Dealing with the object libraries in a structured way, on the other hand, is a contributing step towards standardization and a motivation for undertaking this research.

Generated models are valuable sets of data about the historical evolution [2], the materials and the technics used in bridge construction and can as such be used in cultural, touristic or educational purposes. Next to that, hBIM models may help to analyze structural conditions of a bridge, identify its weaknesses, and plan architectural and engineering interventions, or they can be used to monitor bridge structural health, resilience and maintenance over time.

Several conducted studies through literature, prove the applicability of hBIM to stone bridges.

Wan et al. [3] presented a case study of using the BIM technology to restore the historical stone Xijin Bridge in China, dating back to the Ming dynasty; Sun and Cao [4] discussed the use of BIM technology to analyze stone arch bridges and improve their structural analysis and design; Saback de Freitas Bello et al. [5] studied the use of BIM technology to create a digital twin of a stone bridge, in order to evaluate its structural behavior and to support maintenance and renovation works; Banfi [6] described the use of BIM technology to document and analyze a historical stone arch bridge with the goal to support preservation and maintenance efforts. Last but not least, Aglietti et al. [7] propose a BIM-oriented approach for modelling stone using sensors.

Object libraries are an important segment of hBIM. Typically, these libraries contain pre-embedded, i.e., pre-designed and pre-parameterized objects like arches or pillars that can be inserted into 3D models of built structures. Nevertheless, the level of detailing and the accuracy of available elements from libraries may be unsuitable for specific purposes. The challenge is even more pronounced when dealing with the built heritage structures because they are characterized by uniqueness and originality, and highly present local or regional peculiarities. For that reason, there often is a demand to generate custom object libraries for specific heritage categories, or individual structures and their parts.

Published research features several works where custom object libraries for heritage structures, including stone bridges, were proposed [e.g., 8-10]. Custom made objects help to represent specific historic assets more accurately and to highlight their typological and morphological unique features [11] at the same time. Hence, identified current gap in the offer of the object libraries for hBIM needs to be addressed both in research and in technological development. Particularly, there is a need to optimize between contrasted demands: to enable a sort of standardization, and the efficacy of using hBIM with it, from the one hand, i.e., to pay respect to heritage uniqueness which is time and effort consuming, from the other hand. This duality could be overcome by developing new object libraries that correspond to specific built heritage typological clusters, and such an approach has been taken in this research.

Topological clusters of heritage structures, in case of this work the single arch stone bridges, share several common key characteristics, and creating, disseminating and using their custom objects libraries will bring efficiency, accuracy and better quality in professional work. Prior to that, however, it is needed to harness the data on bridges’ size, proportions, materials and structural features by using digital methods of surveying, and to, subsequently, analyze and compare their characteristics by using hBIM technology. Processing data and deriving common principles and patterns of single arch stone bridges, as demonstrated in this work, ultimately result in creation of libraries for typical single arch stone bridges and their elements.

Further research is necessary to improve the accuracy and functionality of the object libraries in a hBIM. The reasons are mainly due to the difficulties with the historic structures and the different ways they were built and the materials that were used for their construction. The object libraries should be flexible enough to continuously update them with new knowledge about historical construction methods and materials but also follow the heritage standards. Because of this, detailed documentation and preservation efforts may be made, and the objects will faithfully reflect the intricate details of cultural structures. Also, the object libraries must be developed in such a way to appropriately capture the ideas of various specialists because the preservation of cultural monuments necessitates the integration of multidisciplinary knowledge.

In line with the above, this study focuses on developing smart object libraries for hBIM specifically targeted to heritage single arch stone bridges as well as to demonstrate the applicability of a derived universal principle that contributes to hBIM standardization.

To that end, three single arch bridges in different parts of the Balkan peninsula that share many traditional values were chosen as case studies to be analyzed and digitally processed. These bridges were intentionally chosen because

they share traditional values, making them ideal case studies for in-depth examination and digital processing. The selection of bridges from various locations increases the study's comprehensiveness and provides a detailed knowledge of how the generated smart object libraries are implemented.

Section 2 discusses the use of laser scanning in the documentation of the three stone bridges and section 3 provides the description details for the three bridges discussed in this paper. Section 4 presents the methodology for the three-dimensional modelling and the creation of digital libraries for the stone bridges and discusses the results and finally, section 5 gives the concluding remarks of this work.

