

Article

Reconstruction of Lost Cultural Heritage Sites and Landscapes: Context of Ancient Objects in Time and Space

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Abstract: Diachronic studies play a key role in the research and documentation of cultural heritage and its changes, ranging from architectural fragments to landscape. Regarding the reconstructions of lost cultural heritage sites, the determination of landscape conditions in the reconstructed era goes frequently unheeded. Often, only ruins and detached archeological artefacts remain of the built heritage. Placing them correctly within the reconstructed building complex is of similar importance as placing the lost monument in the context of the landscape at that time. The proposed method harmonizes highly heterogeneous sources to provide such a context. The solution includes the fusion of referential terrain models of different levels of detail (LODs) as well as the fusion of diverse 3D data sources for the reconstruction of the built heritage. Although the combined modeling of large landscapes and small 3D objects of a high detail results in very large datasets, we present a feasible solution, whose data structure is suitable for Geographic Information Systems (GIS) analyses of landscapes and also provides a smooth and clear 3D visualization and inspection of detailed features. The results are demonstrated in the case study of the island monastery, the vanished medieval town of Sekanka, and the surrounding landscape, which is located in Czechia and was the subject of intensive changes over time.

Keywords: 3D modeling; diachronic reconstruction; cultural heritage; LOD; smart object; data fusion; Czechia

1. Introduction

Over the course of centuries, the landscape has changed in many places to be unrecognizable. Historical places or entire monuments were significantly altered or even vanished. Virtual reconstruction has become increasingly popular since the virtual model is a valid cognitive medium through which a user can study or even interact with the object. Not only the users from the general public but also the scientists frequently employ three-dimensional (3D) models, as they provide clear understanding of objects of cultural heritage as well as changes of the landscape.

Since Reilly [1], many researchers have studied the applications of virtual reconstructions to the domain of cultural heritage (and natural too) as a tool for preservation, reconstruction, analysis, and promotion [2–4]. The virtual reconstructions are used to address different issues and to target different audiences. Their point of interest ranges from very small artefacts [5,6] over the buildings [7] to whole cities (“Rome Reborn” (<https://www.romereborn.org>); Brno 1645 (<https://www.brno1645.cz>)). Accordingly, the data acquisition and the data modeling techniques vary.

In the literature, there are many studies regarding the techniques of digitization of 2D objects (paintings) as well as 3D monuments, sculptures, and even small objects such as pottery or jewelry. Most virtual reconstructions are based on 3D laser scanning techniques [8] or photogrammetry [9] to produce geometrically accurate as well as photorealistic products.

Different techniques are used for the reconstruction of lost monuments. Such modeling is based on preserved sources from the relevant era. These sources are highly heterogeneous and include charts, engravings, testimonies, or texts in contemporary chronicles. Additionally, an inspiration can be taken from structures that remain in existence, and their design is known to have been similar. As the study elements are no longer present, the original shapes are only being known within a certain probability [10].

For the reconstruction of large environments such as the lost cities or complex monuments, the procedural modeling is frequently applied [11–13]. To avoid the drudgery related to the manual creation of virtual worlds, procedural modeling uses the so-called shape grammars, sets of formalized rules, to automatically generate complex and repetitive geometrical shapes.

The most recent endeavors focus on the diachronic reconstruction of a researched site. Rodríguez-González et al. [10] present through the case study of the medieval wall of Avila (Spain) a 3D model that is enhanced by the time component (forming a 4D model) to represent the wall's condition in various historical phases.

The great spectrum of geomatics techniques and data sources meet in the field of cultural heritage and, clearly, the data fusion of these sources is a necessity. Many scientific works went in this direction. Especially photogrammetry and laser scanning can benefit from the integration of outputs from these methods and provide better results in a broader spectrum of measuring conditions [14–17]. Software products such as PhotoModeler (<http://www.photomodeler.com>), RealityCapture (Capturing Reality s.r.o., Bratislava, Slovakia), Pix4D (Pix4D S.A., Lausanne, Switzerland), CloudCompare, or Agisoft PhotoScan (<http://www.agisoft.com>) are examples of solutions that implemented these methods.

The need for the 3D data model optimizations of reality-based models as well as their online distribution on the web was pointed out by [18] and further elaborated in [19]. A more complex approach to the optimization that goes beyond needs of visualization of the reality-based model can be found in the field of Geographic Information Systems (GIS). For example, the role of topology in the geometry simplification and model generalization process is the key element that preserves the analytical value of the spatial model; see [20].

Moreover, the data model itself and its dimensionality should be considered as a means for data volumes reduction. Often, the use of a 3D scene for the visualization of a model results in a classification of a model as 3D. However, this classification does not recognize the difference between a model that uses 2D primitives in 3D space (sometimes termed as 2.5D) and a model using 3D primitives in 3D space, forming a true volumetric 3D model [21]. The pragmatic hybrid 2.5D/3D solutions exist; for an example, see [22], which react to the structural complexity of pure 3D solutions. In order to avoid it, these approaches utilize the simpler 2D modeling as much as possible and reach for 3D only when necessary. Multiple aspects of 3D modeling, including the suitability of various modeling approaches for data management (editing, future updates) and distribution or spatial analysis, are covered in [23].

Analyses of digital terrain models can stand as an example of the functionality that GIS provides. Although the reconstructions and visualizations of lost heritage sites are an active research area, the landscape in the vicinity and the changes it underwent over the time are paid surprisingly little attention. The change of the bare Earth shape and its impact on the landscape function, land use, or the urban component is rarely discussed. Nevertheless, some works proceeded in that direction [12,13,24–28] in terms of including landscapes among cultural heritage (CH) objects, historical landscape visualization, or providing methods of relevant data processing and means for the rapid procedural modeling of landscapes. The modeling of landscapes usually comprises six

essential elements: landform; vegetation; water; structures including architecture and infrastructure; animals and people; and atmosphere (including sun, wind, etc.) [29].

The virtual representation of a historical landscape can be used to compare present-day and historical conditions and serve as a solid foundation for rigorous spatial and temporal analyses.

1.1. Objectives of the Study

With respect to the studies reviewed above, we observe a gap between solutions to 3D reconstructions of the cultural heritage sites and modeling of the landscapes. It is a context, both spatial and temporal, that current virtual reconstructions or virtual museums fail to provide for individual pieces. Our aim is to add this context to individual objects within the reconstructed monument and to add context to the monument (and even the whole lost city) within the landscape.

Therefore, we propose a complete methodology to create a virtual representation that offers a combined visit to detailed objects originating from archeological findings of a lost monument, to the reconstruction of such a monument and to the ambient landscape including the neighboring vanished city in corresponding historical periods.

