source-photos-mobile-app.

[4] https://historicengland.org.uk/research/current/discover-and-understand/landscapes/discovering-hidden-heritage/.

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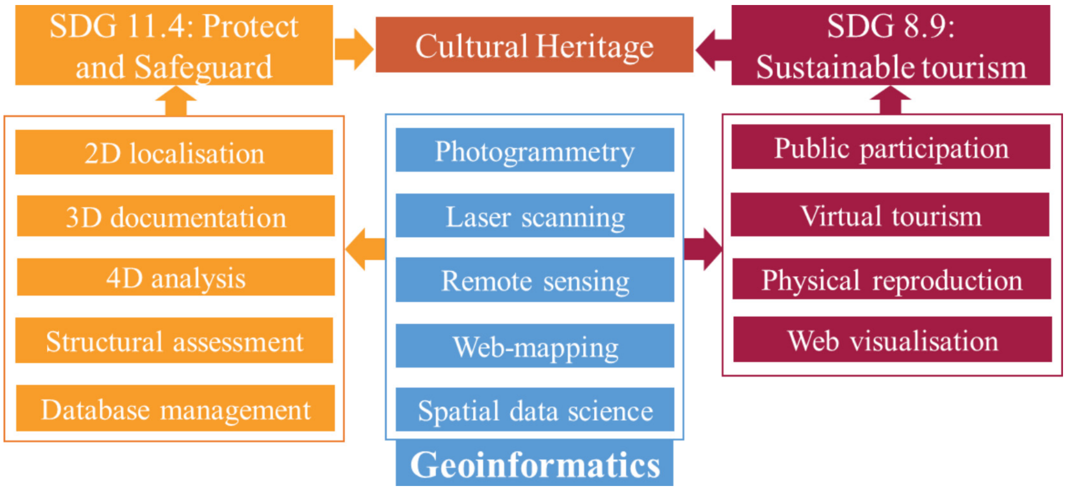

Fig. 2. The contribution of geoinformatics to detailed aspects of cultural heritage protection and sustainable tourism promotion.

photogrammetry and laser scanning, can be found (Remondino, 2011; Yastikli, 2007).

A primary reason for 3D reconstruction of CH is for digital documentation so that the structures or sites can be better preserved and monitored under impacts such as climate change, natural disaster, and human exploitation (Fieber et al., 2017). Both the geometry and appearance can be constantly monitored and evaluated through digital 3D reconstruction. The other usage of 3D models is to facilitate sustainable tourism by, for example, producing high fidelity replicas, facilitating multimedia exhibitions or virtual tourism (Remondino, 2011). Moreover, 3D reconstruction can be used to build accurate CAD models that allow evaluation of the actual behaviour of the construction as a basis for numerical analysis. An example is presented by Sánchez-Aparicio et al. (2014) in which a 3D CAD model of a complex CH object, Saint Torcato Church, located in Guimaraes, Portugal, was used in order to obtain accurate numerical models which allows identification of architectural complications that arise in historic buildings.

Geoinformatics technologies can help not only in digitizing physical assets, but also in documenting intangible CH. Transforming such memories into digital form allows connection with the digitized version of the places where these different forms of CH were developed, creating a far more complete documentation about the culture of a specific place. For example, RGB and depth (RGBD) sensors have been used to capture and decompose dancing motions for documentation and dissemination (Kim, 2017). Alivizatou-Barakou et al. (2017) illustrated the use of sensing technologies, including photo, video, RGBD and other sensors for intangible CH preservation and development. Studies included facial expressions and body motion extraction and analysis.

2.1.3. Evolution over time

CH evolves through time. To properly safeguard CH, and assess the influence of protective measures that have been taken, therefore necessitates monitoring through time. Temporal analyses and multi-temporal 3D reconstruction are enabled by geoinformatics technologies, which facilitates subsequent decision making regarding intervention on CH.

Temporal analyses is the focus of the pan-European project "Cultural Heritage Through Time" (CHT2, 2017) for which the scope is to develop time-varying 3D products, from landscape to architectural scale, to envisage and analyse lost scenarios or visualise changes due to anthropic activities or intervention, pollution, wars, earthquakes or other natural hazards. The main aim of the CHT2 project is to merge heterogeneous information and expertise to deliver enhanced four-dimensional (4D) digital products of heritage sites. CHT2 is working on the full integration of the temporal dimension, its management and visualisation, for studying and analysing CH structures and landscapes through time. The project flowchart is presented in Fig. 3, in which there are four main phases: data collection, processing, fusion, and analysis. Historical analogue and digital, 2D and 3D data is collated and processed using state-of-the-art photogrammetric approaches. Additional up-to-date image-based data, e.g. aerial photographs from UAV, and laser scanning data are fused with archival data for final 4D analysis.

The biggest challenge of 4D CH reconstruction is to fuse, manage, and visualise various data of different attributes, spatial and temporal scales. Rodríguez-Gonzálvez et al. (2017a) summarised the different geoinformatics technologies based on scale, complexity and suitable size of CH artefact, architecture or landscape. Metric and non-metric data were fused and managed by the integration of heritage building information modelling (HBIM) and GIS. 4D visualisation are also discussed as it provides a holistic view for both heritage mangers and consumers. Micoli et al. (2017) demonstrated a case study of 3D reconstruction of Milan Roman circus at three difference ages. This 4D reconstruction helps to better identify the proper reconstruction of the ancient building and all the changes that affected the area from the late roman period until the present time. Fieber et al. (2017) described the observation of landscape change over time at three locations on Hadrian's Wall to help inform understanding of CH sites at risk from natural hazards, notably erosion and flooding.

2.1.4. Structural assessment

Identifying and quantifying the potential causes of damage to a CH construction, as well as evaluating its current stability or degree of damage, have become an imperative task in today's world. Structural change and damage can influence the behaviour of artefacts and buildings, and the use of Finite Element Analysis (FEA) for modelling stress behaviour on ancient objects/structures can be a powerful tool for preserving, conserving and restoring tangible cultural heritage. The potential offered by the combined use of photogrammetric and laser scanning techniques together with numerical strategies based on FEA allow the simulation and assessment of the origin of damage and provide an evaluation of the current CH construction stability. A good example of such CH structural simulation is provided by Sánchez-Aparicio et al. (2014) in which laser scanning and photogrammetry were combined with operational modal analysis to create and calibrate finite

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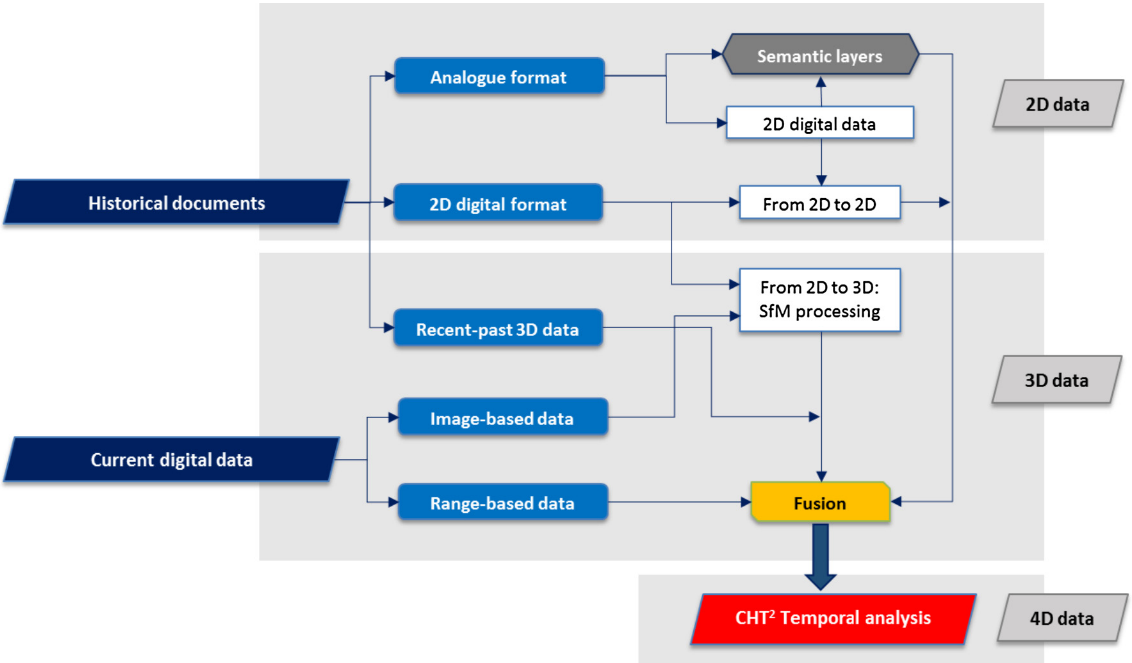

