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Does more mean better? Remote-sensing data for monitoring sustainable redevelopment of a historical granary in Mydlniki, Kraków

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Abstract

The Post-2015 UN Development Agenda includes culture and links the preservation of cultural heritage (CH) to sustainable development. In principle, sustainable redevelopment of CH should preserve historical qualities and ensure the financial profitability of the asset. Still, being a construction process, it has to be under constant change monitoring. Bearing in mind the quality of data achieved by measurement systems, TLS instruments can be used to capture 3D spatial data for cultural heritage. The authors analyse the usefulness of TLS data as the spatial database for the redevelopment and functional reuse of a historical granary. Following measurements on various stages of the redevelopment of the CH asset, TLS data undergo principally simple and rapid analyses (shape analysis, determination of the pace and scope of redevelopment, detection of conservation effort results, HBIM) to improve decision-making capabilities within the project. Contrary to the universal approach, periodic CH redevelopment scanning involves the entire structure, not merely its most valuable heritage components. As a result, not only doesthe remote-sensing data acquisition for monitoring of sustainable redevelopment of cultural heritage record the state of the revitalised building, but it also demonstrates the potential of periodic measurements as the primary source of insight into the heritage asset and the directions and quality of changes it undergoes.

Keywords TLS, Point cloud, Preservation of monument, Cross sections from point cloud, Differential model of point clouds, Unsupervised classification, BIM

Introduction

In the time of universal computerisation, the preservation of cultural heritage (CH) is one of the measures of the economic and intellectual position of the nation [1, 2]. Decision-makers are increasingly interested in the economic potential of cultural heritage, specifically historical monuments [3, 4]. With cultural heritage defined as ‘an asset which embodies, stores or provides cultural value in addition to whatever economic value it may possess’[5], it seems only prudent regarding its protection to readjust its purpose and use, while preserving the material originality and historical value [6]. The universal computerisation of measuring systems has led, among other things, to the increased capturing of good quality 3D data. Therefore, one of good practices in the conservation and valorisation of a heritage structure today should be the application of remote-sensing data acquisition to monitor the preservation of the material originality alongside its historical value.

Sustainable redevelopment of cultural heritage

The interrelation between culture and sustainable development intensified during The International Congress ‘Culture: Key to Sustainable Development’ in Hangzhou

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(China) held from 15 to 17 May 2013. This UNESCO congress was the first meeting in 15 years devoted entirely to the discussion of the role of culture in sustainable development in view of the post-2015 development framework. The introduction of cultural heritage into the Sustainable Development Agenda summarised the congress and set a clear goal: 'culture [should] be included as part of the post-2015 UN development agenda, to be based on heritage, diversity, creativity and the transmission of knowledge and including clear targets and indicators the relate culture to all dimensions of sustainable development' [7]. The sustainable redevelopment of cultural heritage is an effort to restore (or bestow) functionality to cultural heritage assets, which should preserve their historical value and take into account economic considerations related to future asset management [3, 8]. The sustainable development objective in the redevelopment and functional reuseof cultural heritage assets calls for maintaining a balance between economic use and protection. Cultural heritage can be an inherent part of sustainable development only when it provides tangible economic, social, and environmental benefits, making its redevelopment an investment [9, 10] rather than a liability [11]. The monument then becomes a *palimpsest*, for which it is impossible to tell what to preserve and what to let go of [3, 12]. It seems reasonable to monitor changes in a heritage asset during a sustainable redevelopment of cultural heritage to identify a critical line behind which the monument may lose its historical qualities and heritage [3].

Top remote sensing technologies for cultural heritage

New digital technologies made the statutory (international [13, 14], European [15–17], and national [18]) protection and preservation of cultural heritage much more commonplace and widely available. The Charter of Krakow (2000) was a milestone in the application of digital technologies in cultural heritage research (mainly archaeological sites). It transplanted the technological capabilities of the new millennium to the problems of conservation and restoration of built heritage in the spirit of the Charter of Venice (1964) [19, 20]. The London Charter on the Computer-based Visualization of Cultural Heritage (2009) sealed the common access to new technologies for the protection and preservation of cultural heritage [21]. Note that the International Council on Monuments and Sites (ICOMOS) also promotes new technologies (e.g. digital image processing, digital orthophoto production, terrestrial laser scanning, 3D model processing) in cultural heritage protection and preservation [20, 22].

As they revolutionised heritage digitalisation, digital technologies are considered common tools for cultural heritage protection and preservation. Digital technologies modernise the processes of surveying and recording, protection, conservation and reconstruction, and replication and reproduction in heritage digitalisation [23] by accurately transferring real objects into the virtual space [24]. The most popular among them are wide- and close-range remote sensing. Their basic working principle, remote, contactless acquisition of information about an object, is an undisputed advantage for heritage asset digitalisation, especially those heritage components that are hard to reach. On a macro scale, long-range remote sensing, mainly satellite imagery and aerial photogrammetry analysis, helped investigate the condition of the Middle East's cultural heritage during the armed conflicts in Syria and Iraq [25–28]. Moreover, archaeological and cultural studies often use wide-range remote sensing in conjunction with GIS tools to employ digitalisation as a source of insight into past settlements [29], the location of cultural heritage structures [30], or for management of cultural heritage [31]. Whereas on the micro level, the undoubtedly most popular short-range remote sensing tool for historical assets apart from regular digital photogrammetry is Terrestrial Laser Scanning (TLS) [32].

Terrestrial laser scanning for cultural heritage

The terrestrial laser scanner is an active remote sensing system that can acquire data on the shape and surface of the recorded object in real-time as a point cloud [33]. The accuracy of TLS is measured with the quality of the point cloud acquired through scanning defined as the fidelity of reproduction of the object's details, its density, and reduction of noise. The characteristics of the point cloud that define its accuracy depend on systemic and external factors.

The primary instrument attribute that determines the point cloud quality is the resolution defined as the device's ability to detect, differentiate, measure, and record details of an object within the scanner's range and field of view [34]. The basic instrument parameter is the laser spot size. It affects the occurrence and severity of edge effects [35] and co-determines the angular resolution of the system [36]. Other systemic factors include electronic angle measurement mechanisms in scanners and distance measuring mechanisms, the working principle of which affects angular resolution and range resolution. Raw point clouds provide good insight into the quality of the acquired 3D data depending on the type of laser scanner and the sophistication of its algorithms (such as automated noise filters) [34].

The external factors affecting the scanning results standards include the characteristics of the scanned object for the most part. Results of a reflectorless measurement are significantly affected by the object surface's ability to reflect the beam. The albedo of the object hinges on its colour but also on roughness, humidity, and temperature [37]. Its geometric characteristics determine station placement and scanner-object arrangements that offer a good angle of incidence and reduce divergence. An increased normal-surface incidence angle makes the laser spot size larger and reduces laser return intensity [38]. Even though they offer convenient measurements, for example without illumination, terrestrial laser scanners are not insensitive to weather conditions during measurements. Such ambient factors as temperature, atmospheric refraction, and air transparency (fog) degrade the point cloud quality [35].

Cloud quality quantifies the measurement method and results of processing [39]. Properly selected scanning parameters yield a point cloud density suitable for the job, help avoid notorious oversampling, and improve efficiency [40]. Appropriate, conceptual TLS measurement planning is indispensable to reduce3D data registration errors.