2. hBIM data collection methods for stone bridges

The creation of a BIM model can be performed by two main methods: drawings to BIM or scan to BIM. A model consists of 2D and 3D geometry, non-geometric information and any related documents and data as defined in Historic England.

In the first method, drawings to hBIM, the use of historical records and documents, when they exist, is very significant to the documentation of historic structures. Blueprints, drawings, and photographs can provide valuable information on the original design and construction of a bridge. However, creating a hBIM model using drawings requires competency in CAD environment, proficiency in preparing and reading building plans. In general, heritage buildings often lack 2D drawings due to scattered data. This is the reason why this method is considered as an alternative for cases that there are no available detailed data as point cloud workflows. In Fig. 1, an example of using drawings to document a bridge is shown.

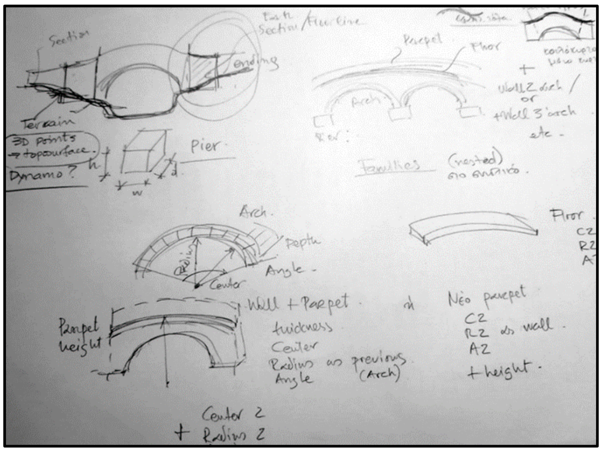


Fig.1: Example of records used for documenting a stone bridge (source: personal data)

The second method, scan to hBIM, involves the collection of data in physical way. There are mutually compatible methods for collecting data for stone bridges in hBIM, and their selection and application will depend on the requirements of a particular project and on available resources. Therefore, the first research step should deal with the identification of project needs and the specificities of research subject.

The basic method for a stone bridge data collection is physical surveys and inspections that help to gather information of the materials and the components used in its construction. Sampling and testing may be used to gather information on physical properties and characteristics of the stone.

In addition, experts and professionals such as architects, engineers and technicians, can provide valuable information on the design and construction process, as well as the current state of the bridge.

Finally, geometric and physical data on a bridge and on its current structural condition can be gathered from a distance by using state-of-the-art technologies such as laser scanning, photogrammetry and total station surveying.

The use of these techniques produces point cloud data (either directly from scans or from digital photos) describing the geometry of the structure. Prior to being loaded into a BIM software, the point cloud data can be further processed in order to add, change, build and manipulate BIM components. The result is a 3D representation of the structure's current condition.

Over the last two decades, non-destructive geo-spatial technologies [12] have taken the lead in data collection for stone bridges.

Laser Scanning systems are used to collect highly accurate 3D geometric information of a bridge, as well as to capture its texture and fine details with ground equipment. 3D models generated using information collected through laser scanning can be used in various purposes [e.g. 13-18].

Photogrammetry refers to the use of photographs collected from multiple viewpoints to document bridge geometry, texture and structure [e.g., 19-21] accurately thus successfully, especially in cases when complex bridge architecture is present.

Unmanned aerial vehicles (UAVs), such as a drone capture photographs and videos of a bridge from the air, and are particularly useful in locations difficult to access.

In the context of hBIM, the data collected through one or more of these methods are used to create a highly accurate 3D model of a stone bridge. The derived digital model is basis for analysis and project-specific actions. It can also be used to create digital twins of the bridge, which are useful for various purposes, such as maintenance, renovation and even virtual tours.

In this study three bridges (Section 3) were selected from a wider preliminary list of a heritage cluster of the single arch traditional stone bridges, and their general information was collected from available published works and historical archives. Interviews with local communities, professional organizations and the responsible heritage protection bodies were carried out to obtain additional information, as well as the permissions to engage in field work.

Based on geographical settings, bridges' accessibility and geometry and the goals of the research, laser scanning was applied as the optimal technology to harvest digital data. Later core work was conducted using BIM technology, as described in Section 4 of this paper.

3 Case study: three traditional stone bridges in the Balkans

The area of the Balkan Peninsula is characterized by diverse and abundant tangible cultural heritage from different periods, reflecting rich history of the territory and the significance of its geographical position at the crossroads of different cultures and religions. In such circumstances, bridges stood out as a particularly important category of the built heritage.