Fig. 3. Methodology for the integration of CH data in order to perform 4D analysis (CHT2, 2017).

element models (FEM). Castellazzi et al. (2015) developed a semi-automatic approach to transform laser scanning point clouds into FEM, named CLOUD2FEM, for historical building structural assessment. Jaafar et al. (2017) proposed a method to determine deformation probabilities and displacement vectors of heritage building parts based on laser scanning measurements and the generalised Procrustes analysis method.

3D documentation of CH structures via geoinformatics approaches mostly represents models in the form of meshes formed by a large amount of triangles and these must be further processed for use in FEA. The typical workflow of such analysis involves the use of 3D CAD models made by mathematical surfaces, representing the ideal shape of the object to be simulated (Brune and Perucchio, 2012). For CH objects, altered by the time that has elapsed since their original creation, the representation with a schematic CAD model may introduce an excessive level of approximation, ultimately leading to incorrect simulation results. As an alternative a new method, based on a wise use of retopology procedures, aims at generating the most accurate 3D representation of a real artefact/scenario from 3D models derived from reality-based geoinformatics technologies, maintaining the accuracy of the high-resolution polygonal models in the solid ones, while minimizing the number of nodes to a level compliant with FEA (Gonizzi Barsanti and Guidi, 2017). Retopology creates a new topology for a 3D model by simplifying the high-density model with a low-polygon mesh and, meanwhile, generating a brand new polygonal organisation that follows the main geometrical features of the original 3D model. The retopologized mesh is typically formed by quadrangular elements (quads). The quadrangulation method samples the original mesh at a lower spatial resolution but preserves its global geometry, re-defining from scratch its topological structure. This allows the generation of FEA results that are closer to the actual mechanical behaviour of the analysed heritage asset.

Such methodology, developed in the framework of the aforementioned CHT2 project, has been applied to generate useful data for gathering information for the diachronic reconstruction of ancient structures. The experiments completed until now have been applied to a variety of CH assets ranging from an entire building to museum artefacts (Fig. 4).

2.1.5. Management and planning

One of the main parts of CH documentation and reconstruction is the connection with a geodatabase for management and planning actions. This aspect is usually neglected but is gaining more attention with the emergence of HBIM (Murphy et al., 2009), which includes all the information of the CH construction (e.g. inner and outer parts of the building and the inventory of assets), state of conservation, monitoring actions, plans for restoration and conservation and even the potential visualisation of the CH for its promotion. An example is presented by Muñoz-Nieto et al. (2011) where a specific spatial system and geodatabase is developed for the management and safeguarding of those buildings which are declared CH sites. The system involves not only a georeferenced inventory of assets, but also a safeguarding plan for fire prevention.

Other uses of CH spatial information systems include well informed urban planning and disaster risk management (Jigyasu, 2013). Rapid urbanisation has put great pressure on heritage structures, so sustainable urban development should consider CH in planning and development. Disaster risk management should also consider heritage as a part of the plan, recognising the potential damage caused by natural and manmade disasters (Maskey, 2013). The integration of HBIM and other spatial data will facilitate decision making on management and planning. 3D heritage models are integrated into GIS using the 3D city modelling framework, CityGML, which provides an interoperable framework for geometry, semantics, topology and appearance modelling for better documentation, visualisation and analysis (Dore and Murphy, 2012).

Petrescu (2007) reviewed the use of GIS technology in CH for heritage management, conservation, restoration, visualisation, and exhibition in 22 countries around the world. Apollonio et al. (2011) developed an integrated e-Heritage GIS to record, process, manage, visualise, and interact with large scale archaeological and architectural sites. An open source web-based national information system for heritage site inventory and management was also developed for the Middle Eastern Geodatabase for Antiquities

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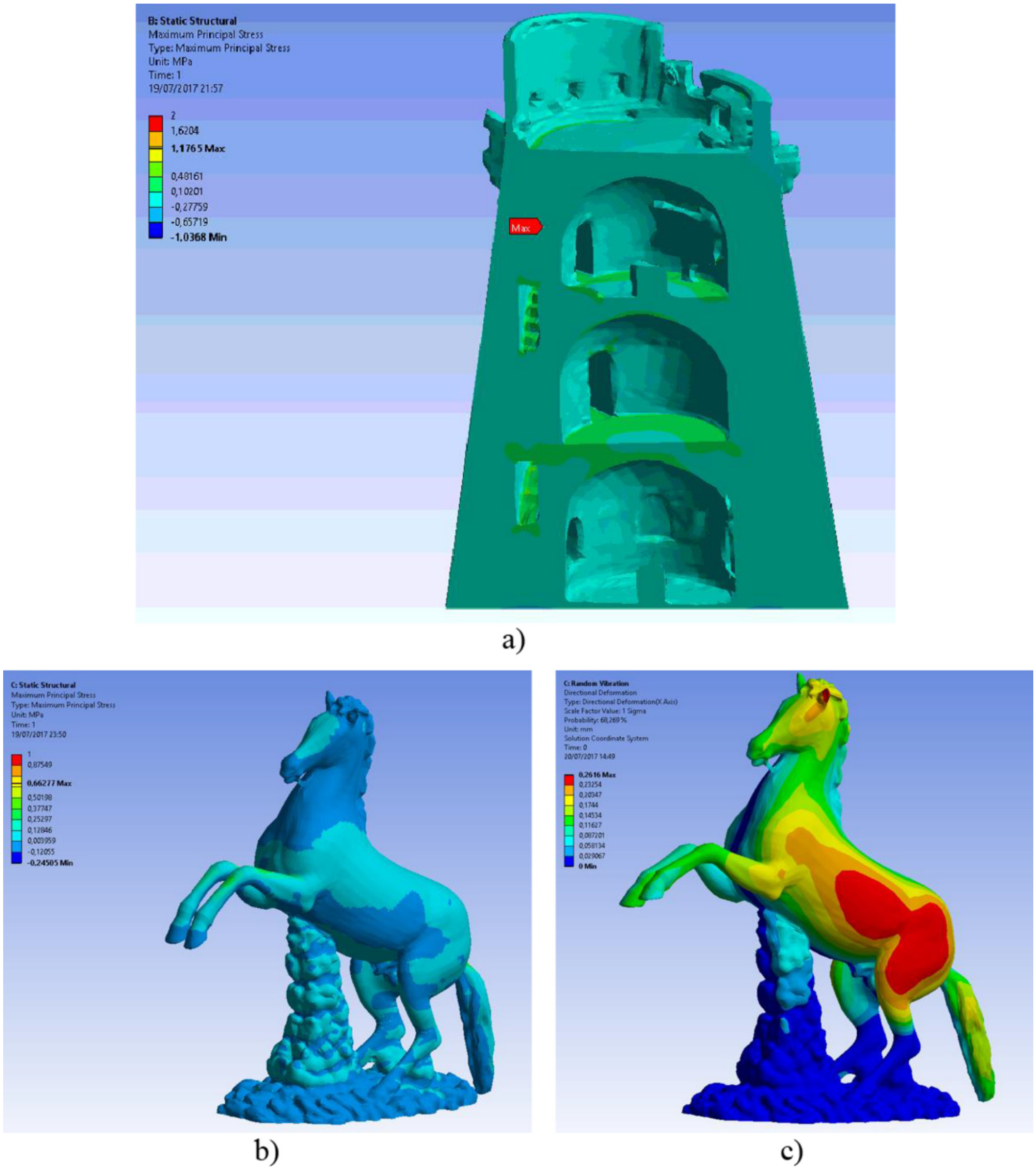

Fig. 4. Finite element analysis of 3D models originating from 3D data captured in the field: (a) stress analysis on the Tower of the Marenyet in Valencia (Spain) with gravity; (b) stress analysis on a Roman sculpture conserved at the Uffizi Gallery in Florence (Italy) with gravity; (c) deformation analysis with a random force applied at the sculpture basement on the x-axis simulating an earthquake.