We start with a brief introduction of the study case, namely, the lost site of Ostrovský klášter (“Island monastery”), the abandoned medieval town on the Sekanka promontory, and the surrounding landscape that has undergone intensive changes over time. Furthermore, we harmonize highly heterogeneous available data sources in Section 2. The available documentation, the chronology, and the accuracy of data sources define their role in the reconstruction efforts (Sections 2.1 and 2.2). The data fusion forms the foundation of the diachronic reconstruction of the site and the environment. That includes the fusion of referential terrain models of different levels of detail (LODs) (Section 2.3), the modeling of historical landscape (Section 2.4), the fusion of a digital terrain model (DTM) with reconstructed historical objects (Section 2.5), and the fusion of 3D data sources of different LODs for the reconstruction of historical objects in the third dimension (Section 2.6). Although the combined modeling of large landscapes and 3D objects of a high detail results in very large datasets, we present a feasible technical solution that provides smooth and clear visualization. The results are given in the Section 3, which is followed by the Section 5.

1.2. The Historical Context of Study Area

The area of interest includes the former Abbey of the Decollation of St John the Baptist (Figure 1). The historical information about the place, including the interpretation of archeological discoveries and architectonic details can be found in [30,31]. The ruins of the monastery are located on the Vltava river island south of Prague near the confluence of the Vltava and Sázava rivers. The history of the monastery goes back to 999 when it was officially founded by Boleslaus II, the Duke of Bohemia, as the second oldest male convent in Bohemia. In addition to the missionary activity, the abbey was a key player in cultural and economic development, state politics, and diplomacy.

The original wooden objects of the monastery succumbed in 1137 to an extensive fire. During the subsequent restoration, new stone buildings were built in the Romanesque style. During the 13th century, the site experienced great prosperity. A medieval settlement (Figure 1) grew up above the monastery on the rocky promontory Sekanka by the river’s confluence. It existed only shortly since its foundation in 1250 until 1278, when it was plundered by Brandenburg soldiers. The town has never been restored. However, the monastery was rebuilt in the late Gothic style during the reign of the Emperor Charles IV. Later, it was pillaged multiple times during the Hussite wars. The monastery gradually fell into disrepair. In 1517, the monastic community decided to abandon the place definitely. In the west bank of the Vltava river, the Church of St. Kilián (since around 999) has been preserved (Figure 1) in the re-built Baroque appearance.



Figure 1. The contemporary state from an aerial view (arheologickyatlas.cz) with marked locations of the lost monastery (red circle), medieval town (green circle), and Church of St. Kilián (blue circle). Source: The Archeology atlas of Czechia (2020; http://www.arheologickyatlas.cz/cs/lokace/davle_pz_mestecko_sekanka) and Open Street Map (2020; geo: 49.8812, 14.3908).

The landscape has also changed significantly over the studied periods. To pull the empty ships back upstream, the towpath was built in the 19th century connecting both ends of the island with the west bank of the river. These barriers even caused one of the river's arms to cease to exist and the island to merge with the mainland. Then, the drained river's arm was used for farming purposes.

However, the most prominent change refers to the rise of a water level of the Vltava river caused by the filling of the reservoir Vrané in 1936. The rise reached approximately 5 m, which caused an overflow of the then banks and significantly changed the shape of the island.

2. Materials and Methods

This section presents historical and geometrical data sources for the 3D reconstruction in multiple time periods originating from archeological research, early maps, or modern geomatics acquisition methods. The method describes the data assessment and fusion to obtain a model of the historical landscape, 3D reconstruction of historical objects, and their integration within a single information system.

2.1. Preliminary Considerations and the High-Level Concept

The concept of the proposed method deals with four categories of data regarding the scale. The employed classification proceeds from [25]; however, the functions of our classes differ. Each category plays distinct role within the proposed solution with specific requirements on the defining data.

Artefact level. There are two main roles of this category in our approach. The first is the digital preservation of an artefact. The raw data should be archived with the highest possible detail in a detached database for possible analytical uses in the future.

The second role is the digital exhibition of the 3D model constructed from the raw data. The LOD of the original data needs to be reduced for this purpose to meet the requirements of web graphic libraries.

Architectural level. This class refers to the objects of a larger extent with a dominant Z dimension such as monuments or buildings. Its purpose is to provide the most possible detailed depiction of the objects in various periods of time. That includes the overall appearance of the interiors and exteriors. Individual pieces from the artefact level play an important role at the architectural level, since the

preserved artefacts are helpful in the reconstruction of lost monuments (position, function, context, or relation to other detailed artefacts).

Urban land. Similarly, the architectural level objects and their mutual composition in space present their development, function, and context at the urban land level. This level integrates the architectural objects, meaning, they are all referenced to its surface. From the data modeling point of view, the surface (2D) is a sufficient data representation at this level, while the architectural objects require the 3D approach (multiple Z-coordinates for a single X,Y-location). The defining data of the urban land need to be at a detail sufficient for the description of man-made or natural changes of the bare Earth shape (embankments, earthwork, landslides, sedimentation). The resolution of at least one point per square meter allows for a convincing visualization of land changes and for basic terrain analyses (slope, aspect, height differences, volumetric changes).

Rural land. Rural land puts the urban area in the context of a broad neighborhood. Functionally, it is supposed to represent the overall shape (lowland, mountainous land), the land cover/land use, and their changes over time. Moreover, within the system, it has a function to navigate between points of interest and support the exploration similarly to Google Earth or other digital Earth engines. From the data modeling point of view, rural land is the 2D surface of a lower detail than the urban land.

Consequently, the proposed solution employs the hybrid data model that combines the second-dimension terrain surface (termed as 2.5D) at multiple LODs with 3D objects (varying LOD according to the purpose). These models are seamlessly joined at constraints to the triangulation of the terrain model. The concept of the proposed solution is illustrated in Figure 2. To model the geometries of interiors and exteriors, the workflow of the procedure uses a combination of software AutoCAD Civil 3D 2018 (DEM creation from elevation points in SketchUp format), QGIS 3.10 (map preparation and surface creation–data fusion), and SketchUp Make 2017 (modeling and texturing). That includes the fused and adjusted DTMs with the footprints (constraints to TIN) for the precise integration with the actual 3D geometry. GIMP 2.8 was employed for the processing and normalization of textures of interiors (frescos).