Historic Balkan bridges not only depict the diversity of traditional construction, but also represent a common motif in intangible creation, especially in the fields of oral practices and literature. The culminating example of translated importance of bridges into literary work is the novel The Bridge on Drina, whose author Ivo Andrić won the Nobel prize in 1961. Therefore, the meaning of the term bridge in Balkans is commonly intertwined between the materialized and the described. The bridge denotes connection, coalescence, encounter, path, direction, or a place. Oppositely, the bridge may also refer to a division [22], or an obstacle that needs to be overcame. This was a frequent case in the Balkans, bearing in mind historical trends, conquests and battles that were fought on this territory in the past. Regardless of neglection or destruction, traditional Balkan bridges still do account for a very rich collection of tangible heritage. Only in the Epirus region in north-western Greece, for example, there exist more than 250 historic bridges [23].

The old bridges of the Balkans were mainly built from stone, a locally available, long lasting, and resilient natural material. Within the stone bridges class, many variations regarding historical background, geometrical features including size, structural complexity and applied construction methods can be found. Most commonly, nevertheless, stone bridges built in the past in the Balkans are arched.

The goal of this study is to develop a hBIM for three selected arched historic stone bridges located in the Balkan Peninsula, namely Politsa Bridge, Nonoulo's Bridge, and the Dušan's Bridge (Fig. 2).

All three selected bridges are important heritage structures, while each of them possesses unique architectural and engineering characteristics. As a digital representation of a historic asset, a bridge in this case, hBIM not only includes physical characteristics, but also cultural, historical, and functional significance. Thus, the hBIM will provide a comprehensive and accurate record of the bridges' current condition, history, and conservation requirements, to aid in their future preservation and maintenance.

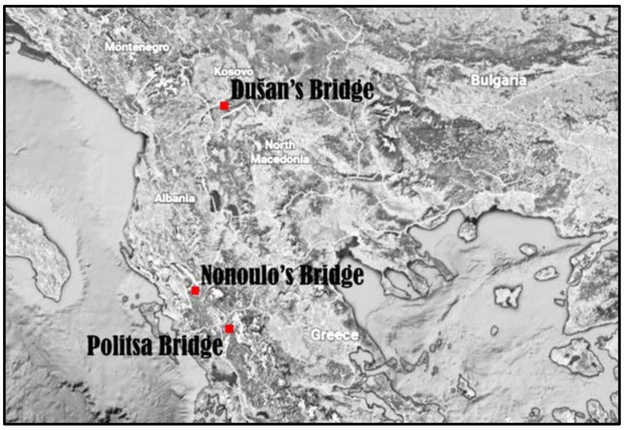


Fig. 2: Geographical position of three selected stone bridges within the Balkan peninsula

3.1. Nonoulo's Bridge

Nonoulo's stone bridge was built in 1908. It replaced an original wooden bridge that connected rural settlements Dolo and Pogoniani in the Kouvaras valley. Over that first wooden bridge, the inhabitants of two villages would cross the river stream Kouvara (tributary to the river Drin), taking with them donkeys with loads of food and the wood. When the river flooded, especially in winter season, the wooden bridge was becoming a real threat. Old lady Nonoulo Galanou, who lived near the bridge, decided to raise money herself and initiate the construction of a new safe stone bridge, even though she was poor. This is how the Nonoulo bridge in its current form was created (Fig. 3, 4).

The main material used for construction was crushed stone. The perimeter of the arch and the top of the parapet, which represents the fence aligned to the same vertical plane as spandrel walls, are made of hewn stone blocks, i.e., the tiles. The height of the arch opening of Nonoulo's bridge amounts to 7m. The total bridge length is around 15m, and the width of the road amounts to 2m, and the width of arched opening is 7m. The side walls are curved, which narrows the width of the access road towards the structure of the bridge and enhances the overall aesthetic quality. Curved parapet crown with the previously described elements softens the form of an otherwise typical single arch stone bridge structure.

With the publication in the Government Gazette in 1997, the stone bridge of Nonoulo's and the adjacent watermill whose construction was also initiated by the old lady Nonoulo Galanou, were characterized as historical monuments, i.e., the typical examples of popular pre-industrial architecture inextricably linked to the memories of the inhabitants important for the study of the evolution of the area [24].