(Myers and Dalgity, 2012). It has been used to register, monitor, and manage thousands of archaeological sites in Jordan and other countries.

2.2. Promotion of sustainable tourism (SDG 8.9)

Butler (1999) summarised various definitions of sustainable tourism at different times. The UN's World Tourism Organisation (UNWTO) defined it as tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment and host communities (UNEP and UNWTO, 2005). Sustainable tourism is committed to minimise the impact on local CH, while contributing to continuous income and employment for the local population. UNESCO's World Heritage and Sustainable Tourism (WH + ST) programme promotes the vision that tourism stakeholders share the responsibility for heritage conservation and sustainable development through appropriate tourism management (UNESCO, 2017). Geoinformatics is not only playing an important role in the safeguarding of CH, but also contributing to the promotion of sustainable CH tourism. This section illustrates different aspects of geoinformatics and related technologies to promote tourism, enhance the tourism experience, and reduce destruction and safety risks in a sustainable manner.

2.2.1. Public participation

The relationship between CH and local communities is important for sustainable development. A healthy and positive relationship can help promote heritage conservation, management and development, and will in return benefit local people (Han et al.,

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2016). History, customs, cultures and social activities are also heritage that needs to be preserved, implying that the participation of local communities in CH conservation is imperative. CH conservation and sustainable tourism should also be considered as a part of community development. Local communities living close to heritage sites understand best their characteristics, economic potential, threats and risks. Community participation enables effective and efficient implementation of conservation measurements.

There are different methods of public participation, in which geoinformatics technologies such as geo-crowdsourcing and web-mapping play important roles. They can be used to strengthen the role of local communities and tourists in the management and conservation of CH in the form of participatory data collection, mapping and knowledge sharing, which will promote partnerships between local communities and public institutions and economic benefits for the communities (UNESCO, 2016b). Geospatial enhanced crowdsourcing has enabled the public to participate in heritage documentation and sharing, thereby improving the engagement with their CH and, more importantly, occasionally saving it from complete disappearance as a consequence of human destruction. Photos taken by tourists have been used to reconstruct heritage structures destroyed during wars. For example, the Buddhas of Bamiyan were destroyed in March 2001, but reconstructed digitally using both research data and tourist photography (Grün et al., 2004). Another prominent example is Project Mosul[5] following the destruction of CH within the Mosul Museum, Iraq, in February 2015. Here a crowdsourcing tool was developed to collect image data from the public, then images were processed to reconstruct destroyed heritage objects using the latest photogrammetric approaches (Vincent et al., 2015). Karl et al. (2014) also developed tools to crowdsource heritage images from communities and to create 3D models of the heritage sites and objects using photogrammetry. Both images and 3D models are documented in the local Historic Environment record, which can be used for heritage change monitoring and assessment, and provide local people and tourists alternative views of the CH. Further crowdsourcing projects can be found for heritage documentation and protection from neglect, conflict and natural impacts, such as the Million Image Database,[6] Curious Travellers,[7] and Heritage Together.[8]

2.2.2. Virtual reality tourism models

3D visualisation techniques based on Virtual and Augmented Reality (VR/AR) open up a vast field of applications for virtual tourism, using new technologies and devices that allow the user to interact with digital objects and navigate through reconstructed scenes. In addition, reality-based digital models, which constitute physical materials, can be supplemented with historical information either in reference to the tangible object or with information about the intangible heritage concerning place and culture, e.g. texts, documents, monoscopic or stereoscopic images and videos, etc. An example of this virtual tourism is exemplified by Mancera-Taboada et al. (2010) where laser scanning and photogrammetry are combined to provide a VR tour of the Medieval wall of Avila.

The use of virtual models for “visiting” heritage assets is particularly important with reference to the UN SDGs. On the one hand, sites not particularly well-known, especially in developing countries not easily reached, can be promoted to a large audience of potential visitors that can be attracted and convinced to organise a physical visit. On the other hand, once the tourist traffic increases, the anthropic pressure on the site can become a significant threat. In such cases, a mixed experience made by an in-depth virtual tour for explaining the place and a short visit in the field to provide the peerless experience of the reality, may help in reducing the amount of time spent on the site. In this way, the CH asset is protected against over-consumption and damage. This also holds true for sites partially or entirely inaccessible for various reasons, such as sites in war zones, or sites developing in the inaccessible underground of a major city.

Finally, virtual models, being a form of digital documentation, can be helpful also for conservation and restoration actions, for simulating different solutions and determining the level of intervention required for the physical structure. Such opportunity allows testing of different restoration hypotheses at a digital level, discussion amongst experts, including the possibility to share the hypotheses via the web, in order to take wise and informed decisions on sensitive matters.

2.2.3. 3D physical reproductions

3D physical models have been created to enhance the heritage tourist experience. They can be used for both onsite and remote exhibitions. Reality-based 3D digital models can be generated by geoinformatics technologies after which physical models can be produced with the help of 3D printing technology (Neumüller et al., 2014). These models can be used not only for exhibition, but also for research, documentation, preservation and educational purposes. Due to its scalability and accessibility, a physical model can be easily used for public outreach activities, especially for those with disabilities, making the heritage industry more inclusive. Onsite multimedia presentations, including virtual and physical reproductions, provide new materials and experiences for visitors, and potentially attract new customers from the wider public. Moreover, these recreated digital and physical exhibitions do not cause any damage to the actual heritage sites or structures, thereby contributing to sustainable tourism.

True-to-scale or re-scaled 3D replicas can be used for interactive and multisensory museums, and also for the temporary or permanent replacement of original artefacts. In this way, it is possible preserve the CH asset while at the same time supporting tourism. Such reproductions do not reduce the tourist experience since, in the majority of the cases, the CH elements are appreciated at a medium distance (Scopigno et al., 2014). Another use is the reproduction of historical building ornamental components at true scale, as shown by Xu et al. (2017). In this work, geoinformatics was employed to acquire the 3D data, by a hand-held structured light 3D scanner, and model the historical building component by reverse engineering. Finally, a cement mortar-based 3D printing technology was used to create the final physical reproduction.

Themistocleous et al. (2015) presented a case study of Asinou Church in Cyprus, in which a UAV with a low-cost camera was employed to take hundreds of images of the church. These images were used to create a 3D photogrammetric model based upon which a physical model was printed. Allard et al. (2005) used laser scanning and 3D printing to create human skeletal remains for a museum exhibit. A hand-held laser scanner was used to capture the geometry of individual bones, which were then exported to a 3D printer to produce physical models. These technologies enabled an accurate and realistic representation of the original skeleton, demonstrating their usefulness in bio-archaeological conservation, research and exhibition.