Terrestrial laser scanning has become a common practice in cultural heritage digitisation over the last two decades mainly thanks to its technological availability and dense cloud models [41]. Faithful mapping of a monument in a virtual space with a high-resolution and topological accuracy point cloud has become the go-to tool for archiving architectural details [42, 43], historical structures [44, 45], and complexes of built heritage [46, 47]. In addition to cultural heritage recording, TLS data help investigate the monument condition [48–50] and provide a platform for managing and promoting them in the global network through virtual realities [51, 52]. The application of TLS in heritage digitisation exemplifies the potential of the technology, which nevertheless, is not perfect. The huge volume of geomatics data requires a system for sharing, collecting, and storing the information so that its quality and reliability are preserved [53].

Regarding analyses, TLS data of historical assets usually undergo modelling through triangulation, differentiation of 3D data for deformation diagnostics, spectral analysis, and vectorisation into 2D views, but also provide foundations for Historical BIM. The capturing of TLS data provides 3D spatial data that already offer a backup of the CH asset's shape saved as open-exchange 3D data files (ASCII, e57, etc.) [54–56]. A point cloud of good accuracy and relatively short capture time is the starting point for object investigation with automated generation of cross Sects. (40), production of surface meshes by reverse engineering software to reconstruct architectural details [54, 57], or differentiation of the point clouds or meshes. Cloud models cover shape and surface condition (excess moisture, vegetation) through unsupervised classification of the raster representation of laser return intensity [58–60] and provide input for 2D and 3D conservation and architectural documentation for conservation or valorisation of CH.

2D drawings from point clouds are the standard tool still preferred by many architects and construction engineers [61]. The significant resolution of scanning data yields complete architectural and construction inputs both from manual vectorisation of cross sections of point clouds and automated generation of the object's shape. 2D drawings from point clouds are very detailed (up to a point where structural anomalies or defects can be detected) [62, 63], which makes them a good underpinning for any conservation or valorisation effort [61]. Regarding research on the preservation of CH, 2D drawings from point clouds are employed to detect changes in the object by comparing it with past analogue sources [64].

However, 2D drawings from 3D data fail to improve data or project management in conservation or valorisation. The structure planning, design, construction, and use processes where a smart 3D model is first created are controlled using Building Information Modelling (BIM). BIM is applied not only to newly constructed structures but existing ones as well. In such a case, the smart model is usually obtained through point cloud modelling [65]. Although BIM is now regularly used for new projects in Western Europe, its application in the monitoring of the sustainable redevelopment of cultural heritage remains occasional and a domain of research institutions [62]. Regarding the protection and conservation of CH assets, BIM provides effective visualisation and archiving of 3D data but also streamlines future conservation management. Nevertheless, it is a complex, time-consuming task to build a Historical BIM (HBIM), mostly due to the intricacy of historical shapes that need to be modelled [62, 66]. All in all, the technical problems are a matter of time, and the progress of HBIM as a discipline is evident from the constant improvement of HBIM software [67].

Consistency with sustainability principles in the redevelopment of cultural heritage should be monitored with available digital technologies. The paper proposes a concept of 3D monitoring of the redevelopment process of a historic granary with TLS and simple, available point cloud analysis tools. Contrary to the universal approach, the present periodic CH redevelopment scanning involves the entire structure, not merely its most valuable heritage components. The main objective of the study is to demonstrate that periodic TLS data can provide 3D data for *rapid* monument redevelopment analyses through 3D records of consecutive stages of the process and assist the decision-making process regarding construction and framework modifications in the historical structure. In addition to in-process controls, TLS data should be used to manage the structure following the redevelopment and store any changes for generations to come. The presented analyses should identify a new trend in sustainable redevelopment of cultural heritage: a comprehensive, 3D monitoring of redevelopment stages as a suitable tool for assessing the level of preservation of material and cultural originality of the asset.

The authors aim at verifying a hypothesis that comprehensive epoch TLS data of an object are an input for versatile analyses that facilitate the assessment of sustainable redevelopment of a historical site. The objective isto complete a quantitative and qualitative study on point clouds of a historical granary during its redevelopment that would unambiguously and objectively identify the results of the sustainable redevelopment.

The paper is divided into five parts. The introduction presentsbasic insights into the sustainable redevelopment of heritage, the potential of TLS, and increasingly popular quantitative and qualitative analyses of point clouds. Materials and Methods depict the study sites, survey design, and methodology and characterise the four proposed cloud analyses: shape analysis (using orthomaps), analysis of the pace and scope of the redevelopment (using point cloud differentiation), detection of conservation results (by unsupervised classification), and HBIM for commercialisation of the redeveloped CH. The results are presented in four subsections relevant to each analysis. Discussion verifies the results against those by other researchers. The effort is summarised in Conclusions.

Materials and methods

Study sites

Remote-sensing data acquisition for monitoring of sustainable redevelopment of cultural heritage was done for a historical granary in Mydlniki, Kraków, southern Poland (Fig. 1a). The building complex that includes the granary was built in the late nineteenth and early twentieth century as part of a manor farm (Fig. 1b). The place hadbeen a laboratory farm of Jagiellonian University's Agricultural School, part of the Faculty of Philosophy since 1904. Since 1953, it has been part of the University of Agriculture's campus. Before the redevelopment, the granary was part of a complex of three farm buildings: a two-storey granary (A), a single-storey livestock building (B), and a storage building (C) (Fig. 1c). The structure is part of the listed heritage of Kraków.

The intention behind the sustainable redevelopment of the century-old building was to add new functionalities while retaining its historical qualities. The construction project consisted of the redevelopment of the existing spaces to suit the changed function of the building and the addition of internal circulation space on the ground floor and a catering hall. The old foundations were buried, and a cast-in-situ reinforced-concrete raft foundation was installed for the entire building. All floors were removed: barrel vaults, timber-frame floors, and arched floors on steel beams and then replaced with beamless, reinforced-concrete, solid slabs. The brick and stone walls were in a good condition. The redevelopment involved damp insulation and conservation treatments to fill in small cavities and protect against moisture and salt. The roof truss system was dismantled and then restored to the original geometry and external appearance of the roofing but with a modified load-bearing structure adapted to the planned use and ceramic-tile roofing. According to the detailed plans for construction, all dismantling operations should be consistent with conservation guidelines regarding elevations with stone and brick bondings, renders, and decorative wooden planking. Regarding the latter, the removal of planks for construction purposes should include marking for future installation following conservation [69]. The redevelopment yielded a university complex with lecture rooms and classrooms, silent rooms, and catering space with equipment (Fig. 1d).

Survey design

The sustainable redevelopment of the granary lasted from September 2017 to March 2019. The structure was laser-scanned three times during construction works. 3D data were captured in February 2018 (Series I) (Fig. 2a), May 2018 (Series II) (Fig. 2b), and March 2019 (Series III) (Fig. 2c).

The captured data represent the object during floor construction (series I), after roofing and during elevation works (series II), and after the completion of the sustainable redevelopment process before the building was handed over into operation (series III). Series I and II cover the entire exterior of the building and the interior of the storage part. Series III was acquired for the entire exterior and interior of the structure.