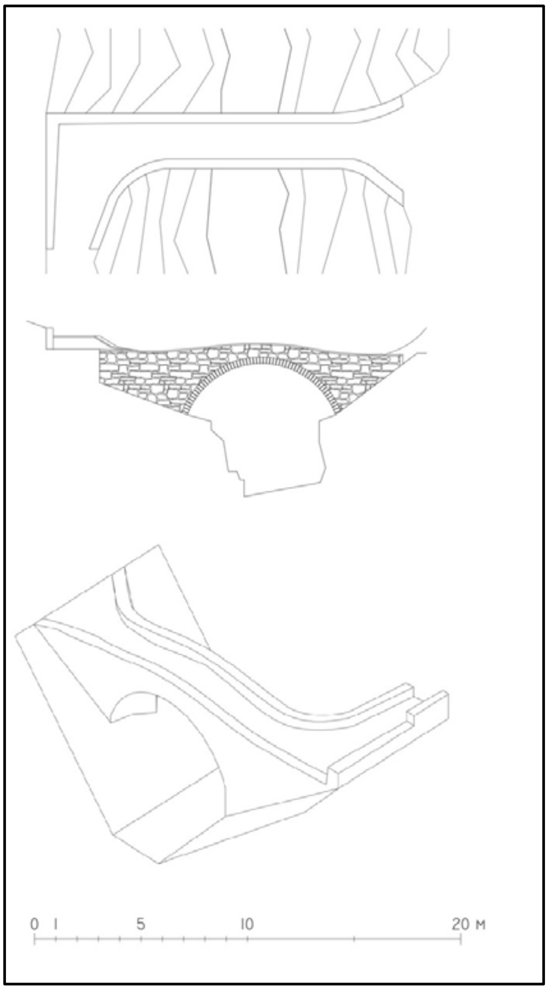


Fig. 3: Plan, front elevation and axonometric view of Nonoulo's stone bridge

Fig. 4: View of Nonoulo's stone bridge

3.2. Politsa Bridge

The Old Bridge of Politsa (Fig. 5, 6a, 6b) is located 30 km away from the city of Ioannina, near the village Ampelochori (old name Skloupo), in immediate proximity to the hamlet Politsa, and above the river Arachthos.

There is no official written data about the construction of the Politsa bridge, but the information that local residents and master builders from Skloupo passed down from one generation to another are known. These narrations were collected and published by a teacher from Ioannina Tolis Dimitrios [25].

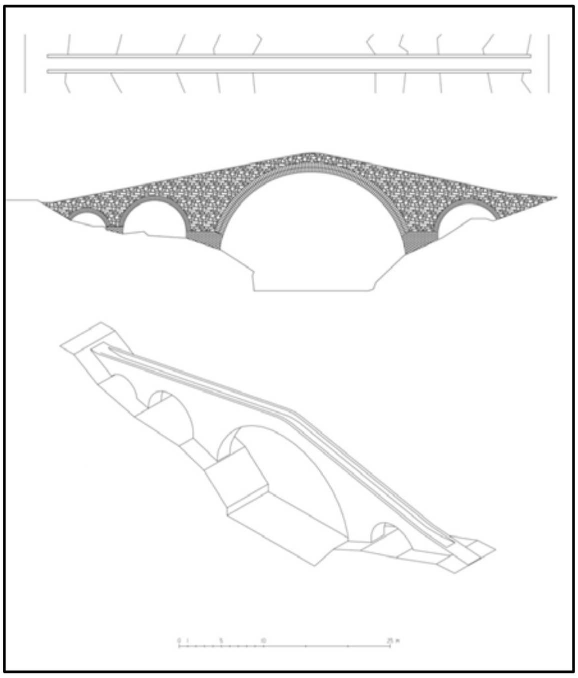


Fig. 5: Plan, front elevation and axonometric view of Politsa stone bridge

Fig. 6a, 6b: Views of Politsa stone bridge.

Work on the bridge began in 1866. Execution was a great challenge, which, unfortunately, had a bad outcome, because due to limited resources, the planned single-arched stone structure was too low and too narrow to withstand more extreme natural environmental conditions, which ultimately resulted in bridge collapse due to the occurrence of a strong torrential rain. The perseverance and faith of local community and the builders led to bridge rebuilding in 1868, on the same site and by using materials from the same nearby sources. The funds for the new construction were again collected by locals themselves, as well as by the philanthropist Giannis Zois Loulis. It was even said that the local master builders sold their land properties to raise necessary common funds. The construction of new stone bridge Politsa was successfully completed in 1870.