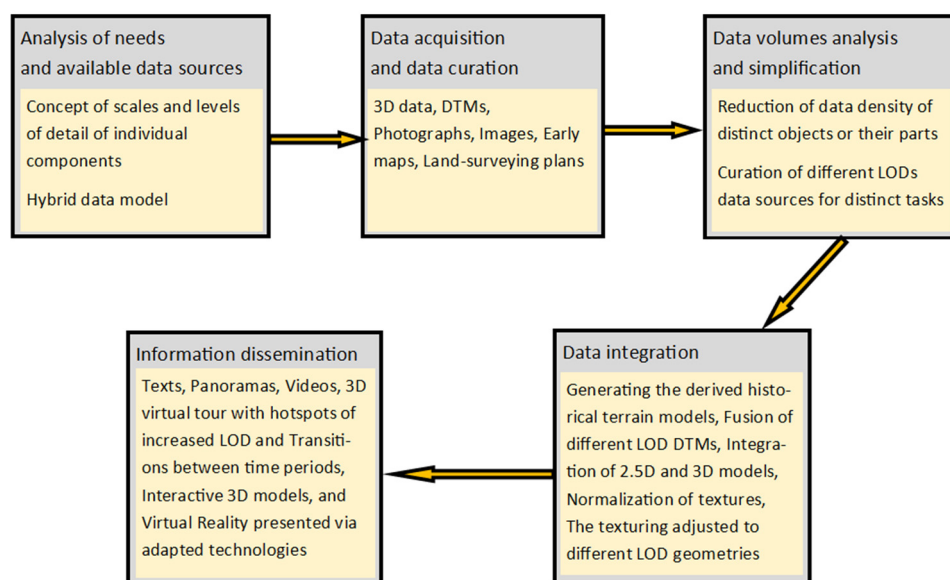


Figure 2. The solution's workflow summary starting with the conceptual analysis to the employment of technology for distribution of variable thematic data layers.

The final rendering was carried out in software Lumion Pro 10.3.2. Rendered panorama images from Lumion were employed in Theasys online software in which the virtual museum was designed. The hotspots in the virtual museum can be accessed during the walk through the overall model and interactively examined by a user in a full detail.

2.2. Archeological Sources

Archeological sources are a key factor of the anastylosis—in this case, the digital recreation of constructions that no longer exist. They provided original architectural and decorative pieces that are unique to our case. Within the overall model of interiors, they form certain hotspots that the user can inspect in higher detail as they can in a virtual museum.

Fragments found during the archeological research prove the high artistic value of the monastery decorations. The incorporation of such authentic features into the virtual reconstruction is an intermediate aim of this work.

The tiles of Vyšehrad type are perhaps the best-known artefact (see Figure 3c) that probably originates from the own production of the monastery's ceramics workshop. Researchers found floor and mural tiles of various shapes including the hexagonal form used for the star-shaped wall decorations, as can be seen in Figure 3a,c.

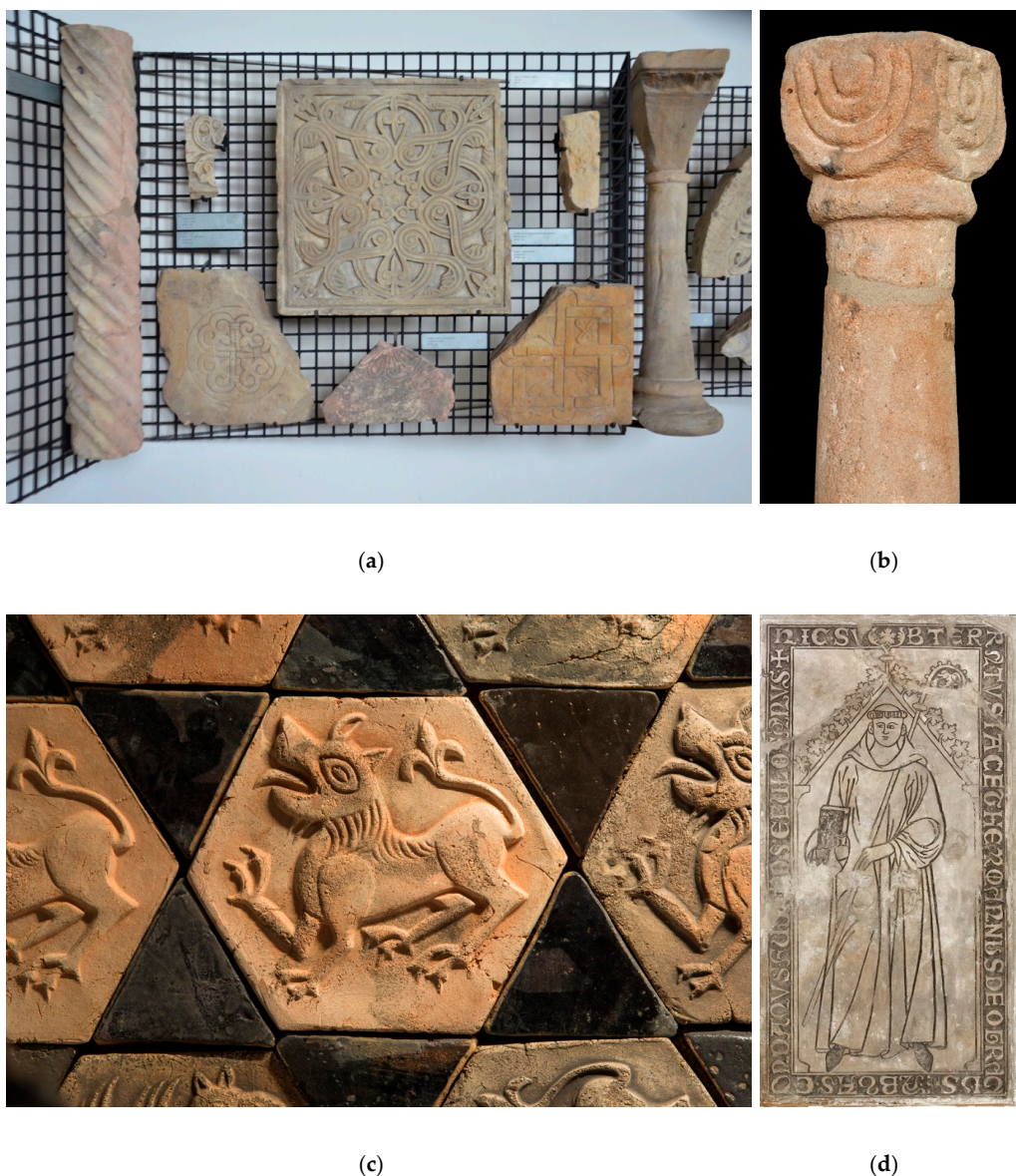


Figure 3. Various historical sources employed: (a) Presentation of artefacts in the National Museum in Prague; (b) The Romanesque pillar of the National Museum collection; (c) The hexagonal tiles of so-called Vyšehrad type; (d) The tombstone of abbot Heřman. Photos: Petr Kríž and Tomáš Palatý (2017).