2.2.4. Web visualisation and analysis

Web visualisation exploits online resources to create browsers, applications, systems and platforms (De Luca et al., 2010) for both remote visualisation and data analysis of 2D images or maps and 3D models. Different users can access and interact thanks to the flexibility and portability of mobile devices and geolocation capa-

[5] https://projectmosul.org/.
[6] http://www.millionimage.org.uk/.
[7] http://www.visualisingheritage.org.
[8] http://heritagetogether.org.

bilities. Web visualisation of CH can provide tourists with rich textual and graphical information, enhancing understanding and enjoyment, which help to bring heritage closer to the public and promote tourism in an efficient and sustainable way. From a tourist's perspective, there are many ways to find an attractive heritage site to visit, such as knowledge-sharing website (Wikipedia), guidebook, travel blog or vlog. However, a web-based visualisation platform that integrates all the background information and graphical presentation is desirable. Web-mapping can provide the public with access to both spatial and semantic data, such as Google maps and Google Earth. A UK public heritage institute, Historic England, has developed a web visualisation platform for the Stonehenge World Heritage Site Landscape,[9] providing both 2D maps and contextual information. Both images and 3D models can be visualised interactively online to attract tourism, such as Photo Tourism (Snavely et al., 2006). Photogrammetric 3D models can be visualised and presented on site, as well as on the web platforms, such as Sketchfab.

Regarding data analysis, different 3D models can be analysed using web processing service standards and visualisation on mobile devices. This allows the creation of shared heritage databases and easy access so that different heritage stakeholders and managers can contribute and collaborate more efficiently. For instance, Potree[10] is a free open-source WebGL based visualisation platform for various spatial data such as point clouds, lines, meshes, and shapefiles. Torres-Martínez et al. (2016) presented a platform that was implemented for archaeological site web visualisation. Data acquired from both aerial and terrestrial platforms, including paratrike, UAV, terrestrial laser scanner and photogrammetry, were integrated, optimized and visualised on a mobile device (tablet or smartphone), offering comprehensive and detailed information to archaeologists and heritage managers for onsite works and later analytics, as well as to tourists who desire a better view of the archaeological site.

3. Case studies

Case studies of three different UNESCO World Heritage Sites, located in both developed and developing countries, are presented to illustrate the contributions of diverse geoinformatics technologies, in a combined way, to achieve the different aspects of the two sub-SDGs (8.9 and 11.4), and to ultimately help the UN realise its 2030 sustainability ambitions.

3.1. The Old Town of Ávila and its medieval walls, Spain

3.1.1. Case study background

The most representative CH asset of Ávila city is the Medieval Wall (Fig. 5). This construction is the most important example of a military structure in the Spanish Romanesque style and also an exceptional model of European medieval architecture. The construction of the city wall is perfectly adapted to the topography. The wall was used not only to defend the town from possible invasions and to protect the people from possible pests or epidemics, but also to control trade between the city and the outside world. The southern sectors are shorter as they are built upon a cliff that acts as a natural defence. The western and northern sections escalate in height, reaching the tallest and thickest points located in the east section. There are nine gates giving access to the town, of which the most significant is the Alcazar Main Door. Some references state that the building dates back to 1090. Other researchers have argued that the wall's construction most likely continued

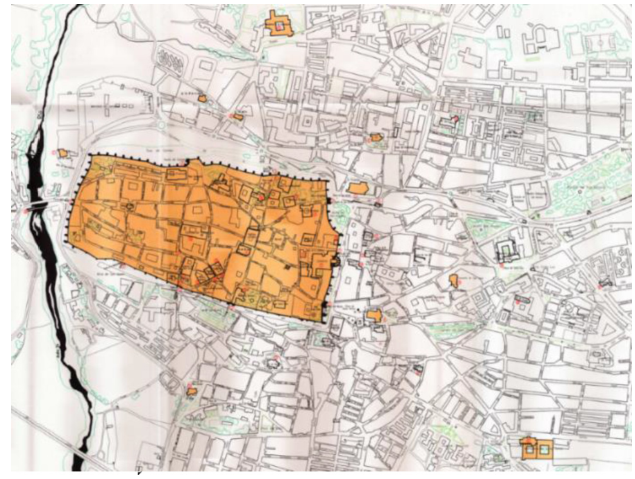

Fig. 5. Map of the Old Town of Ávila and external heritage monuments (coloured in orange).

through into the 12th Century. Beside the medieval walls, the Old Town of Ávila also includes the Extra-Muros Churches, which altogether encompass c. 36.4 ha. The town of Ávila Intra-Muros includes 93% of the protected area, the rest being distributed amongst a basilica, five churches, two convents, a hermitage and a royal monastery. The high density of religious buildings are a reflection of intangible CH, since mysticism is an important element of the city. In 1884 the site was declared a National Monument and in 1985, the old city of Ávila, as well as its churches, were included on UNESCO's World Heritage list. The Old Town and scattered heritage buildings are now the main attractions of the city, supporting the tourist industry and downstream businesses. The protection of these heritage treasures and sustainable development of tourism are therefore vital for the local population.

3.1.2. Geoinformatics technology applied to the case study

The large size of the Old Town is a clear example of a challenging CH site upon which to implement recording and documentation processes. In spite of its linear nature, the distribution of towers and walls, the gates, and neighbouring city buildings complicates data acquisition and processing. It has therefore been employed as a test site to apply and evaluate different geoinformatics technologies, ranging from close-range photogrammetry to recent Mobile Mapping Systems (MMS). Due to the lack of previous metric support for CH management, the selected technique for initial documentation was TLS as it provides a rich representation with high resolution and accuracy. The entire Medieval Wall of Avila was digitalized using TLS with 15 mm resolution from an average scanning distance of 20 m (Fig. 6). The TLS *a priori* range precision was established at 2 mm. A total of 50 control points, measured by RTK GNSS, were employed to georeference the global TLS cloud. The *a priori* precision of these measurements was 10 mm in the horizontal plane and 20 mm in the vertical axis. Due to the wide area of the case study, comparison between the laser scan and GNSS surveys yielded discrepancies of up to 50 mm. In parallel, high resolution images were taken using a non-professional single lens reflex camera to enhance the radiometric texture of the derived 3D model. The combination of focal lens, pixel size and camera-object distance, allowed image acquisition with a GSD of between 5 and 10 mm. Due to the scale and complexity of the site, aerial images were mandatory to complete the final model. For this task, a captive blimp was employed (due to national legal regulations it was not possible to acquire images from a UAV in such an urban environment).

[9] http://services.historicengland.org.uk/rrstonehenge/.

[10] http://potree.org.

Fig. 6. TLS acquisition. (a) Perspective view of the final 3D point cloud, (b) terrestrial laser scanner used in the field campaign.

The derived products of the campaign comprised three main deliverables: (i) 3D point cloud without texture, directly employable for structural monitoring; (ii) 3D photorealistic textured mesh for VR purposes; and (iii) true orthoimagery, which acts as metric support to integrate thematic information for preservation purposes. In addition, several panoramic images were acquired to provide support for CH building management. In spite of being non-metric, images serve as current status documentation, and as a basis to link additional material which ranges from technical data for risk management purposes to historical and cultural information (both tangible and intangible). The CH element is under continuous evaluation using high-end geospatial technology for data collection in urban environments. For example, Alcazar's gate (Fig. 7) was surveyed using MMS in 2014 (Rodríguez-González et al., 2017b) with a spatial resolution of 60 mm from an average scanning distance of 25 m. The accuracy assessment of the MMS point cloud in the Alcazar area necessitated a non-parametric statistical analysis. The georeferenced TLS scans were used as ground truth. The error, expressed in terms of non-parametric estimator for the quantile, indicated that 95% of errors were inside the [−0.046 m; 0.047 m] interval, with a median error of zero.

