Methodology of spatial modelling and visualisation of remains of the fortified Lusatian settlement in Biskupin based on archival data

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Abstract: The fortified settlement in Biskupin, Poland, is a widely known example of a prehistoric Lusatian fortified settlement in which well-preserved remains were discovered in 1934. During archaeological excavations from 1934 to 1974, extensive documentation was acquired, including drawings and photographs. However, during the II World War, its significant part was lost, and consequently, the documentation available today is incomplete, usually lacking information about the relative vertical position of the remains, which is crucial for chronological and functional analyses. This work presents a methodology for generating 3D models and visualizations based on the aforementioned archival documentation. For this purpose, the “general-to-specific” approach was applied, exploiting four methods varying in accuracy and level of detail: Structure-from-Motion together with Multi-View Stereo, the variation of Shape-from-Shading technique and 3D modelling based on single photographs and drawings. The article covers the advantages and limitations of each method and evaluates their applicability in archaeological analyses. This work is related to the research presented in [1–3]. However, the objective of this research is a thorough analysis of mentioned 3D documentation methods and their evaluation with regard to archaeological analyses. Furthermore, unlike in [1], this study concerns the use of terrestrial and low-altitude archival images for the documentation of separate artefacts.

Keywords: 3D modelling, 3D reconstruction, archival data, archaeological analyses, fortified settlement, Biskupin, cultural heritage

1. Introduction
An excavation aims to uncover information about past populations based on preserved artefacts and structures [4]. Excavation works are indeed a destructive process, during which artefacts are isolated from their context while structures are destroyed and for this reason, in situ documentation plays a significant role in further understanding and interpretation process. Graphical documentation is the most efficient way of explaining and disseminating the complexity of archaeological evidence and the contexts and relations between objects [5].
Keeping these facts in mind, archaeologists try to acquire the most complete and informative documentation possible, applying various techniques such as terrestrial laser scanning (TLS) or low-altitude and close-range photogrammetry. Besides traditional drawn documentation containing visual information and interpretation, photographic documentation has quickly gained popularity in this field, not only during excavation works but also at the earlier stage of archaeological prospection [6–8]. More and more datasets containing photographic documentation are published online by scientific institutions, which carry out excavations, or within the framework of numerous projects, to list a few: American Center of Oriental Research Photo Archive [9], Aerial Photographic Archive for Archaeology in the Middle East [10], NPAPH [11]. The University of Princeton published archaeological archives containing thousands of photographs, drawings, journals and other documentation acquired during over 100 years of expeditions [12]. Thanks to modern digital technologies, archival documentation can be given a second life, which often leads to new discoveries, filling the blanks in today’s knowledge and verifying hypotheses.

Notably, archival drawn documentation (plans, cross-sections), sketches and descriptions of complex structures were not intended for their future spatial reconstruction at the time of their preparation. For this reason, it is necessary to apply technologies allowing to overcome the limitations of such documentation [13]. Depending on the research goals, archival documentation of complex objects or building structures can be a starting point for applying more advanced technologies using 2D and 3D data, of which the preferable form is a 3D Geographic Information System [14]. This article covers four methods for the generation of metric and non-metric 3D documentation of wooden remains based on plans and cross-sections. Their unquestionable advantages are versatility and the possibility to recreate topological relations between the remains and, thus, the analysis and verification of hypotheses regarding their chronology and functions.

This work aims to present a methodology of creating 3D models and 3D visualizations based on archival documentation acquired during the excavations between 1934-43 and 1946-1974, as well as using their contemporary derivatives. For this purpose, the “general-to-specific” approach was applied, exploiting four methods varying in accuracy and level of detail: Structure-from-Motion together with Multi-View Stereo, the variation of Shape-from-Shading technique and 3D modelling based on single photographs and vectorised historic drawn documentation. The last technique, as mentioned above, involved generating 3D visualisations based on profiles and cross-sections; in this case, archival photographs and excavation notes played a significant role. In order to integrate these multisource data, AutoCAD and BricsCAD software were used.

For the reasons given above, this work is divided into parts, each dedicated to each method, presenting the methodology, analysing factors influencing the quality of the final products and evaluating their applicability in further archaeological research. Section 1 provides the background for this study: brief characteristics of the most common modern techniques applied nowadays for on-site documentation in archaeology (Section 1.1) contrast to research involving 3D reconstruction of cultural heritage based on historical data using contemporary digital technologies (Section 1.2). Section 1.3 contains an overview of methods of single-view 3D reconstruction. In Section 1.4 the investigated Site 4 in Biskupin is characterised. Section 2 contains a detailed description of the used source data and performed experiments. The results are presented in Section 3, in which the accuracy and overall quality of the resulting products are also investigated. In Section 4 the applicability of acquired results is discussed with regard to further archaeological analyses.

1.1 Digital photogrammetry as a valuable measurement technique supporting archaeological research

In the past two decades, modern measuring methods like photogrammetry and terrestrial laser scanning (TLS) have gradually gained popularity in the cultural heritage documentation field [15–18]. Since both techniques mentioned above allow fast acquisition of accurate and
dense three-dimensional data, they have become a valuable tool during archaeological works and analyses, supplementing traditional drawn documentation acquired on-site and enhancing the analysis experience.

Photogrammetry is a passive measurement technique that allows the reconstruction of a 3D shape of an object or a surface of a certain area based on a set of overlapping images taken from different viewpoints and reference data, providing the proper scale for the model together with its location in space. Nowadays, close-range photogrammetry intensively exploits algorithms derived from Computer Vision. The most common approach uses Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms to retrieve the relative image orientation through a mathematical model [19–21] and, subsequently, to calculate a dense point cloud, which serves as a base for the creation of a 3D model or further analyses. Relative image orientation is calculated via bundle adjustment based on correspondences detected on images [22,23]. Simultaneously, the process of self-calibration is performed, enabling the use of non-metric, uncalibrated cameras. The addition of reference ground-truth data allows for calculating the exterior orientation of images, which is crucial for accurate 3D shape reconstruction.

Considering the documentation of archaeological excavation, which is a rapidly evolving environment, close-range photogrammetry is a very convenient measurement technique appreciated for its high accuracy, fast data acquisition, high availability, mobility and low cost [24–26]. Nevertheless, as the image orientation exploits image correspondences, it can be disrupted by factors affecting the detection and identification of tie points. For this reason, photogrammetry's accuracy and applicability decrease in plain or repetitive textures and on specular and openwork objects [27–30]. Such scene characteristics result in errors also at the stage of dense point cloud generation [31,32]. Thus, in recent works, the possible applications of deep learning methods to enhance the photogrammetric pipeline have been investigated [33].

The scope of applications for close-range photogrammetry in archaeology is very wide, starting from low-altitude aerial imagery acquired by a UAV, which can be used for on-site documentation of archaeological sites [34–37], the documentation of archaeological sites and artefacts [38–40], underwater archaeology [41,42], ending with macro photography used for 3D modelling of very small artefacts [43,44]. Photogrammetric products such as orthophotomaps and orthoimages can later serve as components of Geographic Information Systems [41,45]. Moreover, 3D models can be used for further research and as an integral part of site documentation used at the interpretation stage [24].

1.2 3D modelling based on archival data and multitemporal data integration

3D models, orthoimages and other photogrammetric products gradually become standard components of archaeological documentation, supplementing the traditional documentation acquired on-site and enhancing analyses and material interpretation off-site. However, the interest of researchers reaches further, and contemporary digital technologies allow not only to record the current state of the objects but also to reconstruct the shape of monuments and sites, which today do not exist in their original form. Thanks to the increasing availability of historical materials and the combined use of archival data and state-of-the-art digital technologies, it is possible.

Starting from historical imagery, its use in archaeology and cultural heritage is quite wide. Aerial imagery acquired in the past is commonly used for landscape modelling, which can be further used in GIS landscape analyses [46–48] and multitemporal visualisations [49]. Grussenmeyer and Yasmine [50] used archival aerial imagery to determine the location of buried archaeological structures, which was a preparatory step for following excavation works. Furthermore, photographs taken in the past are frequently used for the reconstruction of architectural heritage as they allow to make assumptions regarding objects geometry and set additional constraints supporting the reconstruction [51–53].
Although the potential of archival imagery is significant, many factors impede its use. Firstly, in contrast to data acquired today, it takes much longer to collect sufficient source material as the data relating to the same object are often dispersed – stored in numerous archives, museums and private collections. In some cases, separate research must be conducted to find appropriate data for further processing.