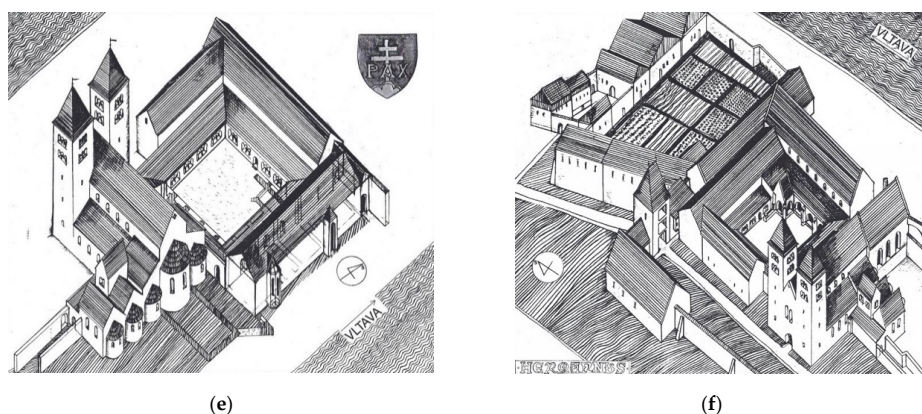


Figure 4. Examples of early maps and land-survey plans originating from archeological research: (a) The Second military mapping; (b) The cadaster mapping (Franzische Kataster); (c) The plans differentiating the structures of monastery's Romanesque and Gothic eras; (d) The plan of the lost town Sekanka (Romanesque era); archaeological drawing of the monastery in Romanesque era (e) and in Gothic era (f). Source: 2nd Military Survey, Section No. 9/2, Austrian State Archive/Military Archive, Vienna (a); State Administration of Land Surveying and Cadaster (b); Miroslav Richter (1982; (c,d)); František Stehlík (1947; original) and Jan Heřman (2009; redrawn with new notes by archeologists; (e,f)).

2.4. Data Fusion—Referential Terrain Models

With the progress in the field of spatial data acquisition, high-resolution Light Detection And Ranging (LiDAR)-based DTMs are often available covering the entire countries. However, for the sake of distinct projects, local data acquisition campaigns provide even higher resolution DTM necessary for the analysis of such an area. However, for visualization purposes, a greater area described with lower detail is required. If the extent of high-resolution DTM is sufficient for visualization, the parts of the model that are more distant from the point of interest (POI) may be progressively simplified [34]. If it is not the case, the fusion with a different DTM is a solution.

In our case, this fusion effort is presented through an example of the Digital Terrain Model of the Czech Republic of the 5th generation (DMR 5G) and the Shuttle Radar Topography Mission (SRTM) integration. The first category of data employed for the production of DTM is the airborne LiDAR system data DMR 5G by CUZK (<https://geoportal.cuzk.cz>). DMR 5G is an irregular network of discrete height points. The total mean error of height measurement is 0.18 m (barren) up to 0.3 m (forested area). This dataset is meant for the close vicinity of reconstructed objects of the cultural heritage site. The burden of high data volumes is introduced using high-density datasets; therefore, for the more distant areas, the SRTM digital elevation model (DEM) (<https://www2.jpl.nasa.gov/srtm>) was preferred. Although there are DMR 5G data available for the entire country and the progressive simplification would be possible, we decided to use freely available SRTM data (DMR 5G is a commercial product). Moreover, SRTM DTM is coherent with digital Earth systems, which similar to Google Earth employs an SRTM data source. Therefore, this choice prospectively supports the use of such platforms for presentation.

The objective of the two DTMs fusion is to provide a transition surface in terms of both the point density and the height adjustment (see Figure 5).

The input to the procedure consists of two-point layers, which corresponds to the source data of the two terrain models. The requirement is that both layers are aligned to an identical coordinate system and that the coverage of the dataset with higher resolution expands beyond the area that is strictly required to be modeled at such an LOD.

The transition surface is defined as a strip of land of a constant breadth. It is outlined on the inner side by the border with a higher resolution surface and on the outer side by the border with a lower resolution surface.

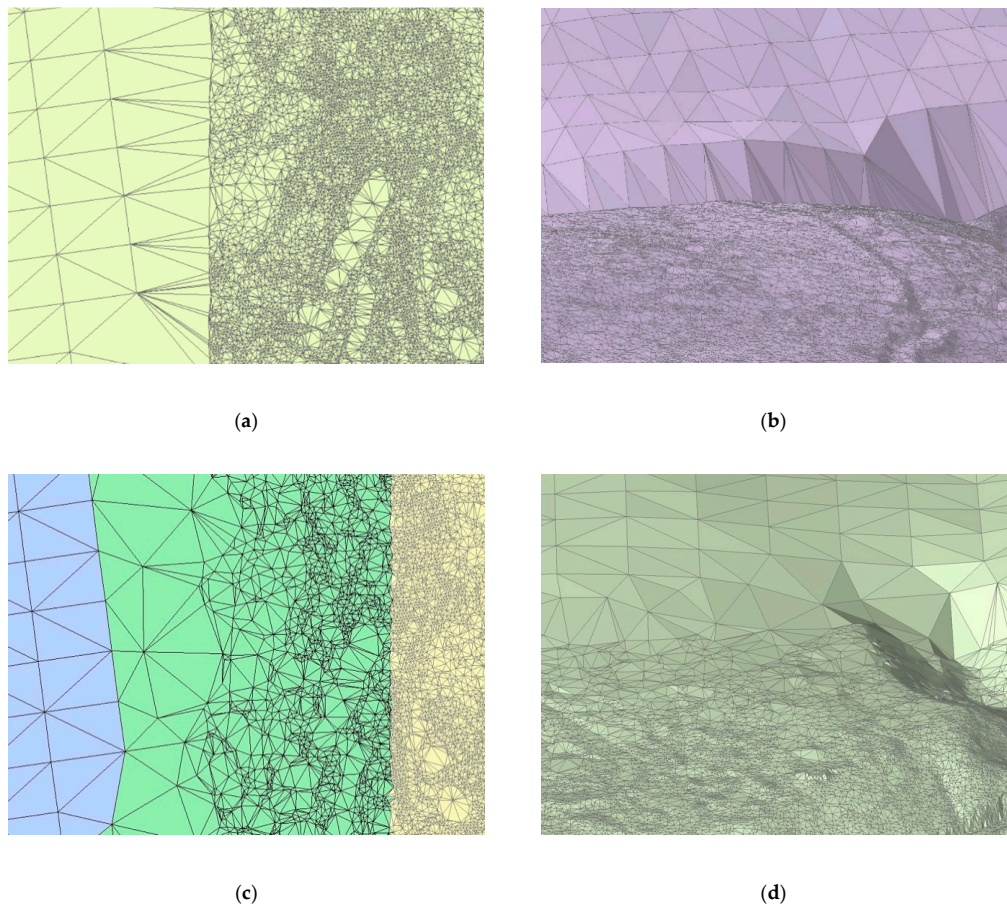


Figure 5. (a) The depiction of the triangulation of two datasets with highly different resolution resulting in a sharp divide and unnatural turn. (b) A 3D view on the boundary line and triangles with too small interior angles. (c) An illustration of the different DTMs geometries in the transition zone—low detail, high detail, and the transition zone illustrated with different colors. (d) The figure on the bottom right depicts a 3D view on the resulting geometry of the terrain. The resulting triangulation consists of triangles with far greater interior angles (more equilateral), which follows the objective of the Delaunay triangulation and therefore adheres more closely to the actual terrain course.