The bridge was without a parapet fence until the 1930s (http://arhiogefirionipirotikon.blogspot.com/). Legend has it that the locals crossed the bridge with great fear, some even crawling, and kept the animals by the tail for safety. The lack of parapets, on the other hand, played a significant role in the defense of the village of Skloupo during the period of Turkish occupation.

The width of constructed bridge arch opening is 22.5m and the height is 14.25m the total bridge length is 60m and the width of the road amounts to 1.5m. The bridge rests on the rock few meters above the water level, thus the height of the main arched opening visually increases, the whole structure seems higher than it actually is, and the image of the bridge looks more impressive. When arched openings of smaller dimensions were formed in side walls in the 1930s, the visual weight of the bridge was further lightened. To date, the bridge of Politsa is considered a remarkable example of continental architecture from the 19th century [24].

3.3. Dušan’s Bridge

Dušan’s Bridge (Fig. 7, 8a, 8b), also known as the Old Stone Bridge, was built in the 14th or the 15th century at the entrance of the gorge of river Prizrenska Bistrica, nearby the Holy Archangels monastery and the city of Prizren. The bridge, the monastery, the castle Višegrad, and several hermitages nested into natural landscape of exceptional value together form the protected memorial and natural monumental entity.

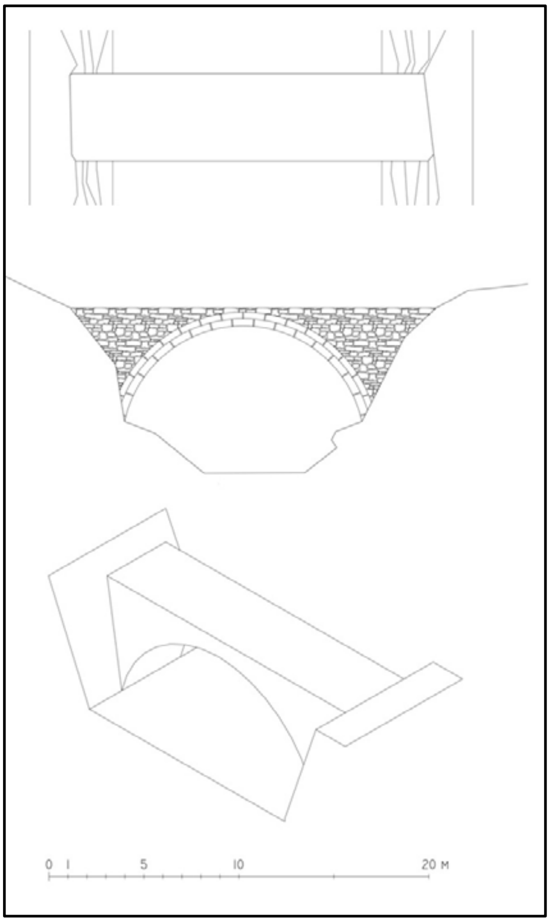


Fig. 7: Plan, front elevation and axonometric view of Dušan’s stone bridge

The exact purpose of construction of Dušan’s bridge has not been revealed, and the accompanying legend is missing. According to the record from the Serbian Academy of Sciences and Arts, (http://spomenicikulture.mi.sanu.ac.rs/spomenik.php?id=342), the primary function of the bridge was to enable efficient transport of stone material from close quarry to the monastery site. Based on another source

[26], Dušan's bridge was made along the periphery road over Šar Mountains, connecting Prizren with Skopje, at the same time when the stone bridge in Prizren was built, perhaps even by the same master builder.

Fig. 8a, 8b: Views of Dušan's stone bridge

The elements used for bridge construction were mainly crushed stone pieces. Only those segments that are forming arch opening and the fence were made from hewn stone pieces interconnected by lime mortar. The road on the top of bridge structure was materialized with cobblestone serving its function until the present day. Dušan's bridge has been recognized as a significant cultural monument and is under protection since 1956.

The size of Dušan's bridge is rather small. The total bridge length is 20m and the width of the road amounts to 3.5m. The top point of the arch, i.e., the vault, is 6m above river level, and the width of arched opening is 13.2m [19].