Terrestrial laser scanning isperformed with Leica ScanStation P40 (Fig. 2d) at a scanning resolution of 1.5–2 mm / 10 m. The georeferencing of the three series of 3D data isensured through black-and-white targets (control network points) outside the construction site fixed to the elevations of buildings nearby (Fig. 2e). This way, the 3D data from the three series hasa common 3D coordinate system. Apart from the black-and-white targets for georeferencing, the authors use white reference spheres[1] and black-and-white targets as tie points (Fig. 2f).

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[1] Device for stabilising reference spheres on terrain surface protected by registered utility model No. W.126075, creator: Dr Maria Makuch.

Fig. 1 Historical granary in Mydlniki, Kraków: **a** Location on the map of Kraków and Poland; **b** Farm buildings in the former manor farm Mydlniki (late nineteenth and early twentieth century) [68]; **c** View of parts of the historical granary (east elevation); **d** Redeveloped granary (east elevation)

Methodology

The research methodology involves the use of TLS data as the spatial database for the redevelopment and functional reuse of the historical granary. A large-resolution point cloud should be a starting point for expert analyses following post-processing involving registration and manual filtration. Ideally, the analyses and tools should be selected according to the need for the monitoring or verification of the redevelopment process with solutions that are available, quick, and simple. The results should provide feedback on the redevelopment stages compared to plans, the dynamics and progress in construction works, or the quality of conservation of stone, brick, or wood bonding. This approach would provide real-time support for project decision-making with the optimum operations on point clouds.

The research methodology isguided by the assumptions for using TLS as a data source on the sustainable redevelopment of the granary (Table 1).

Acquisition of every series of the TLS data to determine the object's condition followed a survey design, which defined data capturing conditions regarding the scanning scope and the number and locations of stations and tie points. With TLS data captured, the authors register scan stations in Cyclone using only control points and tie points. Thanks to the relative redundancy of the

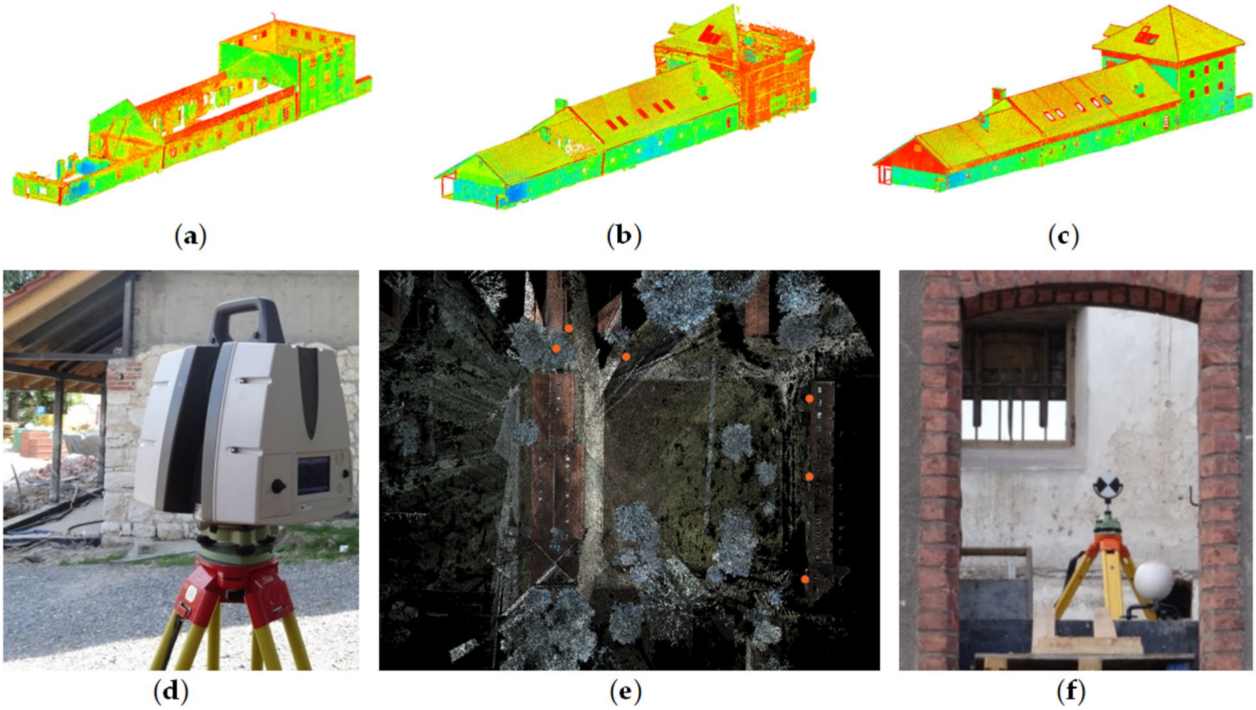

Fig. 2 Terrestrial laser scanning of construction stages. **a** Series I point cloud; **b** Series II point cloud; **c** Series III point cloud; **d** Leica ScanStation P40 during a measurement (series II); **e** Control network points for a common frame of reference for epoch data; **f** Tie points for the measurement

tie points for registration, the authors reject such tie-ins between stations that add to the mean registration error and whose error vector suggests instability on the construction site during scanning. The target registration RMS isat least ± 2 mm. The registration is confirmed a success by an external process control whereby long and cross sections aregenerated from the point cloud for the object's components for which 3D data were acquired from stations of substantial coverage. The sections made of point clouds from several stations exhibit structural continuity, thus demonstrating successful registration. The post-processing of TLS data involves registration and filtration, with the latter determining the reliability of scanning data and optimising in-situ observations and further 3D analyses [70]. According to the literature, 3D object datasets should be *cleaned* at the stage of raw scanning results [71] and further analyses should be free of their influence. However, the authors opt for an arduous but precise and safe manual noise filtration method due to the historical persuasion of the object and 3D data capturing conditions on-site. Manual noise filtration usually removes points resulting from incorrect identification of the object by the laser beam or incorrect scanning range. In practice, it is often employed as the only appropriate filtering method due to alleged excessive indiscrimination demonstrated by filtration algorithms [72]. A registered, filtered, and unified single-series TLS data provide the input for identifying the condition of the object at a specific stage of the granary redevelopment.

The 3D data representing the condition of the object isthe foundation for quantitative and qualitative analyses. Having consulted the matter with construction experts, the authors agreeit is preferable to obtain information to identify the building's shape, determine the pace and scope of redevelopment, assess the quality of conservation of historical wall bondings, and create a BIM (at least for the part intended for commercial purposes). The analysis of the TLS data follows four procedures with as simple as possible point cloud operations.

Shape analysis

The primary qualitative point cloud analysis is shape analysis. Vector architectural and construction documentation from a point cloud is very often used to check the geometric consistency of the structure with the plans after 3D data capturing through arduous *drawing on* the cloud or automated vectorisation. The first method converts spatial data into two dimensions, allowing for a substantial generalisation of architectural details. The other one is burdened by significant uncertainty and often requires manual corrections.

Table 1 Process of employing TLS data as a source of insight into the object's condition

TERRESTRIAL LASER SCANNING	Single-series TLS data as a source of insight into the object's condition	ANALYSIS OF TLS DATA
→ Survey design → Data capturing → Post-processing		→ Shape analysis → Determination of the pace and scope of the redevelopment → Detection of conservation results → HBIM

It suffices to calibrate the cloud section generated automatically from the 3D data in a 2D space against the design to analyse the shape of the constructed object and assess the consistency of the point-cloud data with technical assumptions. The authors compare data from survey measurements with data in the design plans to evaluate the consistency of the redevelopment with the plans at each stage. Theygenerate orthoplans at the height of 1.30 m from point clouds captured during the three surveys. The plans from the point clouds are a faithful representation of the building's shape. They arethen used as raster plans for arrangement drawings of the building. The raster plans arecalibrated with the arrangement drawings with CAD software. Then, the authors assess the consistency of the redevelopment lines (demolition and expansions) with the construction plans. The same point cloud *slicing* procedure isemployed to analyse the redevelopment of architectural details.