Despite the fact that modern image processing approaches exploiting computer vision algorithms like SFM and MVS can be successfully applied not only to contemporary digital images but also to historic datasets, it is noteworthy that in most cases, a historical dataset cannot be easily adapted to modern methodologies. Frequent obstacles are the insufficient number of images, insufficient overlap or inappropriate geometry of the image network, impeding the creation of a correct geometric model [51]. Archival images are also often heterogeneous – differing in resolution, scale and lightning conditions [47], which may affect the accuracy of results and the final visual effect.

The geometric quality of source imagery is crucial in determining the final accuracy acquired by SFM algorithms. Non-optimal conditions can cause geometric distortions affecting archival images during data acquisition and the consequences resulting from the use of analogue technology, i.e. the degradation of the source media or the enlargement process [54]. Moreover, analogue images have to be scanned, which, depending on the scanner quality, may lead to significant distortions or even failure of image processing algorithms [54].

Another notable matter is camera calibration. In the case of archival imagery, the calibration data are often unavailable, and so is the camera used for image acquisition. Of course, image processing algorithms implemented in currently used software packages allow the estimation of unknown camera parameters in self-calibration. However, to estimate these parameters correctly, a proper geometry of image network must be kept [55–57] and this condition is often not fulfilled in archival image collections. There are also techniques allowing the estimation of camera calibration parameters based on single images; however, they usually require additional constraints regarding the geometry of scene elements and assumptions considering some of the calibration parameters [58–60] or the presence of predefined shapes in the scene [61–63]. Numerous works exploit specific patterns or objects during laboratory tests [64–67]. Depending on a specific dataset, the use of the first two groups mentioned above of methods may or may not be possible; nevertheless, since the original camera usually is not available, the latter is rather inapplicable. It is worth noting that source imagery may contain both original negatives and cropped sections. For this reason, the assumptions considering some parameters, e.g. the approximate location of the principal point, should be applied carefully [61].

The next issue is the reconstruction of exterior image orientation. As long as the historical dataset contains photogrammetric imagery, ground control points (GCPs) can be available; however, it can be challenging to identify them on heavily transformed terrain [46]. Nevertheless, in most cases, the images used today for 3D reconstruction were not intended for photogrammetric purposes at the time of their acquisition, so the control points are usually unavailable. However, on the condition that a sufficient part of the original object or area remained in an unchanged form up to now, it is possible to measure such points with contemporary techniques [68].

The inherent difficulty regarding the 3D reconstruction of non-existing objects is the limited amount of source data, which cannot be extended today. Images may be supplemented by other archival data, e.g. drawings, plans, archaeological reports and other documents [69,70]. Depending on the research purpose, the integration of archival and contemporary data can be applied [50,51]. Archival drawings combined with contemporary measuring techniques allow for performing various analyses regarding structural deformations of the investigated objects and their changes through the years or centuries [71,72].

Object reconstruction based on archival data is a specific task for which neither one universal methodology nor standards or guiding principles can be determined. Compared to the object documentation obtained nowadays, the general workflow seems reversed.
Currently applied documentation approaches assume subsequent stages of preparing documentation: firstly, the aim and scope of research are determined together with required accuracies. Then, the methodology is formulated, and the source data are acquired with chosen measuring methods. In contrast, historical materials are already present. Consequently, the aim of the research must be related to them, the methodology must be adjusted to both the characteristics of the historical dataset and the objective of the research, and the accuracies possible to obtain are challenging to predict and frequently known as a posteriori.

1.3 3D reconstruction from single views

The reconstruction of all three dimensions of a scene or an object based on a single view has been a research problem that has posed a challenge for computer vision and photogrammetry for a few decades [73–77]. It is worth noting that “a single view” is not equal to “a single image”, as the 3D reconstruction can be based on a set of images of different properties (e.g. focus) but representing the object or scene from an identical perspective.

The geometric information derived from an image can be of various precision and level of detail, starting from relational information, sparse metric data or depth information, ending with a complete 3D model of an object or a scene [76]. To recreate the 3D data, some information contained in the input image has to be extracted (automatically or manually) and then interpreted. For this purpose, commonly used approaches exploit image and scene properties (“image cues”) such as: shading, shadow, contour edges and silhouettes, the object’s texture, colour as well as image defocus and the location of objects [76,78]. However, some assumptions are made since it is impossible to retrieve 3D information based only on the image content for each abovementioned approach. Such assumptions can consider the scene properties, e.g. geometric constraints like parallelism, perpendicularity, coplanarity, collinearity and symmetry as well as the object volume or known semantic relations between the scene elements. Another group applies shape priors which may be learned from a database of sample shapes [76,77].

According to the type of information extracted from the image and the prior assumptions, several techniques of single-view scene reconstruction should be listed. Shape-from-shading technique is a common approach [79–81] which involves the reconstruction of the 3D shape based on the gradual variation of shading in the image [82]. In contrast, the shape-from-shadow method uses the geometry of shadows cast by the object in a series of shadow images [83,84] based on the fact that if a pixel casts a shadow to another pixel, then these two pixels must be collinear with the lightning direction [85]. Methods like shape from defocus (SFD) and shape from focus (SFF) use focus as a base for reconstructing depth. SFD involves the reconstruction of depth exploiting blurring variation of a number of images of one scene, captured with different focus settings [86]. By contrast, SFF searches for the best focused scene points from a set of images taken at different focus settings, and on this basis, the depth is inferred [87,88].

The reconstruction of 3D geometry based on vanishing points identified on a single image is possible thanks to the main properties of the central projection. Assuming that lens distortions are absent, the central projection preserves the straightness of lines. Moreover, parallel lines intersect at one point (the vanishing point), and the line coming through the vanishing point and the projection centre as well as the related parallel lines (e.g. object edges) observed on the image, have the same orientation. These features can also be used for camera calibration [59,89,90], which is usually unavailable in archival photographs. As the edges are in the object’s faces, the orientation of a face can be reconstructed if at least two edges differing in direction are available [75]. This method has been useful in planar objects, and consequently, it is particularly applicable in 3D reconstruction of man-made structures, especially architectural objects [90–92]. Possible limitations of this method are the incompleteness of a 3D model resulting from some parts of the object being invisible or occluded in the image and the need for assumptions (parallelism and perpendicularity, which
are approximate). Nevertheless, this technique can be successfully used in studies involving archival data as they allow to gain 3D information from sparse datasets where no information about the camera calibration is available.

The techniques described above have been developed and enhanced for over 20 years. However, due to the rapid increase of computational power of computers today, the use of deep learning algorithms is gaining much popularity in the field. Learning depth from single images using deep learning can be performed via supervised and unsupervised methods [93–95]. Moreover, neural networks caused a boost in single-image 3D shape estimation [77,96–99]. In contrast to other methods, they allow predicting of the shape of object parts invisible in the input image, exploiting semantic information [98]. The level of supervision needed and related applicability to real-world objects are still crucial matters in this field.

A great variety of methods exploiting different properties of the image itself, the object and scene, making certain assumptions and setting constraints are consequences of the underlying problem, which is inherent and mutual for all methods described above: as the image is formed, the depth of the scene is lost. Although recent techniques of 3D scene reconstruction involving advanced deep learning models allow deriving 3D information from 2D scenes, most of them still require large training datasets containing data in a specified form. In the case of archival data, such requirements usually cannot be satisfied; for this reason, earlier, less complex approaches can still be successfully used.

1.4 Overview of the investigated site – fortified settlement of Biskupin, Site 4

Site 4 in Biskupin, one of Poland’s most important archaeological sites, is located in northwest Poland on a peninsula covering an area of about 2 1/4 ha (Figure 1), the shores of which are flooded by the waters of Lake Biskupin.

![Figure 1. Biskupin, site 4. Northern, central and eastern parts of the fortified settlement. Photomontage was created from a compilation of aerial photographs showing the excavated area during pre-war archaeological works.](image)

1.4.1 History of archaeological research

The site was accidentally discovered in 1933 by a local school teacher. Initial survey research performed on the settlement area in the same year gave such encouraging results that it was decided to start archaeological research next year (Figure 1). [100]. In the following years, almost 1 ha of the site was examined with intensified excavation works carried out up
to the outbreak of World War II. (Figure 1,2). Before and shortly after World War II, the research was led by professor Józef Kostrzewski.