3.1.3. Contribution of geoinformatics to SDGs

The use different geoinformatics techniques and their integration enabled the generation of a wide range of derived products to fulfil the different aspects of SDG 11.4 and 8.9, as described in Section 3.

Beginning with safeguarding (SDG 11.4), the CH assets of the old town of Avila and its Medieval Wall are well known and protected by local authorities. However, the urban dynamic exposes them to risk due to several erosive and damaging factors. The generated orthoimages were used in the restoration processes at two levels: (i) direct photo interpretation of the wall to characterize the material preservation and deterioration; and (ii) to restitute those areas with pathologies. By mapping pathologies over 2D orthoimages, it was possible to optimize the budget while proceeding only in critical areas. Moreover, the thematic orthoimages helped to identify, locate and determine humidity content, salts, oxides, moss and vegetation. In this way, the local operating council was able to carry out an efficient restoration processes in critical areas, while the remaining areas were monitored (Rodríguez-González et al., 2010). This approach was applied to the Medieval Wall and the highly exposed churches of the monumental ensemble. Another contribution was the short time-series reconstruction by TLS. 3D point clouds from TLS campaigns were analysed, providing structural monitoring of high-risk areas (Muñoz-Nieto et al., 2011). Moreover, a geodatabase with the CH buildings of Avila was created for management and planning actions in case of fire risk. This is a clear example of collaboration of different stakeholders, including the fire brigade, social volunteers, conservators, museum managers and local authorities, and is directly aligned with SDG 11.4.

Moreover, the geoinformatics deliverables have been used to promote sustainable tourism in Avila, aligned with SDG 8.9. The virtual 3D model of the Medieval wall, described in Mancera-Taboada et al. (2010), was converted to CAD format and then printed as a 3D physical reproduction which was subsequently exhibited in the tourism office of Avila. This kind of physical reproduction allows the complete CH element to be exposed to the tourist, including areas closed to the public or with impossible access. Furthermore, a virtual tour was generated using these 3D models. This included photorealistic texture and information about the intangible CH of Avila, enhancing the tourism experience for visitors. In this way geoinformatics helps to reduce the impact on CH, and at the same time attracts tourists which will generate income for the local population.

3.2. The My Son Sanctuary, Vietnam

3.2.1. Case study background

My Son is a large archaeological site located in central Vietnam, made of different groups of partially ruined Hindu temples constructed between the 4th and the 14th Centuries AD by the Champa civilization, living at that time between Vietnam, Cambodia and Laos. My Son is hidden in the forest, in a circular valley located in the Quảng Nam province, 69 km southwest of Da Nang and 35 km from the touristic city of Hoi An. The 72 temples in this archaeological site are grouped according to a strict rule. In each group the main temple (Kalan), containing the most secret religious symbols, lies in a square area limited by a wall defining a holy enclosure whose entrance, aligned with the Kalan longitudinal axis, is called Gopura. Along the same line, out of the wall border and in front of the Gopura, is located a larger building called Mandapa. It was conceived as the room for the reception of the monks, before the entrance of a small selected group of priests in the inner part of the Kalan. A small building called Posa, built to house the temple's stela, was also placed out of the holy enclosure. In My Son several similar groups of temples have been found and labelled with letters from A to H. Group G, located on the top of a hill, was assigned to an Italian mission for restoration and is described here. The buildings considered have the following nomenclature: G1 is the sanctuary (Kalan); G2 the gateway, shaped as a miniature copy of the main sanctuary (Gopura); G3 the assembly hall (Mandapa); G4 the south building (Kosagrha) and G5 the pavilion for the foundation stone (Posa) (see Fig. 8.).

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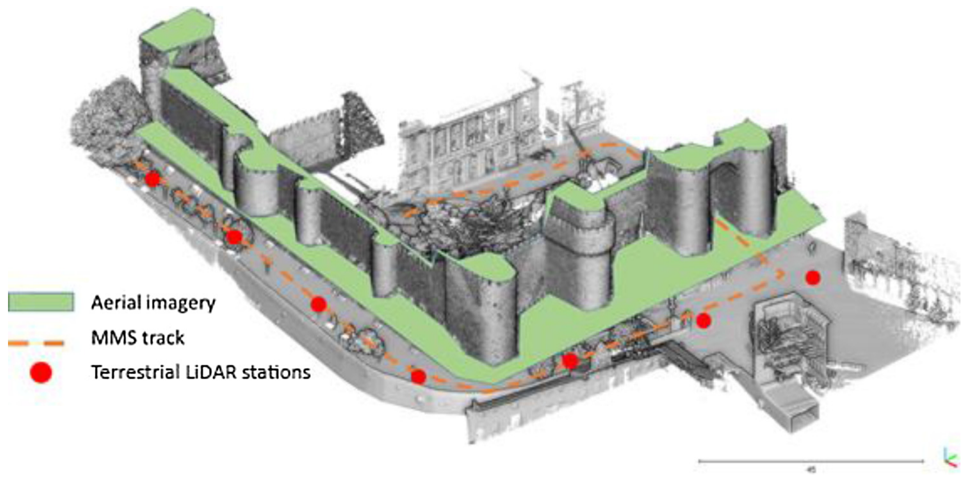

Fig. 7. Example of geoinformatics techniques, including aerial photogrammetry, Mobile Mapping System (MMS), and Terrestrial Laser Scanning (TLS), applied to the Medieval Wall of Avila (Alcazar's gate).

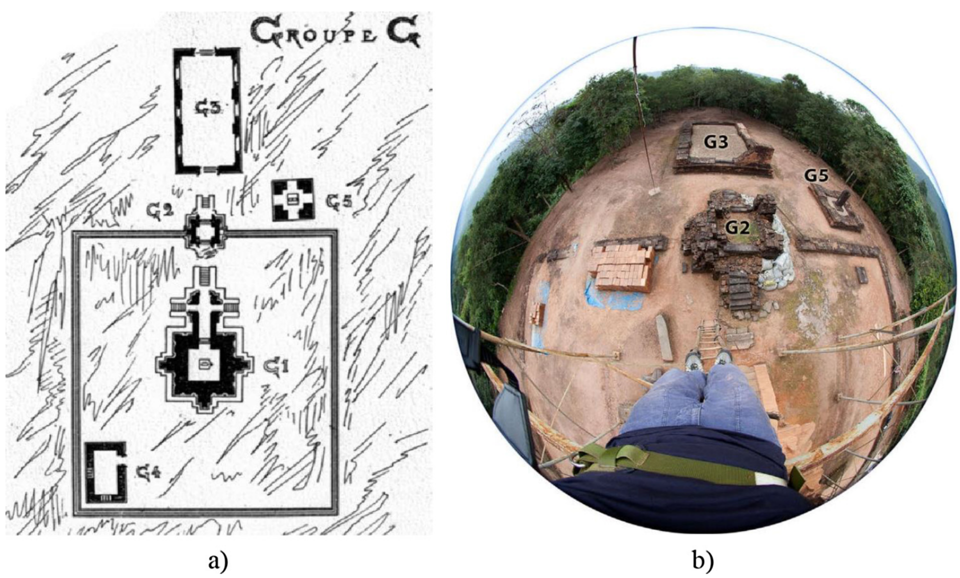

Fig. 8. Group of temples within the My Son archaeological site, indicated as "Group G": (a) Old hand-drawn map of the area (Stern, 1942), and (b) image of the area entrance seen from the top of G1.