Analysis of the pace and scope of the redevelopment

The pace and scope of redevelopment arecalculated with quantitative point cloud analyses that differentiate the clouds. In land surveying, point cloud differentiation is used mainly to identify displacement and deformations, but it can also be employed to identify architectural changes. Point clouds from epochs II–I and III–I arejuxtaposed to determine the pace of the redevelopment and the percentage of the object that isstill historical following the redevelopment. The analysis focuses on the storage part of the building, which was demolished to the greatest degree during the redevelopment. The first stage isto *clip* the storage data from the entire point clouds from three scanning series. As opposed to displacement and deformation analyses, juxtaposing point clouds for a survey and architectural investigation can be performed on thinned data to demonstrate the degree of overlap of the 3D data without slowing the computation process down. Therefore, the same resolution of 10 cm isset for all point clouds to streamline the computation process. It isassumed that changes in point clouds within 10 cm arenot indicative of alterations in the object but of restoration (renders, lime coat, etc.). The points aredifferentiated in CloudCompare using the C2C (Cloud to Cloud Distance) algorithm.

C2C computes distances between two point clouds, the compared cloud and reference cloud. The distances are calculated on the compared cloud with regard to the reference cloud. The software computes the distance between each point in the two clouds. The results of the differentiation are shown on the compared cloud as a colour. The main parameters of the computations are:

- *octree level*—the cloud is divided into eights for computation, which speeds up the process;
- *max. distance*—the maximum distance between two clouds. The farther the points, the longer the computation distance. Point searching is restricted to a certain value to speed up computations;
- *signed distance*—values below which the differentiation does not identify linear differences between datasets;
- *flip normals*—normals to the point cloud are or are not taken into consideration;
- *multi-threaded*—the user decides whether all CPU threads should be used;
- *split X, Y, and Z components*—components of the vector of incidence [73].

Detection of conservation results

Terrestrial laser scanning provides research material to analyse the quality of historical asset surface conservation using radiometry. It is because apart from directions and distances necessary to compute 3D coordinates of points, the terrestrial laser scanner records laser return intensity values. Return intensity depends on the physical characteristics of the reflecting surface, its material, colour, roughness, dampness, or contaminants, such as organisms on the surface [74].

The return signal intensity isinvestigated through unsupervised classification of surface images. The images aregenerated from cloud data captured in line with certain assumptions. Scanning stations for each series aresituated in the same locations as far as possible (the distance between the scanner and the object and the incoming beam incidence angle to the object aresimilar). The surface for which the rasters aregenerated from point clouds is scanned with the same instrument and there isno momentary dampening during scanning. As these assumptions aresatisfied, the temporal changes in the surfaces canbe assessed accurately [74, 75]. Even though rasters that do not satisfy these assumptions could also be used in qualitative analyses of the surface with unsupervised classification, the process would first require arduous data filtration that would normalise them regarding these conditions.

The unsupervised classification of the surface images employsthe Fuzzy K-Means procedure. It is one of the most effective unsupervised classification algorithms according to the literature [75]. Unsupervised classification with Fuzzy K-Means groups pixels into a set number of clusters, which clarifies the analysis of the image scenes of the same characteristics (texture, colour, etc.) and the same reflectivity. Fuzzy K-Means minimises the squared distance between feature values of two points that reside in the same cluster. The Fuzzy K-Means algorithm determines the centroid of each cluster with the minimum of a sum-of-squares cost function (Eq. 1) using coordinate descent.

$$J_q(U,V)=\sum_{j=1}^{N}\sum_{i=1}^{K}\left(u_{ij}\right)^q d^2\left(X_j,V_i\right)K\leq N \tag{1}$$

where:

q any real number greater than 1 that is the weight exponent for u_{ij} and controls the fuzzing of each cluster,

U the division matrix $N\times K$, where N is the number of data points and K is the number of clusters,

V the set of objects in the same object domain,

X_j the j-dimensional feature vector,

V_i the centroid of the i-th cluster,

u_{ij} the degree of membership of X_j to the i-th cluster,

$d^2\left(X_j,V_i\right)$ the distance from X_j to V_i.

Fuzzy partitioning is realised through iterative solving of the cost function (Eq. 1). The solution is achieved through constant approximating the degree of membership of X_j to the i-th cluster and determining the centroid of the i-th cluster with the equations specified below (Eq. 2, Eq. 3):

$$u_{ij}=\frac{\left(\frac{1}{d^2(X_j,V_i)}\right)^{\frac{1}{(q-1)}}}{\sum_{k=1}^{K}\left(\frac{1}{d^2(X_j,V_i)}\right)^{\frac{1}{(q-1)}}} \tag{2}$$

$$\widehat{V_i}=\frac{\sum_{j=1}^{N}\left(u_{ij}\right)^q X_j}{\sum_{j=1}^{N}\left(u_{ij}\right)^q} \tag{3}$$

The iteration is terminated when the ε end criterion achieves values between $(0,1)$ [75]. The conditional solution of the function (Eq. 1) in the Fuzzy K-Means algorithm yields particularly good classification results for pixels between cluster sites [74].

The authors generate orthomaps of the north and west elevations from consecutive scanning series that represent the laser return intensity spectrum as grayscale to detect the results of conservation of limestone, wooden, and brick bondings of the CH. Next, the authors perform an unsupervised classification of the laser return using the Fuzzy K-Means algorithm in CATALYST Professional. The unsupervised classification of rasters of the elevation surface with Fuzzy K-Means involves 16 iterations with 5 clusters of pixels. The classification processes rasters of images where the intensity is expressed as grayscale. The number of pixel clusters [5] isdetermined empirically by trials to classify pixels to a decreasing number of classes so that clusters represent surfaces with the same physical characteristics. The correctness of coating and cluster identification isconsulted with the relevant heritage conservation officer.

HBIM for commercialisation of the redeveloped CH

The 3D data for the historical granary areused to develop a BIM for the commercial part of the building. The purpose of the BIM for the storage building (see Fig. 1c, part C) isto aid future asset management. In line with the assumptions of the sustainable redevelopment of cultural heritage, the storage isintended to be leased for catering services. The availability of BIM isintended as a benefit for the future tenant to help them manage the facility.

The BIM isbuilt in Revit by Autodesk. The software offers smart design, creation, and management of structures and infrastructure and planning of the project implementation process based on an interactive 3D model. Parametric object-oriented modelling of the storage building involves the part of the structure represented by the point cloud from series III. A 5-cm density point cloud isgenerated for this purpose. This (commonly used) resolution of the cloud model retains the shape of the construction components and optimises the cloud in terms of file size.

Results

TLS data acquisition and post-processing

TLS data acquisition yields cloud models of the object from scanning stations (series I—18 exterior stations,

Table 2 Results of TLS data registration

	Series I	Series II	Series III
MAE [m]	0.001	0.001	0.001
RMS [m]	0.002	0.001	0.002

series II—12 exterior stations, series III—16 exterior stations and 70 interior stations) with at least 4 overlapping tie points between each adjacent one.