Archaeological research conducted in such a vast wetland area containing perfectly preserved wood remains posed an enormous challenge to Polish archaeology at that time, as such a big undertaking had never been conducted by polish archaeologists before. The vastness of the studied structures and the excellent preservation of wooden remains (breakwaters, 2-3 rows of ramparts, ground floors of buildings and streets) encouraged the researchers to apply some innovative solutions for the documentation of excavation works. Since 1935 new documentation methods have included aerial photography: initially, pictures were taken remotely by a camera attached to a tethered balloon, and later also, an observation balloon was used for this purpose. In 1935 and 1937–1939, photographic documentation included photographs taken from military planes. During several seasons, the bottom of Lake Biskupin was also searched by Navy divers.

During the German occupation, the SS-Ahnenerbe organisation led research in Biskupin. After World War II, the excavations resumed in 1946. During several dozen years of excavation works undertaken on site 4 in Biskupin (Figure 2), about 75% of the site area was discovered (1.69 hectares). In the 1960s, the enthusiasm for digging further areas of the peninsula gradually faded away. For this reason, some of the exposed fragments of the fortified settlement have been covered with soil, and Lake Biskupin has flooded the remaining fragments of the examined settlement for preservation purposes. Excavation research on the site. 4 was completed in 1974 (Figure 2) [101,102]).

![Figure 2. The plan of the archaeological research area of the defensive settlement from the early Iron Age. The research area was limited to the upper layers of layers related to early medieval settlement was not marked [102].](image-url)
1.4.2. Description of the site

An early Iron Age defensive settlement in Biskupin was established initially on an island separated from the mainland on the south side by a shallow isthmus that could probably periodically dry out. The settlement existed in two stages. Dendrochronological studies have shown that structures from the older phase were made from trees that felled in 739-736 BC ([103,104]).

The buildings in the settlement were surrounded by a rampart made of earth and wood, which was additionally protected by a breakwater from the lakeside (Figures 3-5). The best-preserved wooden structures (approx. 1.6 m high) were found in the northeastern part of the site [105], where, among others, several rows of a breakwater and three rows of ramparts of different stages were discovered. (Figure 3).

Figure 3. Biskupin, site. 4. The plan of the remains from the early Iron Age. Explanations: A1 - outer road, A2 - supposed pier, A3 - circular street, A4 -
transverse streets B - palisade, C - entrance gate, D1 - the oldest rampart, D2 - older rampart, D3 - younger rampart

Presumably, the oldest rampart (Figure 3: D1) was destroyed during the construction of the defensive settlement. It was replaced by the older one (Figure 3: D2), which was erected closer to the interior of the settlement. In the east, and probably in the south, a waterfront was erected in the form of a road, which facilitated access to the lake (in the east) and the interior of the defensive settlement - through a gate in the south-west part of the rampart (Figure 3: C). It is unknown whether this road was connected in front of the gate with the so-called "bridge" (Figure 3: A2), connecting the defensive settlement with the mainland.

![Figure 4. Photographs were taken during excavations: (a) – a view of the best-preserved, north-eastern part of the site, (b) – a view from the south on the northern part of the defensive settlement - row I of buildings coming from the older phase](image)

In the older stage of the settlement, its interior consisted of 13 rows of buildings arranged along the streets (Figures 1,3). All roads were connected by a circular street located near the rampart. The buildings were characterized by a similar interior layout (Figure 4). Much less well-preserved remains of the defensive settlement’s interior come from the earlier stage. Unfortunately, they did not provide such good opportunities to recreate its appearance. The best-preserved remains from that time include the youngest rampart (Figure 5).

![Figure 5. Biskupin, site. 4. North-eastern part of the settlement; the remains of the rampart are the best-preserved structure coming from the earlier settlement stage.](image)
The location of streets and internal buildings underwent numerous changes in the younger phase. Less compact buildings than in the previous stage (few row houses and free-standing buildings) made it possible to mark out the streets in areas previously occupied by row houses. Apart from the circular and transverse roads, several additional roads were discovered. Moreover, unlike the buildings specific to the earlier phase, buildings coming from the earlier stage of development of the settlement were not characterized by a unified structure – they were smaller and varied in interior division and size.

Additionally, several small pole buildings from the youngest phase were discovered in the eastern part of the site. These buildings were usually built on top of former roads built in previous phases.

As it can be seen, the history of the development of the fortified settlement in Biskupin is complex and even after so many years of research, not all knowledge gaps have been filled. The need for chronological analyses is still present, and thanks to contemporary digital technologies, new information can still be obtained.

1.4.3 State of the archival documentation

Difficulties impeding scientific studies of the remains of the defensive settlement in Biskupin resulted from large-scale losses caused by World War II. A significant part of plans, all cross-sections, and almost all photographic documentation took in 1938-1939, and almost all notes were lost [106]. Both before and after the war, a part of the drawn documentation was prepared without three-space references, i.e. no information was provided about the vertical position of remains coming from various stages of the settlement development. The lack of information regarding the vertical position limits the possibilities of constructive and chronological analyses considering complex, overlapping structures. The analytical value of the drawn documentation is also diminished by the lack of uniform standards for documenting the discovered remains [102]. As a result, after the research carried out in Biskupin, an incomplete, qualitatively diversified, mostly non-inventoried collection of drawing and photographic documentation remained. This documentation also does not contain the necessary data on the vertical position of the remains. These weaknesses hinder the chronological interpretation of the structure [3].

2. Materials and Methods

The generation of 3D documentation of archaeological objects located over the fortified settlement in Biskupin was in a greater extent, a part of the project “The design for the development of the Lusatian culture fortified settlement on Site 4 at Biskupin: pre-war research work”, which principles were to perform structural and stratigraphic analyses of the remains providing new information about the chronology and functions of discovered artefacts. Since the settlement's remains have been buried underground for preservation purposes, the main data source for works performed in this study was the archaeological and photographic documentation acquired during the expedition in 1934-1939 and in the second half of the 1940s. Additionally, a vector drawing of the Site 4 containing contours and descriptions of the artefacts were used as a reference and basic source of geometrical data.

2.1 Overview of the approach

A rich collection of varied archival photographs and a vector drawing derived from archival drawn documentation, allowed the application of different 3D modelling and visualisation methods characterised by various accuracy and level of detail. The advantages and limitations of each approach were analysed, considering both the method’s features and the quality of available source data. Obtained results made it possible to evaluate the potential and usability of each method for further archaeological analyses. The workflow of performed experiments is shown in Figure 6.
The requirements concerning the input data were different for each applied method; thus, various subsets of data had to be chosen. Consequently, a thorough analysis of the whole image collection was needed, followed by selecting datasets for each scenario. The investigation involved identifying images (location of the covered area and the time of acquisition), sorting concerning the altitude and angle and excluding images characterized by poor quality. This resulted in splitting the collection into groups containing images taken at high, medium and low altitudes (approximately at the height up to 10 m (low), 10-100 m (medium) and 100-1000 m (high)) separately for nadir and oblique images. Another group included images of details containing photographs of single artefacts and close-ups of archaeological objects. This basic division and identified image location allowed a more precise selection of photographs suitable for each scenario. Then, radiometric corrections were applied to facilitate the readability of the images, including brightness and contrast modification. Preliminary works considering the photographs described above were also the initial step for experiments presented in [1], and for this reason, they will not be described in detail in this article. Notably, these two steps are mutual for all scenarios; however, additional preparatory operations need to be done depending on the approach.

For performed experiments, the “general-to-specific” approach was applied, exploiting four methods: Structure-from-motion with Multi-View Stereo, semi-shape-from-shading technique, 3D modelling based on single photographs, and 3D modelling based on the drawn documentation with the use of CAD software. The area covered by each method is shown in Figure 7.

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**Figure 6.** The diagram of performed experiments

<table>
<thead>
<tr>
<th>1. Preliminary works</th>
<th>2. Experiments</th>
</tr>
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<tbody>
<tr>
<td>Preprocessing of drawn documentation</td>
<td>Scenario I: SfM + MVS</td>
</tr>
<tr>
<td>Preprocessing of photographs</td>
<td>Selection of photographs</td>
</tr>
<tr>
<td>Scanning</td>
<td>Selection of photographs and sections of the vector drawing</td>
</tr>
<tr>
<td>Geometric corrections</td>
<td>Implementation of vectors in CAD software and rectification</td>
</tr>
</tbody>
</table>

1. **Image sorting**
   - High
   - Medium
   - Low
   - Details

2. **Altitude**
   - High (100-1000 m)
   - Medium (10-100 m)
   - Low (up to 10 m)

3. **Scene orientation with Ground Control Points**

4. **Image acquisition into a grid**

5. **Dense cloud generation**

6. **3D modelling of solids**

7. **Setting object position along the Z axis**

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Figure 7. Area covered by each method: red - SfM+MVS, green – semi Shape-from-Shading, blue - 3D modelling based on single photographs, orange – 3D modelling based on the drawn documentation done in CAD software.
The following sections will present the complete description of applied methods and used input data.