2.4.1. Mesh Simplification

First, we want to avoid the disruptive influence that the sharp change of a point density causes to the visualization and cognition of the DTM, namely, to avoid narrow, elongated triangles. To achieve a smooth geometrical transition between both datasets, we progressively removed points from the finer resolution dataset that fell into the transition zone.

For this sake, we have assigned a weight to each point. The weight is an outcome of a combined influence of a point's distance from the inner border of the transition area and a point's importance for the description of the surface shape. The distance component is obtained as a linear weight function, starting with a zero influence at the inner border and reaching the full influence at the outer border.

For the latter component, the metric first introduced in [34] was applied, which describes the error introduced to the shape of the surface by the point's absence.

The resulting weight of a point is obtained as a weighted sum of both weights giving 85% influence to the distance component and 15% influence to the shape-description component. This ratio was determined experimentally for the researched area to achieve a visually convenient outcome.

The simplification procedure stops when a threshold (the value of weight, which was also inferred experimentally) is reached, all points having the weight below the threshold removed. Consequently, the triangles of the resulting triangular irregular network (TIN) gradually grow toward the outer

border and keep their equilateral-like shape (illustrated by the 2D view in Figure 5c and 3D view in Figure 5d).

2.4.2. Height Adjustment

Second, to achieve a smooth transition of heights, we made use of the triangular mesh created from points of the coarser data source. For each point from the higher resolution layer within the transition surface, we have extracted its respective height from the TIN.

To determine the amount of influence of the coarser DTM on the finer DTM points, we applied the linear weight function. Starting from the inner border of the transition zone, where the zero weight is given to the height derived from the coarser DTM (full weight given to the original height of finer DTM), the weight of the coarser DTM increases linearly moving to the outer border, where the coarser DTM heights gain the full influence.

Weight functions different from the linear one can also be applied. For a more detailed description and an analysis of the effects the different weight functions have on the continuity of the resulting surface, refer to [35].

2.5. Modeling of Historical Landscape

Early maps listed in Section 2.2 served as sources for an estimate of the original shapes of the riverbanks, promontory, and island. The most helpful in this aspect was the 2nd Military Mapping, which also provided the location of the now gone medieval bridge that connected the island with the left bank until the 19th century.

Furthermore, the early photographs, e.g., see Figure 6, from the first two decades of the 20th century helped reconstruct the geometry of the embankments that caused the merge of the island with the mainland. Figure 6a shows the connected island with the bank in south. Figure 6b shows the original shape of the promontory before Vrané reservoir filling and the northern part of the island.

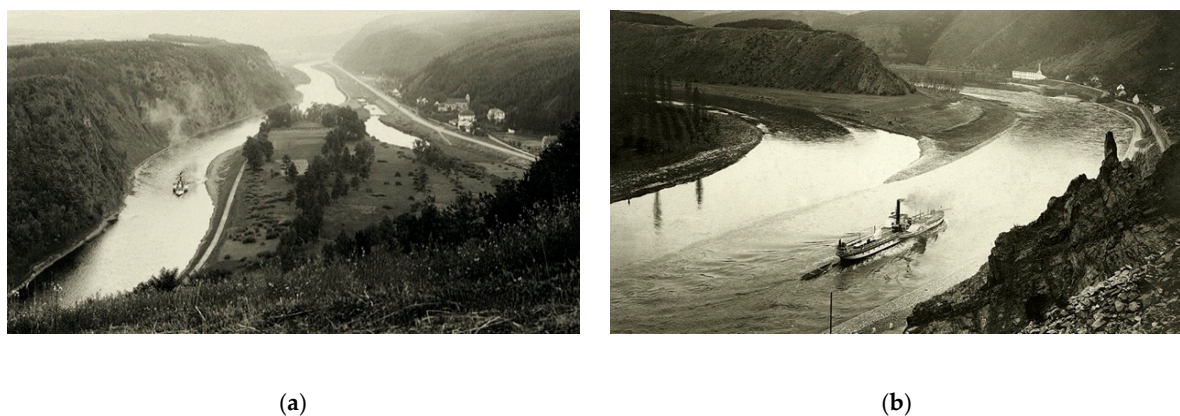


Figure 6. Photographs of the former island and its merge with mainland from the beginning of the 20th century from northeast (a) and north (b). Source: Josef Dvořák (<http://www.dvorak-davle.cz>).

These raster materials were georeferenced and overlaid with the contemporary LiDAR-based DTM. Based on these sources, the outlines of banks and the island were manually vectorized to represent the state before the construction of the weir or the dam later. The artificial height points were generated in the area of revealed banks and their heights linearly interpolated between the original and the new bank. The contemporary island measures 410 m in length, and the promontory measures 65 m. For illustration, the length of the island inferred from the 2nd Military Mapping before water level rise amounts to 597 m, resp. 146 m of the promontory. The root-mean-square error (RMSE) of the georeferencing on the x,y-coordinates reached 7.5 m.

Similarly, the photographs helped delimit the outlines and area of embankments, and the adjusted artificial height points formed the terrain of the newly arisen mainland.

The conventional affine transformation was employed as the rectification procedure. As matching ground control points, the changeless spots such as bedrocks exposures or the church were found. Such reference points were selected that minimized and uniformly distributed residuals across the rectified images.

Moreover, the early maps, panoramas, and chronicles together with consultations with relevant experts helped obtain an idea of how the structure of the path network and the land use (including the knowledge of historical plant ecology in the wider surrounding area) looked at given historical periods. This knowledge was later used for a relevant landscape texturing of the resulting model.

2.6. Data Fusion—DTM and Reconstructed Historical Objects

The land surveying plans (Figure 4c,d) originating from the archeological survey in [32] were scanned and then georeferenced using the tie points and control points acquired in situ with a Global Navigation Satellite System (GNSS) device. The outlines of cultural heritage objects as well as the outlines of their interiors were vectorized. The information of the period of construction, which was the outcome of the same archeological survey, was associated with corresponding geometries. The maximum x,y-coordinates positional error of the rectification procedure reached 0.25 m with the RMSE equal to 0.11 m.