3.2.2. Geoinformatics technology applied to the case study

The survey of G Area was carried out in 2011 and involved both laser scanning technology for 3D geometric acquisition of five different structures with associated findings and 2D image acquisition for texture and environment documentation purposes. Due to its portability and accuracy, a compact 3D laser scanner based on phase shift detection, FARO Focus3D, was used for gathering the 3D information of the structures and creating the DTM of the area. Due to its height, a dedicated 3D acquisition of the upper part of the Kalan was carried out in order to scan all occluded areas of this complex geometry. The scanner was positioned 7 m from the ground in the four corners of the iron structure covering the Temple, acquiring four high resolution scans of the whole structure and the surrounding area. A long sequence of architectonic acquisitions was realized around the building and integrated with a detailed one devoted to survey the decorated basement. To avoid shadow effects generated from the basement, an additional sequence of scans at 3 m height was conducted. The second step consisted of DTM acquisition to create a geometric framework in which to locate all structures in a common reference system. For this reason, a wider surface with respect to the archaeological area was considered necessary to acquire the morphological terrain context. The last phase focused on the 3D acquisition of archaeological artefacts that were found during the excavation of G Area which were then classified inside the storeroom of the local museum. This step was planned both to digitally document these important sources and to create 3D models of decorations that could subsequently be repositioned on the virtual models. An additional photographic campaign was devoted to the acquisition of: (i) architectonic images for texturing projection purposes; (ii) detailed images for the creation of seamless material pictures; (iii) panoramic images to gather a believable representation of the surrounding environment through the stitching of multiple fish-eye photographs; and (iv) image sets taken around four monuments for experimenting with automatic image matching techniques.

The various surveys provided a rich amount of raw 3D data, for example 126 million points for G1, 27 million for the DTM description and 2 million for the 21 artefacts digitized in the museum. The scans associated to each building were then mutually aligned by means of the ICP algorithm implemented in the Leica Cyclone 3D processing software. The resulting point clouds were then decimated at 10 mm sampling step, thereby levelling all over-sampled portions of the structures and lowering the amount of 3D data. Every scan was then uniformly meshed. However, the resulting high-resolution polygonal models presented both several topological errors, due to residual errors that survived the cleaning phase, and a huge number of holes, related to shadow effects from the complex geometry. A rather long post-processing phase was then required to generate a watertight polygonal model. This stage realised the constructions of 10 mm resolution geometry for all five buildings in G Area, a 0.1 m resolution DTM of the hill where G Area is located, and a set of polygonal models of sculpted finds with a geometric resolution of 2 mm.

The starting geometry for the reconstructive models were represented by the existing reality-based models. These were enriched with architectural elements originating from archaeological consideration of the debris found in the excavations, the stylistic patterns of similar monuments, the logic of the rituals carried out in that place, and the size and shape of the decorations excavated on-site. The final model and the CAD reconstruction of the monumental area, developed in tight collaboration with the expert archaeologists, is represented in Fig. 9.

3.2.3. Contribution of geoinformatics to SDGs

The integration of reality-based techniques and CAD reconstruction supported by drawings, documents and archaeologists provides the possibility to document heritage objects in their current state and to hypothesize their past shapes. Geoinformatics technologies enable accurate documentation of the heritage site or structure that is useful for better understanding, conservation and restoration. The typical workflow of reconstructing a destroyed site for archival documentation and archaeological conjecture is supported by accurate active reality-based modelling methods. This integration leads to an enhancement of the reliability of the reconstruction hypothesis and a better collaborative connection among 3D surveys, historical documentation and archaeological knowledge, strengthening the communication of the heritage assets.

The long-term effects of the resulting 3D model can be analysed only now, after some years from the actual work in the field, which commenced in February 2011. The 3D models have been used for the production of videos explaining how each of the five buildings of the reconstructed holy area were shaped, and how religious rituals were conducted. Both the shape of the buildings and the rituals represent two complementary elements (tangible and intangible) of the My Son culture that, being mutually interlinked, allow a full understanding of the archaeological site. The generated multimedia materials are used by local guides as an introduction prior to visits. This enhances the tour experience and at the same time reduces the anthropic pressure on the archaeological site, thereby promoting sustainable tourism (SDG 8.9).

In addition, both during the survey phase and in the management of the multimedia products resulting from this project, a number of local people have been trained either in operation of a laser scanner or in the management of the video projections. Such people are now permanently involved in the management of the site, thereby demonstrating how geoinformatics can indirectly support the creation of jobs (SDG 8.9).

The same material, appropriately rearranged, has been used in an exhibit in Germany entitled "Archaeological Treasures from Vietnam" (SMAC, 2017), that toured around the German cities of Herne, Chemnitz and Mannheim from October 2016 to January 2018. The exhibit was a great success, visited by 700 people in the inauguration day alone, and several thousand since its opening, raising interest for an archaeological area not well known in Europe. This demonstrates how this kind of application also promotes local culture and products in the richest countries that are capable of increasing the touristic flow towards the actual site, again addressing SDG 8.9.

Finally, the rich digital documentation produced by this project, putting together the current state and the hypothetical reconstruction according to expert opinion, was also used by architects in charge of the physical restoration of the monument (Fig. 9). This impacts directly to strengthen efforts to protect and safeguard the CH (SDG 11.4).

3.3. Kathmandu Valley, Nepal

3.3.1. Case study background

Nepal is a country that frequently suffers from natural disasters, such as flooding and landslides, and is highly prone to earthquakes. Among the most devastating natural disasters experienced by the country was the 2015 earthquake, which caused heavy loss of human life, buildings and infrastructure. More than 9000 people are reported to have lost their lives, and around 22,000 more were injured. Reports indicate that 604,930 residential buildings were completely destroyed and 288,856 were partially damaged in the incident (Dangal, 2015).

The impact of the earthquake on CH was also extensive. According to Nepal's Department of Archaeology, around 750 heritage structures of significant cultural and religious value (e.g. temples and shrines) were affected. For example, Bhaktapur, a UNESCO World Heritage Site, was identified as one of the 14 most affected districts in the country. Nepal's Department of Tourism reported that the consequences of the earthquake had a direct impact on cultural tourism, one of the major sources of income for local people. During 2016, the number of non-South Asian visitors (excluding China) entering the Bhaktapur district dropped by more than

Fig. 9. Results of the digital survey and reconstruction of G Area, represented with rendering in a virtual environment: (a) existing reality-based model; (b) reconstructed virtual model.

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Fig. 10. Earthquake damaged heritage building in Nepal supported by poles and scaffolding.

80%, resulting in a loss of income exceeding more than US$3M on entry fees alone. Religious, cultural, social, and economic aspects have hence all been severely affected.

As exemplified in Fig. 10, many heritage structures have been endangered by the earthquake and are now temporarily supported by poles or scaffolding. There is a desperate need to assess the stability and strength of the structures in an appropriate and sensitive manner. Aligned with the UN SDGs and Nepal's national strategy for disaster risk management, geoinformatics approaches are being assessed for the development of a risk based analysis tool to support the decision making process on heritage protection and management to natural disasters. In the long term, this will contribute directly to the recovery of local people's livelihoods and the revitalization of economic development.

3.3.2. Geoinformatics technology applied to the case study

Protection of existing heritage structures requires appropriate techniques to support the diagnosis and structural analysis phases in order to validate expected performance. Geoinformatics is employed to acquire 2D and 3D spatial information to support geotechnical and structural analysis in order to better protect and safeguard heritage infrastructure from natural disasters. One major challenge is the documentation and conservation of CH structures that are widely distributed at a regional or national scale. The most prominent heritage structures, especially those have been listed as UNESCO World Heritage Sites, are of great importance to local people's spiritual and economic wealth. Such sites are normally well resourced and preserved. However, less than one thousand sites are listed. The majority, though holding great value to indigenous people, are not listed and are often not well managed. Indeed some sites may not even be discovered or recognised as of value. In order to identify, document and monitor such unattended heritage treasures, vast resources are needed using traditional methods. Another challenge comes from the destruction and deterioration of heritage structures due to natural or anthropogenic impacts. In such cases structures may need to be regularly monitored and maintained, which means that a one-time documentation campaign will not suffice, and a continuously monitoring solution is required (Dhonju et al., 2017b). Therefore, a ubiquitous approach is essential for such challenges, especially for developing countries where high-end technology and resources are often unaffordable.