2.2 Source data

2.2.1 Archival photographs

Original images used in this work are currently stored in the Archaeological Museum in Biskupin and in the State Archaeological Museum in Warsaw. The archival documentation contained a diverse collection of images, an innovative solution for documenting the excavation works at the time. The images were taken at different heights, starting from aerial images taken from an aeroplane (200 m, 300 m up to 3000 m), a captive balloon and a blimp (50-1100 m), through images taken from a ladder or a platform (several meters high), ending with terrestrial images of single artefacts and their details [107]. The set contained both oblique and nadir photographs. The original glass image plates were scanned with a high resolution of 3200 DPI (pixel size: 8 µm) to provide the highest amount of information possible. A complete characterization of the whole image collection was presented in [1].

Such variety of image scales, covered area and angles, and a large number of images available provided a large scope of information possible to obtain and allowed to use for different applications. A subset of mentioned data has already been used in [1] to generate true-orthophotomaps of the site. The dataset used in the mentioned work contained aerial images taken at high altitudes (mainly nadir photographs taken from the plane, balloon and blimp). In contrast, the image set used for 3D modelling and visualization of archaeological remains included both nadir and oblique, low-altitude photographs acquired from a captive balloon, images taken from the platform and ladder, and images of separate artefact details (Figure 8).

![Figure 8. Examples of images used for 3D modelling and visualization purposes: (a) low-altitude nadir image, (b) oblique image of a whole structure, (c) an image of a single relict (PMA Archive)](image)

2.2.2 Vector drawing

Drawn documentation acquired during the excavation works served as the reference for the creation of the vector drawing covering the area of Site 4. The original documentation contained 1:10 and 1:20 scale plans and profiles of the site together with contours and descriptions of wooden remains of the settlement drawn on a millimetre paper. All in all, the excavation works were conducted in a grid of 10 m x 10 m squares (ares) and covered an area of approximately 1.69 hectares which was ca. 75% of the peninsula. The drawn documentation was prepared separately for each are [102]. Although a significant number of drawings were lost during the II World War, some of them were photographed in 1939 in 10 times smaller scale, providing a reference for the plan in the scale of 1:100 [107].
The vector drawing was the result of vectorization of mentioned drawn documentation, which had been scanned with the resolution of 600 DPI and then rectified and integrated into Autodesk AutoCAD software (Figure 9). Additional descriptive information, which was not included in the drawn documentation, was derived from the field journal and the results of analyses performed by other researchers [102]. The whole drawing was split into layers regarding different object types and corresponding time periods (e.g. road remains – earlier phase of the settlement, stone-separated remains). All data were referenced in the local XY coordinate system established during the expedition – its axes were oriented approximately north-south and west-east, parallel to the axes of the peninsula and the main archaeological site. Moreover, it is known that some levelling measurements were also performed during the expedition, resulting in notes containing the objects’ altitudes. The measurements were referenced to two benchmarks removed during the II World War [108]. Furthermore, relative heights were measured in relation to levelled levelling rods [102]. Unfortunately, the exact location of the benchmarks is unknown, and the number of objects with known absolute height is very small, providing insufficient information about their vertical location in most cases.

Figure 9. A part of the vector drawing derived from processed archival drawn documentation

2.3 Structure-from-Motion + Multi-View Stereo

The first scenario involved the application of Structure-from-Motion (SfM) and Multi-View Stereo (MVS) algorithms, which are currently often used in the process of 3D documentation of archaeological works. However, in this work, their usability was examined on an archival dataset, which was not intended to be used for photogrammetric processing at the time of acquisition. This part of the research aimed to check the applicability of the aforementioned algorithms in the case of available archival photographs as well as to obtain 3D documentation of structures, to which other approaches described in further sections could not be applied.

2.3.1 Source data

The SfM with MVS approach requires a set of images showing the object of interest at different angles with high coverage. However, although the photographic documentation acquired during the archaeological expedition contained several hundred images, it was very hard to find photographs fulfilling these requirements. The analysis of available photographic and drawn documentation allowed to select two test sites for further processing: house no. 12 and the area covering three other houses: 21, 39 and 40 (Figure 10). The image set acquired for house no. 12 consisted of 5 images (3 low-altitude images and 2 images of details), while the second one contained 4 nadir low-altitude images and 3 terrestrial oblique images. The
images were used for the 3D reconstruction of the site together with the vector drawing, which served as a spatial reference to get the proper scale of each model.

![Figure 10](image1.png)

**Figure 10.** Test sites were chosen for processing in Scenario I: (a) – row III of terraced houses; ground floors of buildings 12, and 13 from the older phase and the ground floors of two younger buildings covering them, (b) – row V of terraced houses (in the middle of the row); ground floors of buildings 21, 39, 40 from the older phase

### 2.3.2 Orientation of the images and self-calibration

The image orientation involved relative and exterior image orientation. The relative orientation of images was reconstructed via bundle adjustment performed in Agisoft Photoscan software. In the case of both test sites, double image resolution (*highest*) was used because of significant scale differences between images. Bundle adjustment based on automatically detected tie points only did not provide the alignment of all photos, so a set of manually determined tie points was used.

Along with the calculation of relative image orientation, during the bundle adjustment also, self-calibration of the camera was performed, involving the computation of the focal length \( f \), the principal point coordinates \((c_x, c_y)\) and the parameters of radial \((k_1, k_2, k_3)\) and tangential \((p_1, p_2)\) distortion. However, a non-metric camera was used in this case, and no primary information about its parameters was known. As the images were scanned and cropped individually, no initial approximate values of calibration parameters could be applied.

The images’ exterior orientation was found using ground control points, which X and Y coordinates were derived from the vector drawing since there was no photogrammetric network established on the site. Additionally, in the case of test site II one scalebar could be measured and was included in the calculation. The Z coordinate of the GCPs was unavailable, so the Z value for all points was set to 0. It is worth noting that GCPs were also used as manual tie points supporting relative image orientation.

### 2.3.3. Dense point cloud and mesh generation

Three scenarios differing in the resolution of images used for depth map generation were applied for the dense point cloud generation. Each scenario was performed in two variants varying in the strength of point filtering in the resulting point cloud (mild and aggressive). Mentioned experiments, which results are presented in more detail in the Results section, were essential to identify the best solution, providing the balance between high point density, low noise level and a small number of blind spots. Using resulting dense point clouds, 3D models in the form of meshes were generated and covered with photographic texture.
2.4 The Variation of the Shape-from-Shading method

Unlike 3D modelling methods described in sections 2.3, 2.5 and 2.6, the aim of creating 3D visualisation was not to achieve metric quantitative information but to enhance and support qualitative analyses concerning the structure of single remains. For this purpose, a method similar to classic shape-from-shading was applied. The intensity information was used only to enhance the visualisation and not to obtain the height values of the remains.

2.4.1 Source data

Images of details served as the source data for creating the 3D visualisations. The image set contained three images showing archaeological objects, such as single construction elements and remains of buildings taken from a short distance (Figure 11).

Figure 11. Examples of the images used for 3D visualizations: (a) – the corner upright joined with the ground beam of the older building, (b) – the floor of the older building and the fascine of the floors of the younger building

2.4.2 Generation of 3D visualizations in Blender

The generation of the 3D visualisation in Blender software was based on the images imported into Blender as planes. Since a single plane could not be edited, each plane was subdivided into a dense grid of rectangles. The number of rectangles determined the level of detail of visualizations as well as displaying efficiency, and finally, the number of 262 144 similar rectangles was chosen as optimal (Figure 12).

The next step involved the displacement of each rectangle along the normal to the plane. The former flat grid of rectangles was deformed based on its texture – in this case, it was the photograph. The displacement was determined by pixel intensity: brighter pixels were interpreted as higher, while darker ones were interpreted as lower. The parameter strength meaning the relative height difference between pixels differing in intensity value, was adjusted based on several empirical tests – the values in the range of 0,08-0,12 proved to achieve optimal results.