The elevation of the points that form the footprint of a reconstructed object on the bare ground was derived from the DTM (DMR 5G). The footprint acts as a constraint to the TIN; therefore, the elevation of its points was set as a mean value of DMR 5G height points directly neighboring with the footprint's point in the TIN.

These footprints stand for an exact line of contact between the 2.5D DTM and 3D models of reconstructed objects. The resulting footprint of a building's object also serves as a mask for removal of the terrain height points that are no longer necessary in places of reconstructed 3D objects.

The footprints' line segments were densified (auxiliary vertices inserted where necessary) to provide smooth integration with TIN DTM in terms of triangles' shape.

2.7. Reconstruction of Historical Objects in 3D

The 3D modeling has three main stages in our workflow. First, it is the production of artefacts' models, second, the reconstruction of the buildings and, lastly, their integration.

Despite the limited knowledge of the vertical dimension, there are preserved architectural and functional pieces of the original construction whose location is determined with relevant accuracy. The tombstones (Figure 3d) stand as an example of an artefact whose positional accuracy was estimated in the report [32] to be up to 1 m.

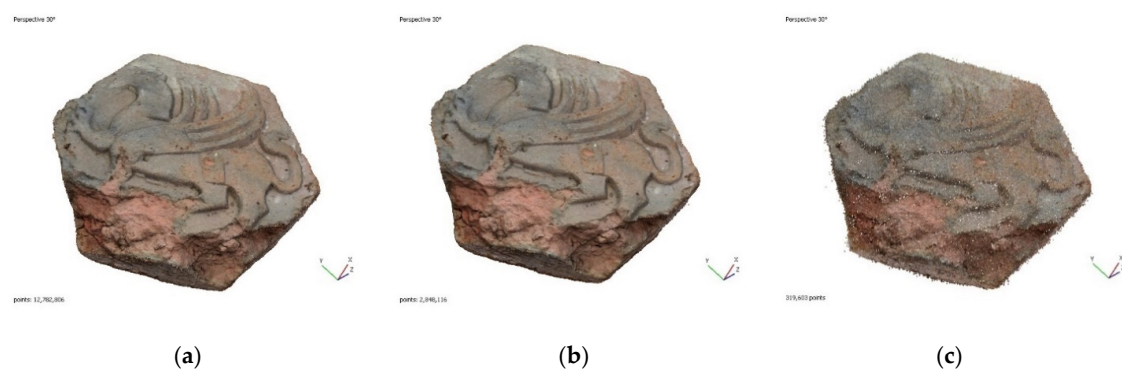
Photogrammetric methods enable the retrieval of 3D information from 2D images. Due to the objects (archeological artefact) proportions, the close-range photogrammetry was applied. The control points were distributed around the object and marked with black-and-white targets. Imaging was gradually conducted around the object while keeping the distance and overlay ratio of the adjacent images. The parameters of the Nikon D750 camera are highlighted in Table 1. Table 2 sums up the processing values of the tile. The varying resolutions of the processed dense point cloud of this artefact can be seen in Figure 7.

Table 1. Camera specification.

Parameter	Value
Image resolution	6016 × 4016 px
Sensor size	full frame (35.9 × 24 mm)
Lens	Nikon AF-S
Focal length	fixed 120 mm
F-stop	f/8
Image format	jpeg

Table 2. An overview of the parameters of a model constructed from the highest density point cloud in Agisoft Metashape.

Parameter	Value
Tie points	319,603
Dense cloud points	12,782,806
Dense cloud quality	High
Dense cloud processing time	1 day 5 h
3D model faces	2,332,552
3D model vertices	1,170,947
3D model processing time	22 min 11 s

**Figure 7.** The dense cloud representations of the tile processed in Agisoft Metashape at different levels of detail (LODs): (a) 12,782,806 points (b) 2,848,116 points, and (c) 319,603 points.

Despite all the above-mentioned sources available, the knowledge of the shape of buildings of the monastery to be reconstructed is quite limited in the third dimension since they are no longer present. Therefore, we have performed our own survey together with historians and archaeologists from the Regional Museum Jílové u Prahy to acquire an inspiration on the missing parts. This survey focused on sacral buildings in the broader region originating from the same era that are preserved to this time. Comparing the ground plans, the monastery in Milevsko was identified as the most similar preserved object to our case (two towers front facade, the Gothic basilica, and the surrounding quadrature).

Other places of interest were monastic objects in Sázava, Jindřichův Hradec a Strakonice. The height and the thickness of walls of these existing objects were surveyed, and their proportions were calculated. Afterwards, the heights of objects that constitute the reconstructed monastery were inferred from the thickness of their principal walls with respect to the discovered proportions of the extant objects.

Similarly, the appearance of interiors was inspired by the extant monasteries of that era. The textures for the final stage of the model design were collected at the referential sites by means of detailed photographs of frescos and architectural features. Nevertheless, the textures needed to be adjusted to fit the distinct extents of the reconstructed building as well as the geometry of incorporated shapes of the artefacts' terrestrial laser scanning (TLS) models, which form certain hotspots in terms of trueness and higher detail. Texture processing was enabled by GIMP 2.8 software. The acquired images were transformed from central to orthographic projection and the saturation and brightness were

adjusted. The white was balanced to restore the look of faded frescos. Subsequently, suitable filters (sepia tone, clarendon filters) were applied to normalize the color balance of individual frescoes taken from places with varying measurement conditions.

The high-resolution models originating from close-range scanning required heavy simplification of the mesh to allow for effective manipulation within the modeling software packages as well as for the consequent web-based rendering and distribution. Blender 2.83.3 software was employed to decimate the numbers of edges and faces up to 1–5% of the original terrestrial laser scanning (TLS) model's resolution. To enhance the realism of the model rendering after the coarse simplification, the edges of the model were smoothed. The AMS Soften Edges free plug-in (version 1.2.0) was applied, as it extends the capabilities of the default SketchUp Soften Edges function, and the threshold of an angle between normals is set to 4%.

3. Results

Three complex reconstructions (Figures 8–14 and Appendix A) were designed for different periods of time forming the diachronic model of the site and its surroundings. The first two comprise all known buildings in the Romanesque and, respectively, the Gothic era. They are placed upon the adjusted terrain and within the landscapes of the period. The third model corresponds to the first two decades of the 20th century with the ruins of the monastery and contemporary buildings. Three variants of landscape related to this recent era were modeled, as it was influenced by the changes of the new embankment, the weir, and finally the dam.