TLS data post-processing (registration and filtration) isdone in Leica Cyclone. The authors assess the accuracy of the conversion from the control system and coordinate systems of the registered point clouds with MAE (Mean Absolute Error). The RMS (Root Mean Square) or the standard deviation between reference points of relevant stations describe the accuracy of elementary transformation parameters. The registration of the point clouds for each series yields 3D research material of registration accuracy below 0.001 MAE (Table 2). Data registration accuracy of ±1 mm is the absolute TLS criterion in shape analysis [72]. With manual data filtration, the authors extract a noise-free cloud model.

Results of sustainable redevelopment monitoring with TLS data

The result of shape analysis

Results of the assessment of redevelopment consistency with the plans (Fig. 3) unambiguously demonstrate that the redevelopment followed the plans. Differences in the structure's parameters regarding the height, length, and width do not exceed the acceptable deviations for construction and installation works specified in design plans and specifications (2% [76]).

An investigation of the architectural details (wall cavities) using the point cloud *slicing* method also demonstrates absolute conformity with conservation

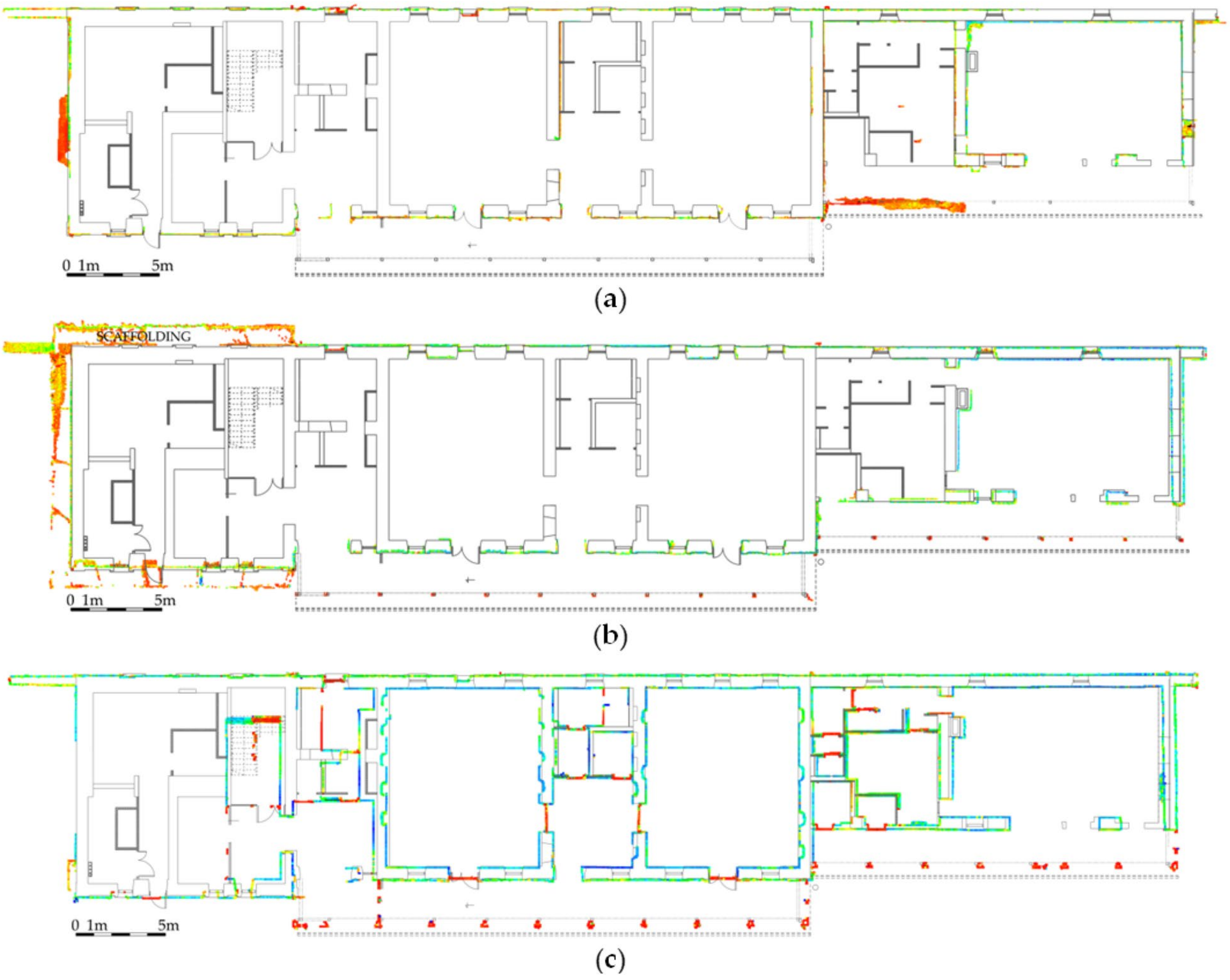

Fig. 3 Granary shape analysis results: **a** Series I; **b** Series II; **c** Series III

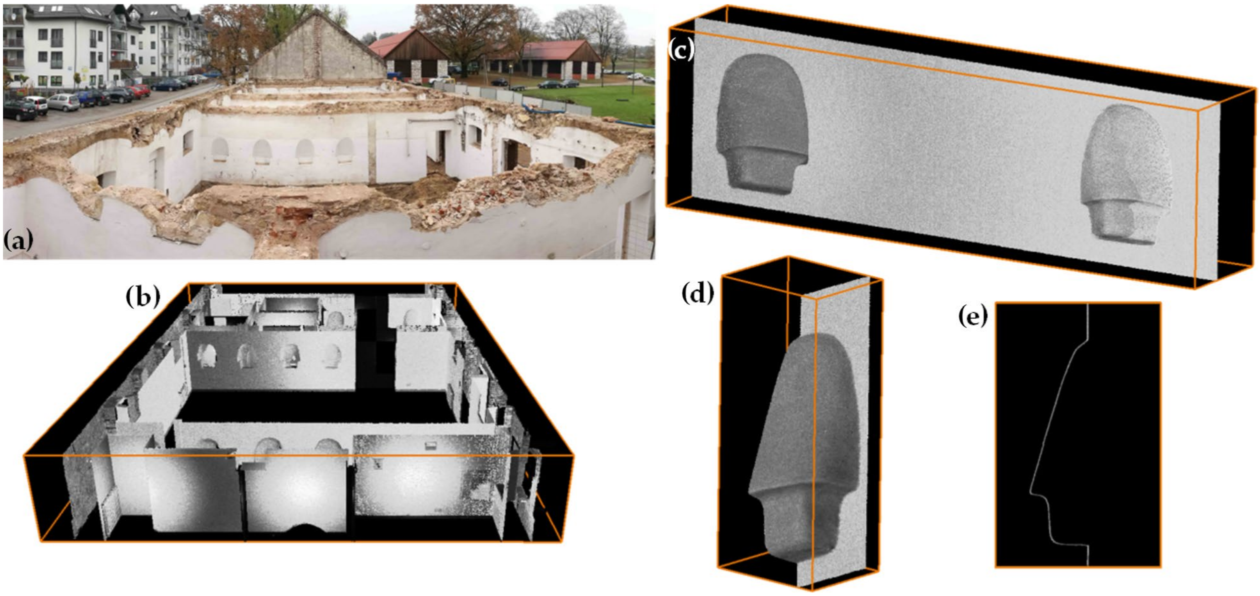

Fig. 4 The shape of wall cavities using cloud *slicing*: **a** a photograph of the details during demolition in February 2018; **b** effects of wall cavity scanning in March 2019; **c** wall cavity point cloud; **d** cavity shape in cloud space; **e** long section of a cavity using cloud *slicing*

specifications. The features were only coated with new plaster. The original irregular shapes arepreserved (Fig. 4). Shape analysis during Series I and II scanning provides data to control demolitions and preservation of original wall structures with characteristic cavities that are valuable cultural heritage typical of old Galician farm buildings. Moreover, results of shape analyses of the original walls areconsistent with the redevelopment premises to preserve the original and continuous fabric and complement it with a reinforced concrete structure with new reinforced concrete floor slabs.