The resulting surface appeared to be very rough and irregular, hindering the interpretation. For this reason, an additional modifier Smooth was added – its parameters: the smoothing factor and the number of repetitions were also tested: the optimal values of the smoothing factor ranged from 0,5 up to 0,8 while the number of 30 repetitions gave satisfying results. Subsequent steps of creating the visualisations are shown in Figure 12.
2.5 3D modelling based on single images and the vector drawing

2.5.1 Source data

Similar to the first scenario, photographs and vector drawing were used as the input data in this instance. However, this time the vector data served as a source of geometrical information providing contours of the artefacts, and the images made it possible to measure their heights and, thus, to supplement the 2D shapes with the third dimension. Nevertheless, since the site covered a vast area and the documentation was extensive and complex, it was impossible to create one complete model of the whole site. For this reason, 3D models of single buildings and roads were created separately.

The amount and the quality of source data varied significantly depending on the part of the site, so the objects selected for this task and corresponding source documentation had to meet several requirements:

- the images should cover the object from many perspectives
- both nadir and oblique images of the object should be available
- the quality of images should provide reliable measurements and good texture quality
- the corresponding fragment of the vector drawing should be available, complete and its content has to be consistent with the content of the images

At this stage, it became clear that the creation of 3D models of some buildings was not possible due to the lack of sufficient data. In several cases, photographic or drawn documentation was incomplete and insufficient to reconstruct the objects’ shapes. It also

Final visualisations were exported to the *.obj format.
appeared that the contours of the artefacts present in certain regions of the site did not match those seen in the photographs due to different data acquisition time. Finally, 36 objects were selected for further processing: 33 houses, 1 probable farm building, 1 transverse road and 2 fragments of the circular road (Figure 13).

![Exemplary input data for 3D modelling of the building 19: (a) – a fragment of the vector drawing, (b) an archival photograph](image)

**Figure 13.** Exemplary input data for 3D modelling of the building 19: (a) – a fragment of the vector drawing, (b) an archival photograph

2.5.2 Orientation of the drawing sections relative to each photograph

The next step involved the orientation of each section of the vector drawing in relation to photos showing the objects. For this task, the “Match Photo” function available in Google Sketchup 8 software was used. In order to enhance this process, each section was translated near the (0,0) point, and the layers containing object contours were merged into a single layer, resulting in simplified drawings, each oriented in their own local coordinate system with preserved proper scale.

To match the vector drawing with each photo, 2 pairs of vanishing point bars and a horizon line were adjusted so that the contours of the artefacts visible in the picture matched their vector equivalents present on the drawing (Figure 14). Consequently, the OX and OY axes matched perspective lines, and the OZ axis corresponding to a vertical observed on the image. Notably, this operation involved the orientation of the coordinate system of the vector drawing, not the drawing in a certain coordinate system. This means that independent on the chosen image, the position of the drawing and its scale was preserved.
The method described above has been proven to work well with photographs showing structures made mostly of right angles (e.g. building edges) and taken so that they contain two vanishing points. However, on the site area there were almost no straight-line objects which would allow to alignment of the perspective lines unambiguously. Moreover, the objects visible in the images were mostly of low height, making it difficult to adjust the OZ axis precisely. For these reasons, the positions of perspective lines and vanishing points were specified approximately along the lines determined by the objects visible on the images (e.g. walls of houses, road edges etc.). They were adjusted iteratively until the contours of objects on the images and the drawing matched the best.

2.5.3 Height measurements performed on the artefacts

Modelling of the objects located on the site required knowledge of all three dimensions of each artefact. Since the vector drawing was a metric product containing information about both the shapes and relative positions of the artifacts, height measurements were crucial for this task. The horizontal planes of each section of the drawing and the horizontal plane of the local coordinate system established on the site had been aligned so that the vertical axes of these coordinate systems coincided. The correct scale of the OZ axis was provided as the drawing matched the photographs. Fulfilling these two requirements allowed measuring the remains' height based on a single oblique photograph (Figure 15).

Figure 15. Height measurements performed on the artefacts visible on an oblique image

Considering factors impacting the measurements' accuracy, such as image quality, estimated accuracy of the orientation process and the object's features, the authors decided to measure height with 1 cm precision. During this stage, several features influencing the measurement accuracy were identified: the unambiguousness of ground level determination, the presence of water on the site, the method of height measurement (direct or indirect) and the complexity and irregularity of the artefact's shape.

The overall workflow assumed that the ground level visible on a photograph served as a reference for the measurements. However, in many cases, the determination of the ground level was troublesome due to the presence of more than one ground level within one structure – in such cases, the differences between levels had to be determined and taken into account
during height measurements. If it was impossible, a note considering the used ground level was enclosed. Another factor impeding the determination of the ground level was its irregularity resulting from its swampy, muddy character. The fact that the images were black and white made it difficult to distinguish the harsh surface of artefacts and the ground, decreasing the measurement accuracy.

The aforementioned swampy character of the site resulted in some regions of the site being temporarily flooded, which could be seen in many images. Usually, such images were considered useless, and the objects visible on them were excluded at the earlier stage of processing. However, in a few cases, it was possible to determine the mean water level on the image by comparing it with images taken when the area was dry. Consequently, this allowed to calculate the corrections to the measurements referenced to water level, yet, this method was applied only for a few artefacts of the circular road since the risk of the incorrect result was high. The values of the abovementioned corrections ranged between 5 and 7 centimetres.

The artefact’s position in relation to other remains within the same structure as well as the direction in which the image had been taken, made the direct measurement from the ground impossible for some objects. The height of such artefacts was either measured relative to other artefacts of height measured directly from the ground or by visual comparison with neighbouring objects. The first solution was applied mainly for artefacts lying on other objects, while the other was for structures containing artefacts of the same kind and similar height, located very close to each other (e.g. floorboards). The applied measuring method also depended on the artefact’s shape. As the measured objects were the remains of buildings and roads, most of their components were flat boards or other construction elements that shape allowed explicit measurements. The heights of rounded objects were measured with regard to their highest point if it could be identified. Furthermore, many objects were placed at a certain angle or had a more complex shape which could not be described by one height – in such cases, the minimum and maximum height values were measured.

The vector drawing contained not only the contours of the remains located over the site but also some additional information, which included the results of levelling performed during the excavations. It was possible for several artefacts to measure their height on a photograph and derive their altitudes from the description included in the vector drawing. Based on this data, it was possible to determine the estimated altitude of the ground level (under the assumption that the ground was flat on the area covered by the image) and, thus, to calculate the height of the artefacts, which could not be measured in any way described above. This solution was applied for several elements of the circular road and house no. 34.

All methods of height measurement presented above were attempts to overcome the obstacles related to the features of objects. Besides, the quality of measurements – their accuracy, reliability and completeness – were also affected by the source data quality. In contrast, the quality of the images and the vector drawing had not led to the developing of separate measuring approaches; nevertheless, the lack of vector data or poor quality of the images reduced the number of examined objects and decreased the quality of measurements.

2.5.4 3D modelling of the remains

Similarly, as in the previous two stages, 3D modelling was done in Google SketchUp 8. The vector drawing contained the contours of the remains along with descriptive data. For modelling purposes, all elements containing non-geometric data were removed, and the contours were filled so that a polygon represented each element. Objects that were not visible on photographs or incomplete contours were excluded from further processing.

The next stage involved 3D modelling of the remains. The polygons corresponding to artefacts were extruded by known heights measured in the previous step so that a prism represented each one. Since most of the remains were boards and poles, prisms served as a good approximation of their shape. In the case of objects lying at an angle or those
characterized by a more complex shape, additional shape modifications were performed (Figure 16).

![Figure 16](https://example.com/figure16.jpg)

**Figure 16.** 3D modelling of the remains: (a) – artefacts represented by polygons, (b) – 3D modelling by extrusion

According to section 2.5.3, the heights of the remains were measured in different ways, influencing the measurement accuracy and resulting in heterogeneous accuracy within one archaeological structure, i.e. a house or road. For this reason, all models were divided into layers depending on the applied method of height determination, factors decreasing the measurement accuracy and other features.

### 2.5.5 Texture preparation

The last phase of 3D modelling of the remains was texture preparation. To obtain a photorealistic effect, archival photographs were projected onto the top surfaces of each model. Texture preparation was preceded by the orientation of the vector drawing relative to each photograph used for texturing, which workflow was described in detail in section 2.5.2. The process of texture preparation consisted of two steps: the image was projected onto the whole model, and later the texture was individually adjusted so that it would match each artefact. The texture on each element was moved, rotated and scaled with the use of “pins” (Figure 17) – which allowed to perform the 2D DLT transformation and partial image rectification.