Figure 8. Visualization of the reconstructed middle age town Sekanka.



Figure 9. Illustration of the incursion of the Brandenburgers.



Figure 10. Visualization of the monastery in the Romanesque era in the summer season.



(a)

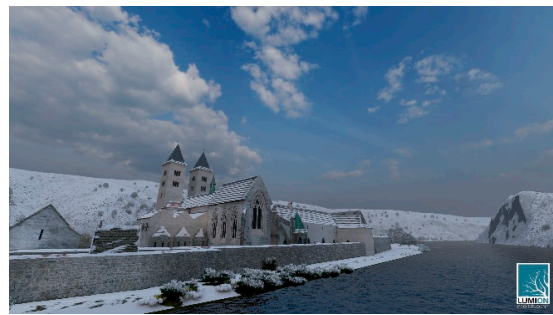


(b)

Figure 11. Visualization of Church of St. Kilián on the left bank in the Romanesque era (a) and in the Gothic era (b).



(a)



(b)

Figure 12. Visualization of the Gothic era in the winter season from southwest (a) and southeast (b).

The visualization and distribution of results were carried out by Lumion Pro 10.3.2 and Theasys online software. The Lumion provided all essential elements of both the landscape's and monument's modeling: landform; vegetation; water; structures including architecture and infrastructure; animals and people; and atmosphere. The format of the results includes high-quality images and videos. Moreover, these outputs are reused within the more interactive system providing the exploration of the CH site—the online virtual museum implemented within the Theasys application. The virtual museum's tours offer predefined trails for a visitor, panorama images, and predefined time machine transfer between different eras with identical view frustum for the sake of comparison. Moreover, the hotspots with higher-detail images of artefacts and descriptive texts are available as well as the 3D interactive models of artefacts, which are as a detached product linked with the museum. The figures below illustrate the results.



Figure 13. Gothic basilica interiors including paintings of the period and tombs. Own work (2020).



Figure 14. Interiors of the Gothic quadrature nearby the cloister including paintings of the era and the floor formed from tiles. Own work (2020).

In the foreground of Figures 8 and 9, there is a DMR 5G terrain model around the town Sekanka. The fused DMR 5G and SRTM can be seen across the rivers. In the background, there is the SRTM-based model of lower resolution. The transformed DMR 5G forms the ground of the island (Figures 9–12).

The Lumion software also allows for a convincing presentation of seasonal or weather changes, the layout of shadows, and the position of the Sun, which enables a significantly more persuasive presentation of the site in a given era, see Figures 8–12 and 14. The advanced visualization tools helped depict historical events in a dynamic way, e.g., the devastation of the town Sekanka in Figure 11. In Figures 13 and 14, the rendered images of modeled interiors can be seen. Textures and models of preserved objects were used for creating realistic scenes. Figure 13 shows stone tombs and ceramic

tiles created with textures (from original preserved objects) and hand-modeled window pillars (their originals can be seen in Figure 3).

Figure 15 compares two approaches to interiors modeling. The first proceeds from the textures acquired in extant monasteries and adjusts them to fit the geometry. The use of texture has limits due to the rectangular shape, which is problematic in corners of the room, and due to the pattern, which is too repetitive and makes visualization unrealistic.



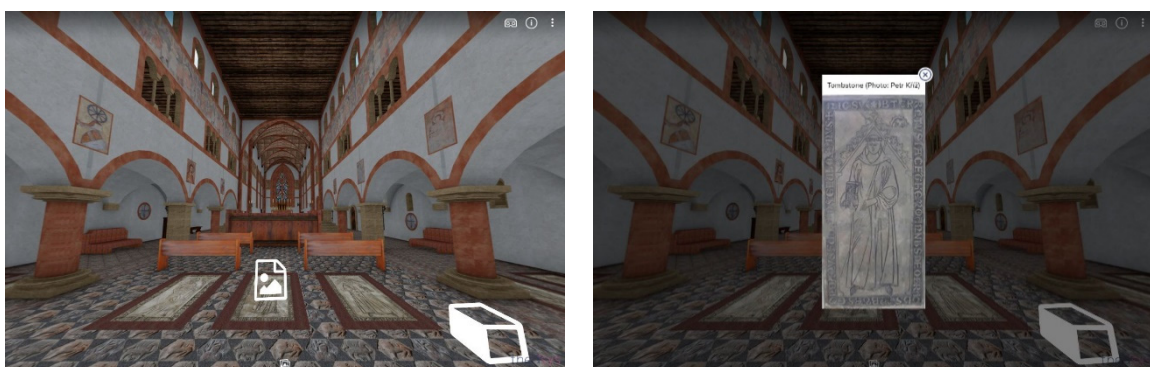
(a)

(b)

Figure 15. The gothic tiled floor created using adapted textures only (a) and using the processed terrestrial laser scanning (TLS) model (b) for comparison.

The second approach employs the textured 3D model of preserved floor tiles and assembles the individual pieces into the whole. Although the model is vastly decimated, the outcome is more realistic and elaborate. It is at the cost of increased computational demand (cf. Tables 3 and 4).

Finally, the rendered panorama images from the Lumion software were also used for the design of the virtual museum web app (the prototype can be accessed at <https://ths.li/3azGDH> and <https://ths.li/1HOfvZ>) (Supplementary Materials). It was carried out in the Theasys software. The result, which can be accessed from the desktop as well as from the mobile devices over the Internet, is illustrated by Figures 16 and 17, including the presentation of the digital walk, triggering the hotspot, or the transition between times. The virtual reality (VR) is also available using VR glasses or the augmented reality using gyroscope or gyrocompass in users' devices.



(a)

(b)

Figure 16. The virtual museum application with hotspots (a) that can be studied in detail in its own pop-up viewer (b).



(a)

(b)

Figure 17. The navigation between historical periods (a) the Romanesque era view and (b) the Gothic era view from the same spot and with the same view frustum.

Tables 3 and 4 show the quantitative summary of parameters of the designed model as they were natively recorded and provided by the processing software packages. For illustration, a sample of DMR 5G data (2×2.5 km) in area of our interest consists of 805,900 points (of which a 370,819-point subset was used), whereas the SRTM of this area is made up of 7283 points. The currently presented model covers approximately 5×5 km. The data reduction is significant especially with a prospect for future extension.

Table 4, which presents the statistics for models of interiors, also describes the influence of the TLS models when incorporated into the overall model. The influence of different intensity of simplification, which the original tile model was subject to, is also evaluated. The floor composed of tiles of 5% of the original resolution is the component of the clearly highest numbers of faces and edges. Incorporating the TLS models also effects the startup times and tests the limits of software; e.g., the Lumion was not able to contain the floor designed on the basis of tiles having either 5% or 1% of original resolution. For the sake of rendering, only a part of floor using tiles of 1% of the original resolution was used.