The shape analysis method employed here provides sufficient 3D data accuracy for rapid verification of construction works. A point cloud combined with design drawings helps verify whether construction works proceed as planned relatively easily and quickly compared to point cloud vectorisation. Similarly to cloud vectorisation into 2D often proposed in the literature [62, 63], rasters from clouds can detect structural anomalies and defects. Apart from the generation of the orthoplan and its calibration to the design plan, the proposed approach does not require extensive analyses contrary to popular vectorisation [62–64], while preserving the crux of the survey, which is to provide means for redevelopment control. It is of significance on a construction site where time is usually of the essence. This approach has certain limits compared to vectorisation [61]; it must not be used in engineering or architectural documents.

The result of analysis of the pace and scope of the redevelopment

The analysis of the construction pace with the C2C algorithm in CloudCompare yields differential point cloud models. The visualisations of the differentiations in epochs II–I and III–I present new, recently built parts of the storage building juxtaposed with the original situation (Fig. 5). Grey parts are those that appear both in the compared and reference cloud, the preserved old components of the structure. The distance criterion for these parts is ± 10 cm. The other colour areas result from the alterations under the sustainable redevelopment of cultural heritage.

The authors calculate the percentage of the newly built parts in the entire structure with numerical data for the point clouds (the number of points in each cloud). In May 2018, during the second survey, new parts of the building amounted to 67.7% of the entire structure (the preserved historical part constituted 32.3%). The new parts total 77.0% of the structure leaving 23.0% of it as the preserved historical part following the third, as-built, survey. Differentiation of point clouds to determine the pace and scope of redevelopment is a tool for direct monitoring of the sustainability of interventions. Thanks to 3D data differential models that identify the percentage of intersections of cloud data from consecutive epoch surveys, the authors quantified the part of the cultural heritage asset that was preserved and new additions.This

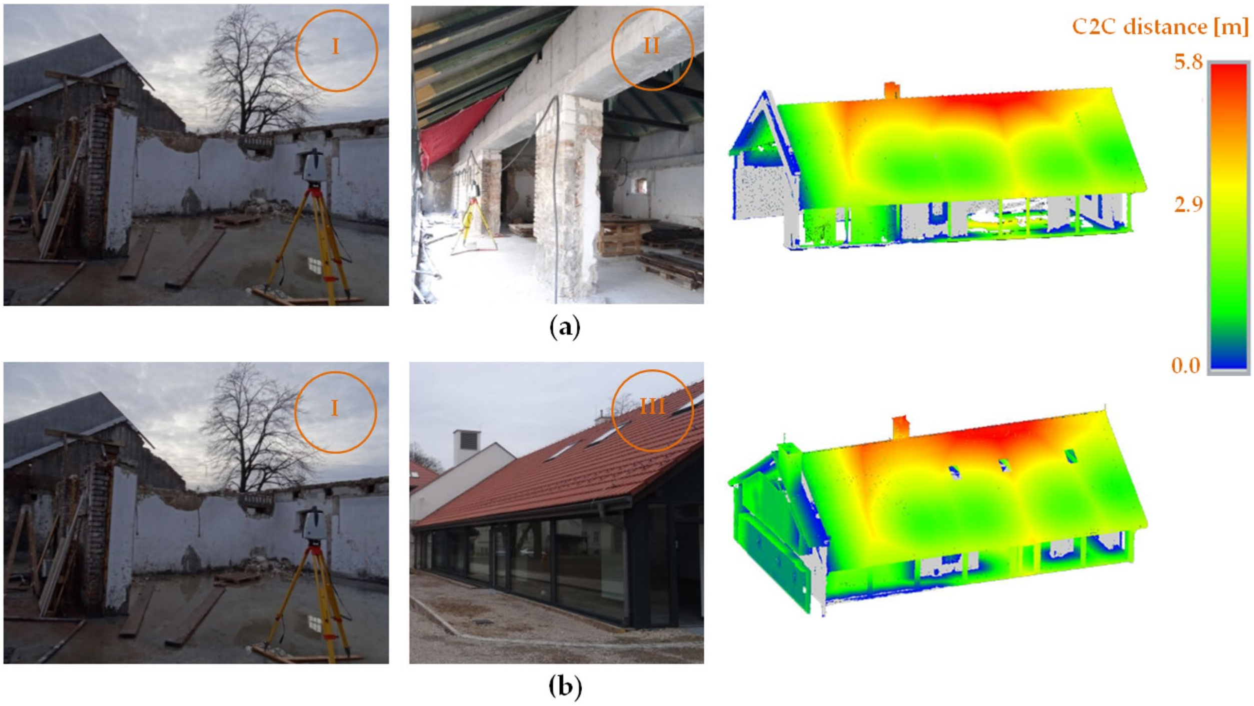

Fig. 5 Results for the pace and scope of the redevelopment: **a** Epoch II–I; **b** Epoch III–I

degreeof *palimpsest* preservation conforms to the conservation requirements in redevelopment documentation of 20% [69].

The way epoch point cloud differentiation tools areused here to analyse the pace and scope of CH redevelopment is a reversed C2C algorithm approach. Spatial data differentiation procedures, which are amply discussed in the literature and popular in surveying practice, are aimed at identifying changes in objects over time due to external factors (such as displacements or deformations) [75]. Researchers globally promote the micro-C2C approach to historical granaries to determine the extent to which restored monuments (bas-reliefs, sculptures) overlap with the original [77]. C2C is just as useful for CH redevelopment pace and scope analysis as it is for smaller objects, but it requires 3D data thinning as opposed to the classic approach.

The result of detection of conservation effect

Unsupervised classification of the orthomap of the north elevation surface identified conservation effort results in five classes for limestone bondings and wooden planking (Fig. 6). The classification generalised the elevation image into areas representing: Cluster 1—background, Cluster 2—limestone, Cluster 3—masonry, Cluster 4—wood and metal joinery, Cluster 5—any metal roof fixtures (Fig. 6). Wood and metal joinery areclassified as one cluster due to very similar reflectivity values [75, 78]. Any signs of pathological changes, dirt, and minor vegetation were successfully removed from the elevation (Fig. 6C, Series I). Door and window openings were repaired with materials imitating historical surfaces (Fig. 6C, Series II). Missing bonds were filled in, and elevation colours were made more uniform (Fig. 6c, Series III). The unsupervised classification evidently demonstrates uniform properties of the limestone wall and wooden planking surfaces in the third series, which is indicative of proper renovation of the north elevation.