![Figure 17](https://example.com/figure17.jpg)

**Figure 17.** Preparing texture of the 3D models: (a) – projection of the image onto the whole model, (b) – individual texture adjustment

The optimal solution assumed that the texture should be made using one nadir low-altitude, high-resolution photograph covering the whole object. It would provide uniform texture with consistent lightning conditions, equal resolution and quality. However, following this rule was impossible in many cases due to the lack of proper images covering certain objects. For this reason, the texture was prepared in numerous cases based on a few images differing in resolution and angle. In the case of the artefacts, which were not visible on any nadir image,
the texture was derived from neighbouring objects of the same kind. The objects, which could not be textured in any way, were painted with uniform grey or white, harmonizing with neighbouring artefacts. Finished models were exported into the *.skp SketchUp format.

2.6. 3D modelling in CAD software

Computer-aided Design (CAD) allows not only simple vectorization of drawn documentation (Figure 18), but also makes it possible to transform them to obtain three-dimensional images of remains and archaeological layers, becoming a more effective source of information about discovered remains. While visualizations of the building remains support the structural and functional analysis of the studied structures, the integrated model of interpolated archaeological layers is a potentially important source of information on relative chronology [3].

**Figure 18.** (a) - in the upper part, an example of a plan of the remains of the defensive settlement in Biskupin, site 4 (ares no. 126-128) from both phases; at the bottom, the same plan after vectorization and rasterization of documentation is shown. The colours of the remains indicate the phase (older, younger) and the type of structure; (b) – 3D visualization of remains (ares no. 126-128)
The modelling involved remains with a known vertical position, and those whose vertical location can be indirectly determined in relation to other remains with known spatial position (e.g. horizontal logs forming walls of buildings), or with an interpolated position (e.g. logs forming floor surface – Figures 18, 19). Remains that did not contain information about their vertical position were placed on a separate vector layer.

Levelling measurements performed during excavations were referenced to a local spatial reference system established on the site. In the case of the excavation within ares no. 126-128, additional levelled boards were embedded in the edge of the excavation, showing the “level 0”. Unfortunately, cross-sections of archaeological layers often contained neither marked “level 0” nor any other information about their vertical position. In such a case, it was necessary to find common reference objects: wooden remains lying on the edge of the excavation, visible both on a plan and cross-section (Figure 20). All the drawings were georeferenced in the aforementioned local coordinate system of the site. The vector drawing of the site was referenced in this coordinate system, and the “level 0” was marked as Z=0 in AutoCAD.

The challenge was to determine the position of the vertical elements below as the levelling points referred to the upper parts of the remains). It was assumed that these elements at the bottom were in contact with the bottom of the archaeological excavation. This assumption was supported by photographs (Figure 19). The level of the trench bottom was determined based on entries in the excavation journal.

Generating spatial images in CAD software requires many time-consuming transformations of vectorized documentation. In order to create solids, open polylines need to
be transformed into closed polylines. The outlines of posts, flat elements, or archaeological layers formed the wireframe, which was later used to create solids. Remains characterized by oval or irregular cross-sections required manually set parameters and geometry (usually ovals, ellipses, points) to create solids. They also had to be rotated according to the XYZ coordinate system (or systems) adapted to the geometry of the solid. Then, the position of the wireframe sections was arranged vertically and horizontally – so that they coincided with the outline of the remains in the perpendicular view from above and from the side. Due to the fact that these solids were modelled with the “surface smoothing” option enabled, the sections of the solid wireframe had to be placed very densely in the places of curves, branches and around them (Figure 21). Otherwise, the smoothed solid in the places of curvatures would not coincide with the outline of the remains in the perpendicular view - as a consequence, imprecise geometry would be created. In order to give the solids an appropriate shape, simple modifying tools are used (e.g. chamfering, rounding edges, making holes). In the case of remains characterised by complex geometry, the solid was transformed into a mesh which could then be modified using edges, polygons, and tangent edge points.

**Figure 20.** Orthogonal projection of three-dimensionally modelled remains of wood (green) on two overlapping cross-section drawings – northern and central part of Are No 127 (colours: brown, yellow, diagonal hatching); A, B - wooden elements of the building walls

**Figure 21.** The wireframe of a complex solid was created by manually arranging the solid cross-sections (circles, ellipses) in the XYZ space (top); solid fragment (bottom)
3. Results

The experiments mentioned above resulted in the creation of the following products: 37 3D models based on single images, 2 3D models based on the computer vision approach, three 3D visualizations done with the use of a variation of the shape-from-shading method and 1 model based on vector drawing with the use of CAD software. This section will perform the quality and accuracy analysis of these products. In the subsequent part, the applicability of each method in terms of archaeological analyses will be discussed.

3.1. Structure-from-Motion + Multi-View Stereo

The first scenario involved the generation of 3D models using the SfM with MVS approach. The results of subsequent stages, including image orientation, dense cloud generation and mesh generation, are presented below.

The coordinates of GCPs were derived from the vector drawing. All points also served as manual tie points. However, in the case of test site II, additional manual tie points had to be established to support the image orientation process. The number of images, tie points, and GCPs (both control and check points) used on both test sites is presented in Table 1.

Table 1. The number of images, tie points and GCPs used at each site.

<table>
<thead>
<tr>
<th>Test site</th>
<th>Number of images</th>
<th>Number of automatic tie points</th>
<th>Number of manual tie points</th>
<th>Number of control points</th>
<th>Number of check points</th>
</tr>
</thead>
<tbody>
<tr>
<td>House no. 12</td>
<td>5</td>
<td>3931</td>
<td>11</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>Houses no. 21, 39, 40</td>
<td>6</td>
<td>3610</td>
<td>19</td>
<td>7</td>
<td>4</td>
</tr>
</tbody>
</table>

The distribution of manual tie points and the GCPs together with sparse point clouds are shown in Figure 22.

![Figure 22. Sparse point clouds generated for both test sites: (a) – house no. 12, (b) – the area covering houses 21, 39 and 40. Distribution of control points (green), check points (red) and additional manual tie points (blue).](image-url)}
Table 2. The results of the relative and exterior orientation of the images.

<table>
<thead>
<tr>
<th>Test site</th>
<th>Reprojection error [pix]</th>
<th>RMSE control points [m]</th>
<th>RMSE check points [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>House no. 12</td>
<td>0.898</td>
<td>0.062</td>
<td>0.074</td>
</tr>
<tr>
<td>Houses no. 21, 39, 40</td>
<td>0.753</td>
<td>0.197</td>
<td>0.148</td>
</tr>
</tbody>
</table>

Additionally, on test site II one control scalebar was established, and the error value was 0.016 m.

Despite mentioned obstacles, on both test sites, the reconstruction of relative image orientation was successful, which can be concluded from the reprojection error of the images, which value in both cases was below 1 pix. RMSE values acquired on check points on test site I suggest that the image orientation was accurate enough for approximate measurements. On the other hand, error values obtained on reference points on test site II are twice as high as those achieved on test site I, suggesting low accuracy is insufficient for archaeological analyses. Significantly lower accuracy of exterior orientation observed on test site II was probably caused by the poorer image quality, higher altitude and resulting lower image resolution (GSD = 3.5 mm on test site I, while on test site II GSD = 7 mm). Due to the low accuracy achieved on test site II, the resulting 3D model could be used only for visualization purposes. Since this particular approach aimed to create a 3D model for measuring purposes, the remaining part of the research covered in this section will be focused on results acquired on test site I.

The next processing stage included dense point cloud generation performed in three scenarios. The Authors decided to test two values of filtering strength due to various noise levels of generated clouds and the differing number of blind spots acquired with different settings (Figure 23).

Figure 23. Issues observed in dense point clouds: (a) – noise, (b) – blind spots
Table 3 shows the number of points and point density acquired for all of them in two variants of the strength of cloud filtering.

Table 3. Statistics of dense point cloud generated on test site I.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Pyramid level (quality)</th>
<th>Filtering strength</th>
<th>Number of points</th>
<th>Average point cloud density [pts/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>-1 (ultra high)</td>
<td>mild</td>
<td>7 498 801</td>
<td>3.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aggressive</td>
<td>9 768 638</td>
<td>4.63</td>
</tr>
<tr>
<td>II</td>
<td>0 (high)</td>
<td>mild</td>
<td>2 640 676</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aggressive</td>
<td>3 311 199</td>
<td>1.57</td>
</tr>
<tr>
<td>III</td>
<td>3 (low)</td>
<td>mild</td>
<td>238 876</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>aggressive</td>
<td>283 341</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Analysing Table 3 it can be concluded that the highest point density was acquired for scenario I, a variant with “aggressive” cloud filtering. However, as seen in Figure 24, the point cloud generated in this scenario was characterized by a large number of blind spots.