A low-cost and easy to use, image-based crowdsourcing approach has therefore been developed. Photographs from tourists, local people, and heritage managers are collected via an online geo-crowdsourcing platform,[11] which has been designed and developed using free and open source software. The holistic system comprises three main components: (i) a web interface as a web-mapping, visualisation and user interaction layer where crowd users are able to upload images and basic information regarding the heritage structure, including geolocations; (ii) a geospatial server through which images and metadata are processed and published; and (iii) a database management system in which crowdsourced information, e.g. the image library, and local processing software packages are stored and managed. Through this platform, a registered user can create a unique album for a heritage structure and upload a series of images with contextual information, such as a brief introduction or the degree of damage to the structure. Aside from the web interface, a mobile phone application is under development with which users can upload imagery directly from their smartphones. The images are geo-tagged by coordinates so that they can be mapped and visualised on the platform, as illustrated in Fig. 11 (Dhonju et al., 2017b). Images are then used to reconstruct 3D models of heritage structures. The 3D data of complex heritage assets is used to form a decision support information system with capacity to automatically generate geometrical domains to be used in structural health inspection and model updating using advanced structural engineering open source code.

Selected monuments in danger at Kathmandu, Bhaktapur, and Patan Durbar Square have been reconstructed (Dhonju et al., 2017a) and provided to the local heritage management offices and UNESCO Kathmandu for documentation and further analysis. An example is given in Fig. 12. The monument is in danger of collapse so is currently scaffolded and will be demolished completely for subsequent reconstruction. Under its current condition, it is difficult to record measurements directly on the monument. Previous images from local people and managers have been collated and used to construct a 3D model that can be used for reference in the building's restoration.

3.3.3. Contribution of geoinformatics to SDGs

In the case of a disaster, such as that presented in this case study, one major difficulty of estimating and mapping the damages to CH is that sites are distributed widely in both dense urban and remote areas. A huge amount of resources are required at a short time to identify, locate, and document such heritage sites. Moreover, the afflicted heritage structures need to be regularly monitored for stability assessment or restoration documentation. To effectively record and preserve heritage structures at a large scale and on a regular basis, appropriate data acquisition techniques are required. In this case, geo-crowdsourcing and web-mapping are used to quickly collect CH damage information such as location and degree of damage, which support timely reactions and proper decision making and risk mitigation (Dhonju et al., 2017b).

The collated spatial data and images can serve further analysis to better protect and safeguard the heritage (SDG 11.4), such as visual inspection of structural health for those structures that have suffered damage or decay. The reality-based 3D models can be used as input to generate CAD models for structural analysis. The resulting structural assessment and health inspection will directly assist local stakeholders (heritage office, municipality) to take proper measures for heritage protection and restoration. Any subsequent reconstruction process can also be measured and monitored using the developed integrated system. Moreover, the spatial information can be integrated into geospatial databases so that all stakeholders, e.g. city planners, designers, government agencies/policy makers, and the public, can have access to the information, engendering better understanding and management plans. Colour and texture realistic digital models can be visualised using online platforms, which facilitates virtual tourism to potentially attract more visitors to the site, as demonstrated in the previous two case studies.

[11] http://soch.ncl.ac.uk.

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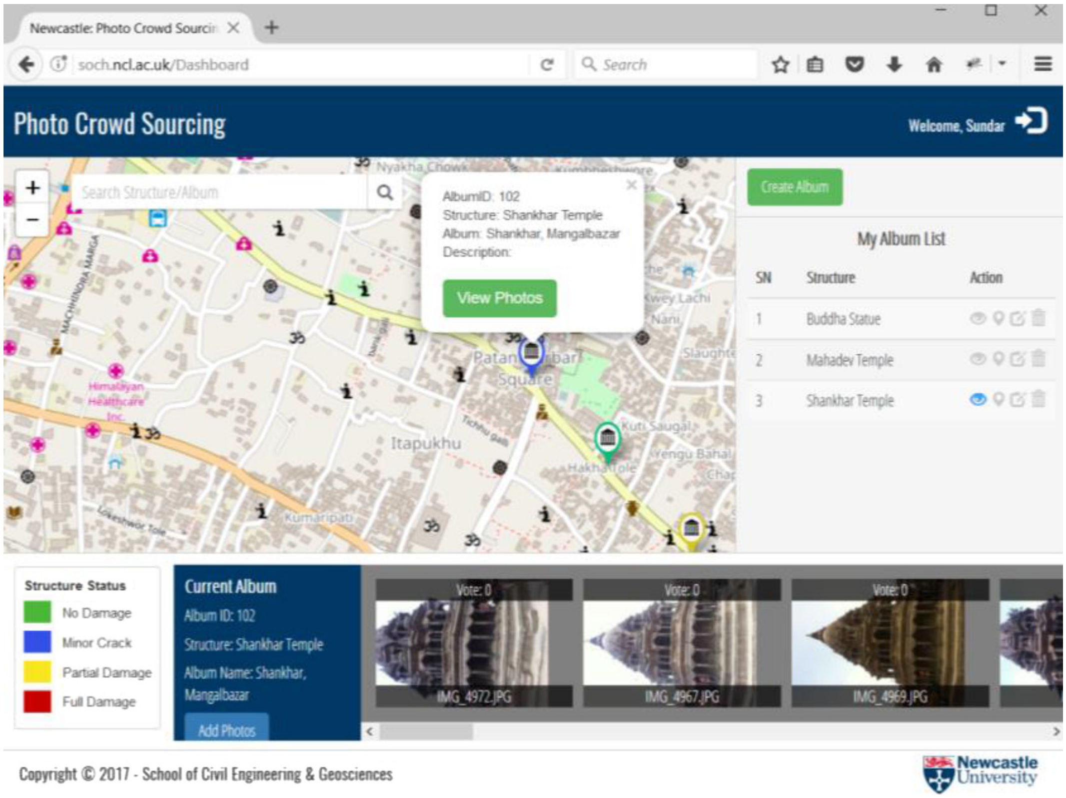

Fig. 11. Web interface of the developed online crowdsourcing and mapping platform.

Fig. 12. Crowdsourced images for heritage structure 3D reconstruction, (a) examples of crowdsourced images, (b) current status of the monument, encased in scaffolding, and (c) 3D model generated from crowdsourced imagery.

A further contribution of such platforms is community engagement for sustainable tourism development (SDG 8.9). A local community is able to contribute to information collection, and they can benefit throughout the process of knowledge sharing, for instance in discovering unrevealed recordings or histories of their indigenous heritage. This platform will help to build up an online community to promote local heritage to younger generations and people in the wider world. An engaged community with local knowledge will support better heritage protection and exploitation. Such technology can engender stronger engagement of local communities with their CH, thereby facilitating improved possibilities for sustainable preservation.