Table 3. Models of exteriors—an overview of components.

Content Part/Group Type	Roman Terrain and Surroundings (with Medieval Town)	Gothic Terrain and Surroundings	Romanesque Monastery	Gothic Monastery
Edges	1,128,516	452,650	92,110	715,102
Faces	542,375	271,295	36,948	299,393
Component instances	4653	337	65	165
Groups	3264	46	134	102
Component definitions	186	42	5	36
Layers	6	3	1	1
Materials	173	100	51	93
Size in the SketchUp 2017—without vegetation (MB)	54.5	41.9	16.4	34.7
Size in the Lumion 10—with vegetation and without rendering settings (MB)	159	118	35.9	148
Startup time with the SketchUp Make 2017 (in seconds) *	16.8	11.5	4.5	15.7

* tested model: Macbook 12" (Early 2015, Intel Core M 1.1 Ghz dual core, 8 GB 1600 Mhz DDR3, Intel HD Graphics 5300 with 1536 MB, 256 GB SSD, macOS Catalina) with background opened Mail and Safari, SkeethUp pre-opened, Finder active; measured with iPhone XR.

Table 4. Models of interiors—an overview of components.

Content Part/Group Type	Basilica	Cloister	Basilica's Floor Using Tiles of 1% of Original Resolution	Basilica's Floor Using Tiles of 5% of Original Resolution	Cloister's Floor Using Tiles of 1% of Original Resolution
Edges	860,048	893,553	66,049,248	425,160,789	66,942,801
Faces	374,231	390,417	41,115,014	278,209,820	41,505,431
Component instances	334	143	1862	2416	2005
Groups	618	337	33	31	370
Component definitions	100	36	1	1	37
Layers	3	1	1	1	1
Materials	106	77	3	5	80
Size in the SketchUp 2017—without vegetation (MB)	76.1	65.7	4.4	30	70.4
Size in the Lumion 10—with vegetation (in case of exteriors and cloister) and without rendering settings (MB)	207	213	-	-	-
Startup time with the SketchUp Make 2017 (in seconds) *	15.5	10.1	16.5	170	23.7

* tested model: Macbook 12" (Early 2015, Intel Core M 1.1 Ghz dual core, 8 GB 1600 Mhz DDR3, Intel HD Graphics 5300 with 1536 MB, 256 GB SSD, macOS Catalina) with background opened Mail and Safari, SkechUp pre-opened, Finder active; measured with iPhone XR.

4. Discussion

The contributions of the presented work inhere in two main aspects. First, the proposed methodology facilitates a smooth integration of geometry originating from heterogeneous sources ranging from the small archeological artefacts up to the large areas of landscape. As a result, it puts the available knowledge of a researched site in the spatial context. Second, the models of the studied place were designed following this methodology and covering several historical eras. The derived diachronic reconstruction served both the professionals and the general public as a basis for presentation purposes, comparative analysis, and CH maintenance policies during numerous opportunities, which provided valuable feedback.

Beyond the technological aspects of 3D reconstruction of the CH site, the experiment dealt with harmonization of the LOD of the source data. Despite the recent hardware developments, using the finest detail of all data that enter the final reconstruction would just produce extremely big data. Such data volumes prevent smooth responses when processing and analyzing the geometry of data in GIS desktop software or when rendering the final visualization. The distribution of the model and therefore the web compatibility is an even greater further challenge because of the limitations of web graphics libraries. That was already observed in [19], where the TLS and close-range photogrammetry models needed to be decimated up to 0.07% of the original size to meet such limitations, which leads to the loss of potentially important details.

The hybrid solution proposed here combines geometries of different dimensions and LODs. This approach allows preserving the detail only where needed and intensifies the simplification in less important regions, where only an outline is required. Therefore, the method allows the preservation of selected important details. The practical outcome of our work indicates it is a promising solution for systems that combine features of virtual museums, digital Earth, GIS, or even BIM. Although the BIM concept is apparently more meaningful for CH sites that are significantly more preserved than our case, the vision of intelligent objects demonstrating their function and relation to other features in the information system is enabled by contemporary BIM technologies. The intersection of CH, GIS, and BIM wins increasing interest within the scientific community [36–38]. Another interdisciplinary prospect emerges from the utilization of game engines (Unity, Unreal Engine). Especially in terms of increased navigation capabilities and interaction with 3D objects [39,40], their use would enhance the

CH virtual museum based on Lumion and Theasys with its predefined visitor's trails. The aspect of navigation between various POIs is a core of digital Earth technologies although at a far smaller scale (greater spatial extent). The integration of these systems is a future challenge.

5. Conclusions

We proposed a novel solution that combines the approach of a virtual museum with a reconstruction of the cultural heritage site and the landscape. We provided the most comprehensive diachronic reconstruction possible considering a complete range of available data sources. By those means, the known story of the site was reconstructed from existing fragments, interpreted, and visually conveyed.

As a result, a user can experience a detailed representation of objects coming from archeological findings in the context of the whole monument and the monument within the landscape in selected periods of time. Our approach integrates multiple data sources resulting in a hybrid data model. Regarding the dimensionality, the referential terrain model remains in the second dimension (2.5D) and consists of two different LODs with the smooth LOD change in between. The constraints to the TIN-based DTM act as an interface at which the DTM is joined with the true 3D models of reconstructed monuments. The archeological pieces scanned with very high resolution were incorporated into the reconstructed missing parts of the monument. Moreover, they were also modeled as a detached product, the hotspot, which a user can interactively discover in a high resolution.

The presented solution combines different dimensionalities and consists of multiple LODs of reality with a higher detail applied only where needed. This hybrid approach has proven to be effective when dealing with increasing data volumes and the current limitations of web graphics libraries such as the polygon count or textures.

On multiple occasions, the presented system, which combines the inspection of detailed features with the building or even landscape level, promoted the site and attracted the attention of both the general and the professional public to the case. Such popularization events include the national-level television news, popular science media, lectures, or a part of the permanent exposition in a regional museum.

Supplementary Materials: The virtual museum application with hotspots: <https://ths.li/1HOfvZ> and <https://ths.li/3azGDH>. The ceramic tile from Ostrovský klášter: <https://skfb.ly/6RHZ8>.

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Appendix A



Figure A1. Illustration of the incursion of the Brandenburgers (the Romanesque era).



Figure A2. Visualization of Church of St. Kilián and the monastery in the Romanesque era.



Figure A3. Visualization of Church of St. Kilián and the monastery in the Gothic era.



Figure A4. Visualization of the monastery in the Gothic era.



Figure A5. Visualization of Church of St. Kilián and the monastery in the Gothic era.

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