Comparing the results obtained in three scenarios, point clouds generated at “ultra-high” resolution contain the largest number of blind spots, while point clouds generated at “low”
resolution lack the least data. However, the cloud is sparse in their case, providing the least detailed representation. Due to the high noise level observed in all point clouds, the variant with “aggressive” filtering was chosen. Meshes were generated for all three scenarios (Figure 25).

![Figure 25](https://example.com/figure25.png)

**Figure 25.** 3D models (meshes) generated for test site I based on dense clouds of different point cloud resolution: (a) – Scenario I (ultra high), (b) – Scenario II (high), (c) – Scenario III (low)

The highest point density resulted in the highest level of detail in the case of scenario I. However, when compared to the mesh generated in scenario II it can be observed that the second mesh contains nearly as much detail as the first one but is less noisy. Still, in both cases, the lack of data is visible, especially in flooded areas. On the contrary, the mesh created in scenario III is the most complete model, however, due to severe generalization, single
artefacts are hardly distinguishable. For this reason, it cannot be applied in archaeological research.

The results of performed experiments led to the conclusion that scenario II was the optimal solution representing a compromise between the model resolution and completeness. Therefore, the mesh generated in this scenario was textured with photographic texture based on the original images (Figure 26).

![Textured 3D model created in the SfM and MVS approach seen from two perspectives (a, b)](image)

**Figure 26.** Textured 3D model created in the SfM and MVS approach seen from two perspectives (a, b)

However, the quality of the resulting 3D model did not allow structural and chronological analyses, as the relative height of single objects could not be precisely measured.

### 3.2. 3D visualisations based on a variation of the Shape-from-Shading approach

The 3D shape of visible objects was derived based on the pixel brightness, and consequently, the relative height of the objects resulted from their relative brightness. Since the level of displacement was also dependent on user defined tool parameters, the resulting product is not a metric 3D representation but a visualization which main aim was to emphasize the object's structure and enhance the interpretation of the images.

The described technique appeared to be particularly useful in depicting the wood structure (Figure 27, (a,b)). Since the displacement occurred along the normal to the image plane, the best results were achieved for nadir images and relatively low objects. However, the specific nature of investigated objects and available source data limited the potential of this method. The principle of this technique involved the darker areas being interpreted as located lower. Since most of the photographs were taken on a sunny day, strong shadows cast by the objects were visible, causing shadowed areas to be incorrectly shown as cavities (Figure 27 (c,d)). On the other hand, the presence of water in many images caused the areas where the sky was reflected to be “higher”. As the grey level tells more about the object's structure rather than its relative height, it is also more recommended for low, approximately flat objects rather than high poles.

![3D visualisations based on a variation of the Shape-from-Shading approach](image)
Figure 27. Situations in which the method was useful (a, b) and in which it failed (c, d)

The level of detail resulted from the number of similar rectangles into which the source image plane was subdivided – the denser the grid was, the more detailed and irregular the visualisation was. It is worth noting that with the increasing number of rectangles, the size of the resulting file also increased and any operation performed on it required more computational power. For this reason, the compromise between the level of detail and the processing efficiency must be found.

3.3 3D modelling based on single images and the vector drawing

As a result of performed experiments, 37 3D models of archaeological structures located on the site were created. For each model, 1 to 9 archival images were used. The quality assessment of resulting 3D models involves estimating model accuracy and photorealistic texture quality. Chronological and functional analyses performed by archaeologists require knowledge of the relative heights of excavated artefacts. For this reason, height measurements were crucial for further works.

As it was mentioned in Section 2.5, height measurements were performed with a precision of 1 cm. A series of factors influencing their final accuracy was identified. These factors were related to the quality of source data (the photographs and the vector drawing), the accuracy of fitting the vector drawing into images and the applied measuring method itself. Different images available for each object and their diversified quality induced the use of various methods for determining the artefacts’ heights, including direct measurements and indirect height estimation. The limited number of images also decreased redundancy, especially in the case of artefacts, where height could be measured only on one photograph. For this reason, the final accuracy of their heights cannot be considered equal, and consequently, each measurement was denoted with regard to its reliability and the artefacts were placed on vector layers corresponding to the measurement method. Measurements, which were considered the most reliable, included direct measurements with reference to the ground or neighbouring artefacts, while in the case of the others, some uncertainties had to be taken into account due to limited visibility of their edges, viewpoint distance and angle, unknown accuracy of levelling measurements and the presence of water on the site. An example model divided into layers with respect to measurement reliability is shown in Figure 28.
Figure 28. (a) – The model of house no. 19 divided into layers with respect to the height measurement reliability, (b) – legend

However, the influence of the applied height determination method cannot be assessed exactly – they must be taken into account during archaeological analyses.

The accuracy of fitting the coordinate system of the vector drawing into each photograph also affected the height accuracy as it decided whether the scale and the direction of the vertical axis would match. As mentioned before, the accuracy of image orientation was the highest in the foreground and gradually decreased in the background. The influence of deviation from the “true” vertical can be described as (Equation 1)

\[ H' - H = H' \cdot (1 - \cos \alpha) \]

where \( H' \) – measured height, \( H \) – true height, \( \alpha \) – the angle of deviation between the “true” vertical and OZ axis of the coordinate system of the vector drawing. However, during the measuring stage, the maximum deviation did not exceed 15° and considering the heights of the artefacts and measuring precision, this factor can be treated as negligible.

The accuracy of 3D shape reconstruction was also affected by necessary simplifications considering the shapes of the artefacts as well as the assumptions considering the ground level on the site. The artefacts were modelled in the form of prisms, which in most cases were good approximations of their shapes as the majority of structures were wooden boards and poles. Considering the ground level, it was assumed flat within one archaeological structure (e.g. a building), although small denivelations could be observed. Nevertheless, in most such cases, the artefacts' heights could also be measured in relation to neighbouring elements, preserving their relative location.

Photorealistic texture enhanced the 3D models visually and improved their interpretation value. The application of low-altitude nadir photographs, which were scanned with a high resolution of 600 DPI, provided high-quality texture in grayscale. However, nadir images covering the whole structure were unavailable in several cases. In such cases, more than one image was used, and in the case of probable farm building, oblique images were the source for texturing, which resulted in the non-uniform quality of texture within a model.

The geometric accuracy of the 3D models cannot be determined precisely as there are no reference data, which would allow the calculation of any RMS values. Moreover, the specificity of the aforementioned factors does not make it possible to measure their influence on the final accuracy. However, considering all circumstances relating to the properties of
source data, the characteristics of the site and measuring methods, the Authors estimate the final accuracy of the relative height of the artefacts within one structure to be ± 2 cm for most visible artefacts up to ± 4 cm for the least reliable height measurements.

3.4. 3D modelling in CAD software

The last scenario resulted in creating one 3D model of the remains in the ares no. 126 and 127. The model contained a detailed reconstruction of separate wooden elements of the archaeologic structure. Both horizontal and vertical positions of the remains were recreated, providing full three-dimensional visualisation of the area. Additionally, the visualisation was complemented by the reconstructed arrangement of cultural layers (Figure 29).

Figure 29. A fragment of are no. 127 showing interpolated cultural layers and visualization of wooden remains [3]

The model is georeferenced in the local coordinate system of the archaeological site, which places it in the context of the whole excavation. Since the vertical positions of the remains were reconstructed, derivatives such as additional cross-sections (Figure 30) could be made, and chronological analyses were conducted.

Figure 30. Visualization of part of the remains on the are no. 127 in a perpendicular view with interpolated models of selected layers [3]; (a) – view of the remains and the layer (No. IV) covering the structures from the older and younger stage; (b) – the view as above with an additional layer (No. V) related to the younger

The accuracy of such a 3D model is difficult to determine since it cannot be checked directly as the original objects are unavailable and cannot be measured in any way. Similar to the third scenario, the accuracy of the resulting models depends on the accuracy of the source data. The accuracy is influenced by such factors as the level of detail and unsure accuracy of
the drawings, deformations of the material, and deformations resulting from scanning. The estimated accuracy of shape reconstruction or the position in the coordinate system varies from several up to several dozen centimetres. However, in this case, the emphasis was placed on the reconstruction of the relative vertical position between the elements and this goal was achieved.