The same unsupervised classification procedure isapplied to the west wall of the structure, which needed to be dried as part of the CH redevelopment. Results of the wall injections are reproduced in the classification results: damp and salt patches on the west wall expressed as pixel Cluster 4 in Series I (Fig. 7c, Series I) were gradually removed (Fig. 7c, Series II and III).

The results of the conservation effort aresuccessfully verified using a radiometric approach without specialist investigation by CH redevelopment and renovation experts through unsupervised classification of rasters representing laser return intensity values. Although it is quick and objective, such an approach to conservation monitoring has to be interpreted by CH redevelopment experts who can confirm the identification of individual clusters with the relevant part of the object they represent. Nevertheless, this type of collaboration is much better than visual and manual assessment. Still, even though

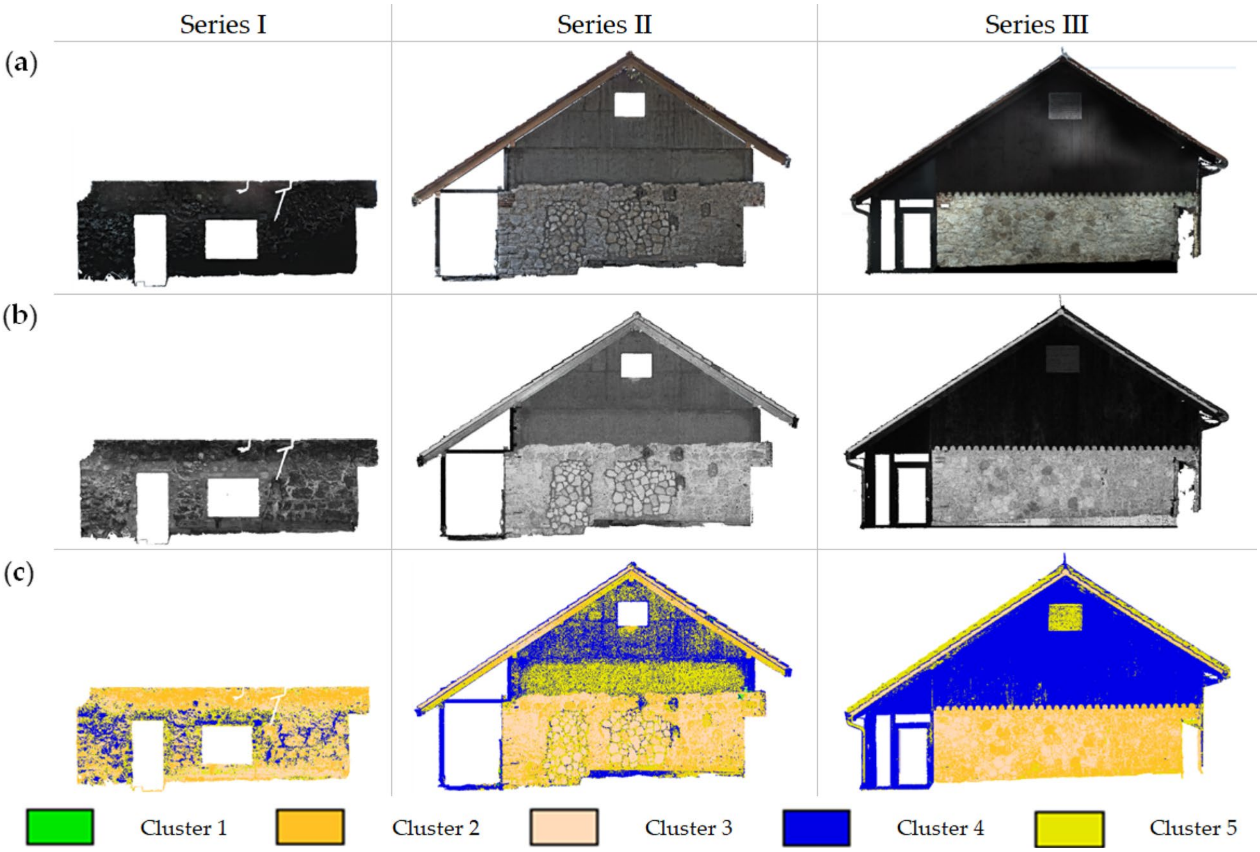

Fig. 6 Raster representation of the north elevation surface point cloud: **a** RGB; **b** intensity as greyscale; **c** following Fuzzy K-Means unsupervised classification

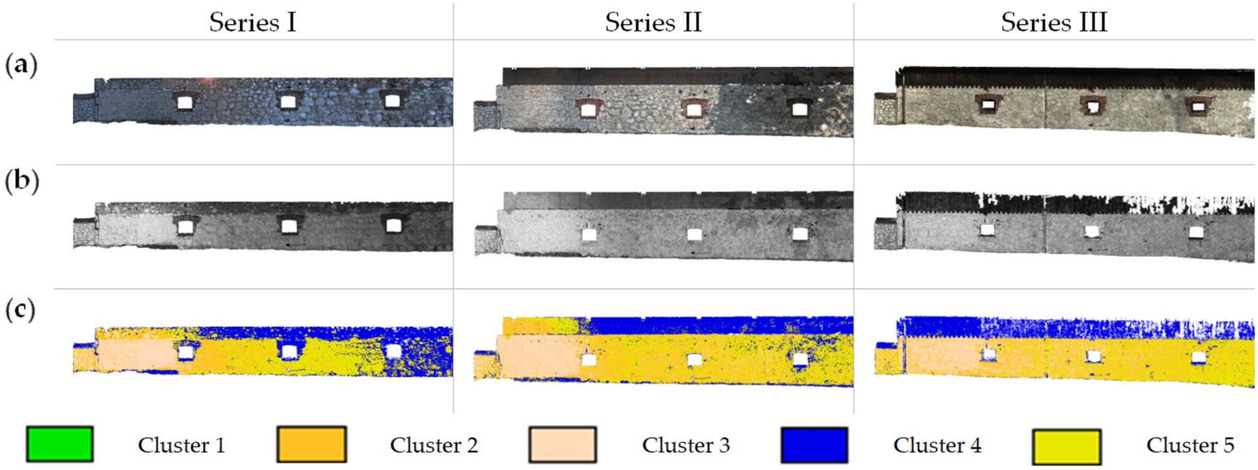

Fig. 7 Raster representation of the west elevation surface point cloud: **a** RGB; **b** intensity as greyscale; **c** following Fuzzy K-Means unsupervised classification

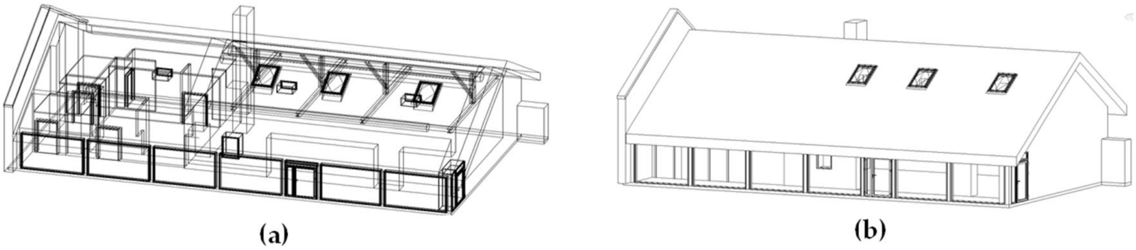

Fig. 8 BIM of the storage building **a** wireframe model view; **b** 3D model view

research organisations seem to appreciate the method [60, 75], it is far from being counted among classic detection solutions.