4. Discussion

Geoinformatics, and supporting or downstream technologies, are often harnessed to comprehensively protect CH and promote

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sustainable tourism. Close-range photogrammetry and TLS, for example, have been extensively applied together for detailed 3D modelling of CH artefacts and sites. 3D modelling with CAD, by integrating historical sources with present day 3D data, is also a form of documentation that, once georeferenced as in CityGML models, maintains accurate spatial and geometric features (Li et al., 2017). It can thus be integrated into geospatial databases to support improved urban planning and design, in addition to documentation, restoration and promotion purposes. Mesh and CAD models can be used to enable remote touristic exploration with VR (Gonizzi Barsanti et al., 2015), enrich a visit to the actual site through AR, or even create physical reproductions through additive manufacturing methods. Reality-based modelling and multi-temporal data have opened new potential for 4D documentation of CH (Remondino and Rizzi, 2010; Fieber et al., 2017), which can provide valuable resources for studying the evolution of heritage sites and for comprehensive visualisation and virtual tourism. Thanks to increasingly ubiquitous data resources and advances in digital technologies, the documentation of CH structures has therefore become routinely achievable for many UN member nations to generate reality-based 3D models that describe the current status of CH assets, thereby supporting effective planning and decision-making. In spite of the significant contributions, there are still challenges regarding the application of geoinformatics technologies and the use of spatial data in CH conservation and promotion. There are many different techniques for 3D reconstruction, with each approach subject to its own advantages and disadvantages, and the optimal integration of them necessitates further exploration (Guidi et al., 2014). Moreover, achieving high levels of automation with satisfactory modelling results remains a significant research challenge. Multi-modal data sources at various spatio-temporal scales and resolutions presents further challenges (El-Hakim et al., 2004; Rodríguez-Gonzálvez et al., 2017a). Nevertheless, the continual development of geoinformatics technologies has created new opportunities and perspectives for sustainable CH preservation and promotion.

Three case studies have been presented to demonstrate the contribution of geoinformatics technologies to the CH related SDGs. They were selected for multiple reasons. Firstly, they are located in countries with different levels of development, which has obvious implications for the safeguarding and promotion of CH. Spain is a developed country, whereas Vietnam is considered as a lower middle-income country and Nepal is listed as a least developed country, as of June 2017 by the UN.[12] Secondly, the three studies demonstrate the combined application of different geoinformatics technologies and platforms. For the case study in Spain, both photogrammetry and laser scanning technologies were used, and different platforms, e.g. MMS, tripod, aerial blimp, were adopted. For the case study in Vietnam, TLS and photogrammetry were also used, and more interestingly further processes for VR and exhibitions were illustrated. For the case study in Nepal, geo-crowdsourcing and web-mapping were the primary technologies and 3D photogrammetric modelling was presented to illustrate the usage of the platform. Thirdly, these cases demonstrate different aspects of the CH SDGs. The case in Spain emphasised aspects of 3D documentation and 4D analysis. The case in Vietnam focused on both 3D modelling and virtual presentation for tourism. The case in Nepal addressed aspects of public participation and web visualisation.

As presented in Section 1.1, the UN and UNESCO have proposed indicators to measure the progress of the achievement of SDGs. The UN's SDG CH-related indicators tend to focus on an economic perspective. For SDG 11.4, "Strengthen efforts to protect and safeguard the world's cultural and natural heritage", the indicator is the total expenditure spent on the conservation of heritage. A strengthened effort means an increased expenditure on protection and safeguarding activities for which geoinformatics technologies are playing important roles, as detailed in Section 2.1. With the further development of geoinformatics, increased employment in heritage conservation is envisaged. For example, a white paper produced by the UK Department for Culture, Media and Sport (DCMS) concluded that investment in the CH sector will drive wider regeneration, job creation, business growth and prosperity (DCMS, 2016). A £30 million Cultural Protection Fund was therefore created to support cultural heritage protection around the world. Moreover, the UNESCO Institute for Statistics is developing a new internationally comparable indicator for the total expenditure per capita every country spends on protecting its natural and cultural heritage in order to monitor the achievement of SDG 11.4.[13].

The indicators for SDG 8.9 emphasise the growth of the proportion of tourism in GDP terms, and the number of jobs in tourism industries. Tourism is an important sector for economic development and job creation. In 2016, the World Travel and Tourism Council (WTTC) reported that the sector directly contributed US$ 2.3 trillion to the global economy and 109 million jobs worldwide. Indirectly, figures amounted to US$ 7.6 trillion and support for 292 million jobs (Turne and Freiermuth, 2017). It is forecast that the direct contribution of tourism to GDP will grow at an average of 3.9% per year over the next ten years. By 2027, travel and tourism will support more than 380 million jobs globally, contributing 23% of new jobs created, and will outperform global economic growth. It is foreseen that more heritage authorities will adopt state-of-the-art geoinformatics and supporting technologies such as 3D printing, AR and VR, as discussed in Sections 2.2 and 3.2, to boost their tourism industries, while simultaneously creating sustainable jobs working in these new technology sectors. Numerous examples of VR tourism from various countries can already be found, such as the Beijing Palace Museum,[14] the Casa Batlló,[15] the Louvre Museum,[16], and even the UK Houses of Parliament.[17]. Studies suggest that with enhanced experience in 3D virtual tourism, customers are more likely to develop destination awareness, and that tourism authorities should develop easy-to-use informative and interactive 3D virtual tourist destinations to facilitate trip planning (Huang et al., 2016, 2013). A technology enhanced tourism industry can bring added value and enjoyment to visitors, manifesting itself in economic growth. New policies and activities can be introduced to take full advantage of technology advancement.

The UNESCO CDIs of heritage sustainability proposes a multi-dimensional framework that analyses different types of public commitments, efforts and results directed towards heritage protection, safeguarding and valorisation (UNESCO, 2014). Geoinformatics can significantly contribute to all three components. Firstly, for component one, 'registrations and inscriptions', remote sensing and laser scanning are widely used to identify and locate hidden or undiscovered heritage (Section 2.1.1). For the second component 'protection, safeguarding and management', geoinformatics can contribute through 3D modelling, monitoring (Section 2.1.2) and community participation (Section 2.2.1). For the last component 'transmission and mobilization of support', web-mapping and visualisation can be employed to raise awareness and facilitate education in an efficient and sustainable manner (Section 2.2.4).

12 https://www.un.org/development/desa/dpad/wp-content/uploads/sites/45/publication/ldc_list.pdf.

13 http://uis.unesco.org/en/topic/sustainable-development-goal-11-4.

14 http://v.dpm.org.cn/.

15 https://www.casabatllo.es/en/virtual-tour.

16 http://www.louvre.fr/en/visites-en-ligne.

17 https://www.parliament.uk/visiting/virtualtour.

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5. Conclusion

The paper is founded on the recognition that culture plays a vital role in sustainable development. CH has been introduced into the sustainable development agenda (UNESCO, 2013a), and is directly referenced in SDGs 8.9 and 11.4. Echoing the ICOMOS action plan 'Cultural heritage and localizing the SDGs' (Yıldırım, 2017), we define the concept of Sustainable Cultural Heritage as the protection, safeguarding and promotion of the tangible (e.g. historic places, monuments, artefacts) and intangible (e.g. customs, practices, crafts, artistic expressions and values, traditions or living expressions) in a manner that does not diminish the socio-economic-environmental processes necessary to maintain human equity, diversity, and prosperity. Sustainable CH is therefore considered as a significant component of sustainable development that incorporates both the protection and safeguarding of tangible and intangible CH, as well as the promotion of tourism that generates jobs and promotes local products.

Different geoinformatics technologies have been applied to CH conservation and promotion. This paper analysed all aspects (Section 2) of CH conservation as well as sustainable tourism promotion, including identification and localisation, 3D reconstruction and documentation, 4D evolution analysis, database management (contributing to SDG 11.4), and public participation, virtual tourism, physical reproduction, onsite and online visualisation (contributing to SDG 8.9). The paper has focussed on how geoinformatics technologies are employed for the various aspects of sustainable conservation and promotion of CH, and demonstrated this through three case studies covering both developed and developing countries and using different geoinformatics technologies.

Geoinformatics, as the art, science and technology that deals with the acquisition, storage, processing production, presentation and dissemination of spatial information, is indubitably contributing to both heritage conservation and sustainable tourism promotion from all manner of different perspectives. It is heavily integrated and growing together with related disciplines, such as computer science, VR, sensor technology, structural engineering, architecture and urban sciences. Geoinformatics, as a part of a multi-disciplinary science and technology, will therefore doubtless continue to serve sustainable CH and sustainable development in general.

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