4. Discussion

The developed methodology of spatial modelling based on archival documentation provides a wide range of analytical possibilities. Analyses of the remains of the fortified Lusatian settlement in Biskupin are largely based on archival documentation, which is incomplete and usually lacks direct information on the vertical position of individual objects. For this reason, several methods of 3D modelling and visualisation were used to obtain this information indirectly.

The method based on light and shadow, a simplified variant of the shape-from-shading (SFS) method, allowed the generation of non-metric 3D visualisations. It has been successfully applied to analyses limited only to the demonstration of height variation or verification of structural details and the structure of individual relics. This technology is particularly suitable for analyses of relics whose drawing documentation has not survived or is an insufficient source of knowledge about the investigated structures, and there is no possibility of its verification. The most important advantages of the described method include the increased interpretative value of the source photographic documentation depicting individual structures. At the same time, it does not require specialised knowledge to achieve satisfactory results. From the point of view of the analysis of settlement relics at Biskupin, the best results were obtained from visualisations based on nadir photographs taken from a low ceiling. This method, however, proved to be of limited use in areas flooded with water - relatively abundant at the archaeological site due to its saturated nature, as well as in the case of photographs taken in harsh lighting with long shadows - in these circumstances, erroneous results were obtained. Identifying this problem allowed satisfactory results to be obtained for photographs where these circumstances did not occur.

The present study also attempts to use the Structure-from-Motion with Multi-View-Stereo approach, which is nowadays quite commonly used in the documentation of excavations. However, the use of archival photographs for this purpose has demonstrated the limited usefulness of this method in the context of ongoing archaeological analyses. As indicated in Chapter 3, the irregular geometry of the images network, their insufficient number and the small amount of metric data that could serve as a reference resulted in too low an accuracy of the photogrammetric study to be useful from the point of view of archaeological analyses. Equally important in the case of the area being developed, water was present over much of the site, resulting in glare and fewer feature points. These factors had a negative impact on the accuracy of the orientation of the photographs and on the quality of the dense point cloud, which was heavily distorted, as was the underlying 3D model in the form of a triangular grid. This analysis does not invalidate the usefulness of this approach for archival data but indicates that it is case-specific and determined by the quality of the available data.

Suppose the possibility of a detailed analysis of complex building structures is exhausted due to the lack of information on their vertical position or the impossibility of obtaining 3D images in the form of a point cloud in the Agisoft PhotoScan software. In that case, making 3D models in the SketchUp application is possible. On the basis of the spatial models obtained using this method, detailed analyses of the relics of buildings were carried out, i.e. chronologically and structurally identical structures were isolated from the remains of buildings from various phases and stages of modernisation, and they were subjected to functional analysis. This method played a special role when reconstructing the vertical position of compact, sometimes overlapping structures (e.g. floors, streets, hearths). The comparative analysis carried out at the stage of fitting the contours of the relics into the outlines of the relics visible on the photograph also fulfils the function of verifying the precision of the execution of
the drawing documentation, thanks to which it is possible to determine what part of the drawing documentation was executed imprecisely. This method is dedicated to creating visualisations of relics of buildings exposed in small areas (e.g. the basement of a building). It should also be borne in mind that reliably generated visualisations made using this method require a number of methodological considerations to be taken into account, which must be confronted with each other to correctly reconstruct the vertical position of the relics its possible slope. To determine the elevation of the relics above the ground, flat elements with clear edges are best suited to estimate their vertical position with greater precision. When attempting to model building relics using this method, it becomes a challenge to identify elements that are located in the background in the photographs, including those that are partially obscured or have convex surfaces. It is also difficult to identify the elevation of objects made up of rounded elements, such as the piles of stones that support the walls of buildings or form the building blocks of hearths. Because of their shape and layout, which varies in the photographs and drawings, their reconstructed height was determined by measuring individual stones, which were considered representative of the object.

The modelling method described required several assumptions that had to be considered during the archaeological analysis phase. As the models of the relics were, as a rule, prism-shaped, they best represented the surfaces of flat objects, which for the most part, was a good approximation of their shape, but posed difficulties in modelling rounded or irregularly shaped objects. This problem applied to stone hearths or prisms supporting the walls of buildings. Due to their shape and layout, which varied in photographs and drawings, their reconstructed height was determined by measuring individual stones that were considered representative of the object. However, the total height of the wooden, vertically aligned columns with irregularly shaped gable ends could not be determined precisely by this method. The fact that the height of the columns could only be determined approximately had to be taken into account during further analyses, as the columns are sometimes the only remains of buildings, and their reconstructed height is one of the indications determining their chronology. Furthermore, the accuracy of determining the height of the relics within a given site was not uniform, which was due to both the modelling method and the shape of the relics described above, as well as the quality of the source photographs, the completeness of the vector drawing and the way in which their mutual orientation was determined. For this purpose, the lines of convergence of perspective were used, the unambiguous indication of which in the photographs was often difficult. Given this fact and the difference in the geometry of the photograph (which is a median projection) and the drawing (which is an orthogonal projection), the heights of relics located at a greater distance from the observer were treated with greater caution during archaeological analyses, which was related both to the lower accuracy of the height measurement and the difficulty in identifying individual objects located close to each other (e.g. street logs).

Spatial modelling with CAD applications of the relics of the Biskupin defensive settlement together with archaeological layers is applicable to the analysis of complex, multi-phase building structures, which are difficult to interpret even on the basis of complete archival drawing and description documentation. An additional difficulty in interpreting these structures lies in the close vertical position of street surfaces and building foundations, which lay directly on top of each other. A prerequisite for making correct models and, based on these, for a structural-chronological interpretation is knowledge of timber construction and familiarity with settlement issues in a 'wet' environment. These requirements are an indispensable prerequisite for modelling, the aim of which is to reconstruct all exposed, but not always fully documented remains of walls, streets, floors, etc., together with their correct geometry and sometimes reconstruction of their vertical position - this also applies to relics obscured by higher objects or those without information on vertical position. An additional tool supporting the chronological interpretation of structures are models of the archaeological layers in which these relics were exposed. The layer models, together with cross-sectional drawings, properly fitted into a spatial frame of reference, allow verification of the relative chronology of the building relics. An oblique photograph of the structures and details plays an auxiliary role.
The most significant advantages of CAD applications include integrating both types of drawing documentation - scanned plans and cross sections- and visualization of remains and models of interpolated archaeological layers. The main advantages can be divided into two categories:

- the ability to verify drawing documentation and recreate the missing three-space information;
- possibility of functional and chronological interpretation of remains;

With integrated images and visualizations, you can recreate the vertical position of remains and layers in cross-section documentation that does not contain this information. This possibility is illustrated in Figure 29. The perpendicular projection of the visualization of remains with a known three-space location (in the local spatial information system) on scans of documentation of archaeological cross-sections enables the identification of building elements on the documentation. By adjusting the vertical position of the remains outlines visible in the cross-section with the visualization of relics that were created on the basis of three-space plans, it is possible to recreate the vertical position of relics and archaeological layers (Figure 29).

The possibilities of functional and chronological analyzes are very wide, and the scope of their application depends on the questions posed. Thanks to the possibility of giving the modelled solids a different degree of transparency, it is possible to assess the stratigraphic position of the remains of the structures (Figure 30). An alternative option is “switch off” interpolated archaeological strata to determine their position in relation to significant archaeological strata. These activities are aimed at establishing the relative chronology, deposition processes before and after the end of the function of a given building object, chronological and construction verification, etc. (Figure 30).

5. Conclusions

This paper aims to present the possibilities and limitations of 3D modelling techniques based on archival data without georeferencing, spatial location information, complete metadata or the correct geometry necessary for processing by photogrammetric methods. As reference data, images (from different altitudes) taken during the archaeological excavations at Site 4 in Biskupin from 1934–1939 were used.

The wide range of applied spatial modelling techniques (Structure-from-Motion with Multi-View Stereo, Shape-from-Shadow, 3D modelling based on one image and vector drawings and 3D CAD modelling) makes it possible to apply various solutions - appropriate to the specifics of the documentation under analysis and all its limitations. The elaborated methodology of spatial modelling of the relics of the defensive settlement, using incomplete drawing documentation, devoid of descriptions and often also information on the vertical position of the relics, as well as an incomplete collection of archival photographs, made it possible to overcome one of the barriers which significantly prevented the source study of the fortified settlement.

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