Conservation effort detection with the radiometric approach can also assess the uniformity of elevation conservation assumptions. The preservation of the stone and brick bonding or wooden planking typical of nineteenth and twentieth century farm buildings from the Kraków area and their homogeneity are visible in uniform clusters from unsupervised classification of a raster representation of the object in Series III. The classification facilitates monitoring of the sustainability of the elevation's authenticity as the direct quantifier of its times.

The results of HBIM generationfor commercialisation of the redeveloped CH

Parametric object-oriented modelling inherently preserves the orthogonal properties of the structure. Old buildings often fail to satisfy this prerequisite, calling for generalisation during modelling. The modelling process focuses on delivering an orthogonal model of the object regarding the relative positions of walls, floors, ceilings etc. even at the expense of data generalisation. The degree of the model's deviation from the point cloud should be specified when standards for the job are set. As no such standard was defined, the authors strive to achieve model-cloud compatibility equal to the resolution of the point cloud used in the modelling (±5 cm). Consecutive components of the structure aremodelled by implementing the object in the software space and editing it, if necessary. The authors import object families from generally available online resources (www.revitcity.pl, www.bimobject.com) to model door and window joinery and the ventilation system.

The BIM of the storage part of the granary (Series III point cloud, Fig. 8) istested for coherence with clash detection tools. The authors then verify the correctness of the model architectural component embedding in the point cloud. The BIM of the storage structure based on the point cloud conforms to the accuracy of±5 cm as per the standard. The largest, marginal model deviations from the point cloud arelocated in bearing walls and caused by the age of the building. The results of the modelling arearchived as open.ifc files to be shared with the future building administrator.

The results are consistent with experts' views that HBIM has significant potential because it describes a building's shape and stores data on the condition of materials, library of materials, and architectural documentation [79]. The parametric object-oriented approach to the CH documentation process calls for significant generalisation, mostly regarding orthogonal conditions, which was confirmed by research from Padua [80]. In their work, these authors discussed limitations to parametric modelling of such architectural details as columns, openings, cavities, or belt course mouldings, which were not reflected in the analysis due to how the redeveloped object was modelled. Regardless of its technical limitations, researchers who use HBIM agree with the authors that data provided in HBIM facilitate proper planning of maintenance, conservation, and condition monitoring [79, 81]. BIM of a heritage site should eventually be the primary basis for asset management and better preservation of the cultural heritage it conveys through, for example, repairs with materials listed in the database for the granary's BIM typical of this specific site. Moreover, an HBIM is a basic tool for managing the object's use in line with cultural values by using the infrastructure included in the model that reflects the actual structure and avoiding modifying it or redeveloping the heritage.

Discussion

The research on point clouds of the heritage site confirms the hypothesis that comprehensive epoch TLS data of an object are an input for versatile analyses that facilitate the assessment of sustainable redevelopment of a historical site. The primary insight into the potential of the presented analyses is their versatility and complementary character. The above-mentioned four methodological approaches to the investigation of point clouds of objects under redevelopment and right after works are completed provides information on the quality and scope of the works and donot yield redundant results.

The proposed shape analysis method involving generating an orthoplan (floor plan, cross-section, and details) and its calibration against a technical drawing offers satisfactory analytical accuracy relative to commonly used vectorisation (for example, by [62]), means to verify the as-is redevelopment against design plans, and assessment of the preservation of culturally valuable components of the object. The use of an orthoplan to analyse shapes comes with a significant technological advantage over time-consuming vectorisation while ensuring the same level of shape assessment. However, it yields to vectorisation in that it cannot be used as a technical drawing for design. The potential of orthoplans from point clouds was appreciated by Xiao et al. [82] in their work on 3D data acquisition by TLS for the protection of historical buildings. Orthoplans and ortho-images from TLS are becoming more popular among researchers of TLS in HBIM [83].

The point cloud differentiation analysis of the pace and scope of redevelopment unambiguously identifies the original part of the redeveloped structure. Point cloud differentiation quantifies and graphically represents the preserved part in the new, redeveloped palimpsest. Point cloud differential analysis is a common method with which researchers detect micro-level changes, such as with the Okotoks Erratic— 'Big Rock' historical site [84] or changes in the remains of the Batavia shipwreck identified in point clouds from images before recovery and those generated through subsequent museum scans [85]. C2C detection is common and versatile, alas rarely employed on a macro level. The proposed method for investigating the pace of redevelopment reverses the common approach: it compares macro point clouds, which requires data thinning.

The unsupervised classification of orthoplans from point clouds of restored elevations provides a clear-cut and objective assessment of the quality of construction, drying, and conservation works. Until now, unsupervised classification of point-cloud orthoplans was employed globally mainly for damage detection of historical buildings [58]. Although research organisations tend to value this approach more often [60, 75], it is yet to be counted among classic detection methods. It is partially because, being a novel way of evaluating conservation effort, it still needs to be interpreted by CH redevelopment experts to confirm the correct identification of clusters with the parts of the structure they represent.

A CH BIM from scan data is the *sine qua non* of effective object management, regrettably still employed mostly by research and academic institutions [62, 79, 83, 86]. The authors had to synergise multiple sources of data: scan data, photographs, and the object's documentation to create the BIM of the historical granary to streamline its management. This way, they created a library of parametric objects typical of the specific case study with which the modelling was completed. The modelling process suggests a conclusion that it is the parametric object library building that is of paramount importance in HBIM creation. These conclusions regarding HBIM creation are consistent with findings by researchers who developed models of historical objects in Jeddah, Saudi Arabia [81] or Porta Savonarola in Padua [80].

Conclusions

Sustainable redevelopment of cultural heritage requires constant monitoring of changes in the object to preserve its heritage. The analyses facilitated generalised conclusions that characterise the potential and importance of remote-sensing data in CH monitoring:

1. Consistency of the scope and character of the redevelopment with the design could be verified in real-time on the construction site with point cloud processing tools by juxtaposing cloud slices with the design.
2. The degree of changes (such as demolitions) in a historical structure and the pace of its redevelopment can be determined with point cloud differentiation algorithms with sufficiently thinned 3D point data.
3. Classification of the laser return intensity value successfully demonstrate the results of heritage surface conservation on rasters with no manual analyses by restoration experts.
4. HBIM significantly helps with the preservation of data of materials used during the sustainable redevelopment of CH, design documents, shape, planning and carrying out repairs, overhauls, or conservation of the structure, and virtual tours of its interior and exterior.

Periodic laser scanning of CH is a robust method for redevelopment monitoring. Cloud data provide beyond any doubt comprehensive insight into the construction progress regarding the shape and the radiometric approach. The cloud data analyses demonstrate the potential of scanning objects under redevelopment not only in construction works monitoring, but also, or rather mainly, in CH protection. The palette of cloud data analyses is extensive and growing. Therefore, TLS data capturing is a reasonable way to acquire a spatial database for the redevelopment and functional reuseof historical structures.

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Availability of data and materials
The datasets used and/or analysed in the study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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