4 Development of BIM for stone bridges

The process of developing hBIM for stone bridges includes a number of steps, with the primary being to import the survey data obtained from on-site measurements. This data may include 3D point clouds, drawings and other relevant information (e.g photographs, written records etc) which will enable to set-up the basic geometric structure of the structure, such as the walls or beams to outline the primary shape and dimensions of the bridge.

For the architectural elements of the stone bridge such as arches, columns, parapets, decorative elements etc. that need to be accurately represented in the 3D model, these are usually available within digital libraries of object families that a user may implement for the specific structure.

Some structures, however, are unable to make direct use of the object families that are already available in the BIM. In these cases, new object libraries must be created based on the information acquired to represent complex bridge components like arches, pillars, and abutments with the appropriate details, proportions, and distinctive qualities of the stone materials used in the bridge's construction.

The historical record for the construction may also require the addition of details like carvings, ornamental embellishments, or other decorative components. Adapting material attributes like colour, texture, and reflectivity to the historical features of the stone may also be included in the details.

The following sections discuss in detail the methods for developing the hBIM for the three stone bridges, with a focus on creating customised object libraries that are not currently available in BIM software but can be easily implemented in similar applications.

4.1 Data Collection

The geometric documentation of the three Balkan stone bridges described in Section 3, was carried out using laser scanning technology. The data collection was performed with the time of flight (TOF) terrestrial laser scanner Leica Geosystems BLK360 Imaging Scanner, in order to create a 3D model [https://leica-geosystems.com/products/laser-scanners/scanners/blk360] and lasted about seven hours for each bridge.

The measurement accuracy of the instrument quoted by the manufacturer is 6-8mm (for a range of up to 10m and 20m respectively). The scanning speed is 360,000 pts/sec and gives a complete scanning and image capture panoramic and thermal (Fig. 9) in less than 3min.

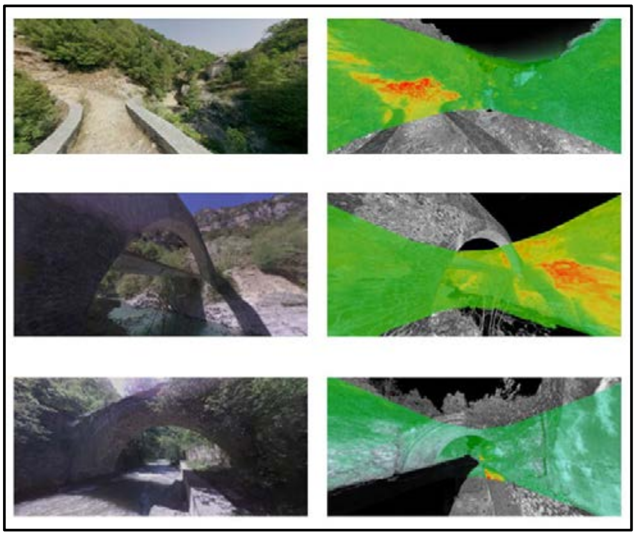
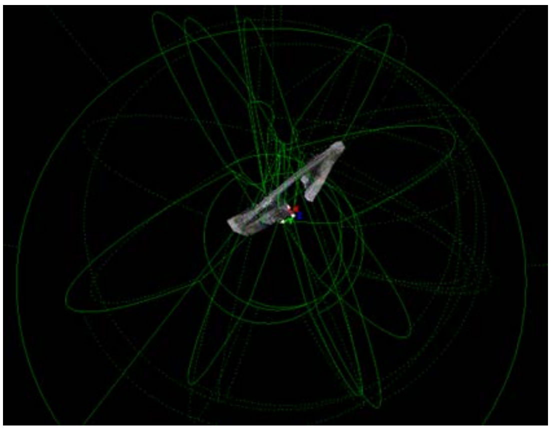


Fig. 9: Panoramic and thermal image capture of three stone bridges

In each bridge, scans were acquired all around in order to avoid gaps. The measurement mode was chosen with the highest resolution and the distance between the object and the scanner was maintained at approximately 10m. The percentage of the scan overlap ranged from 40% to 60%. For the bridges of Nonoulo and Politsa a total of 34 at 360o scans (19 scans in Nonoulo and 15 scans in Politsa) were taken covering the whole area of the bridges under study (Fig. 10a, 10b). In addition, 5 scans were taken, due to size and accessibility at Dušan’s Bridge.



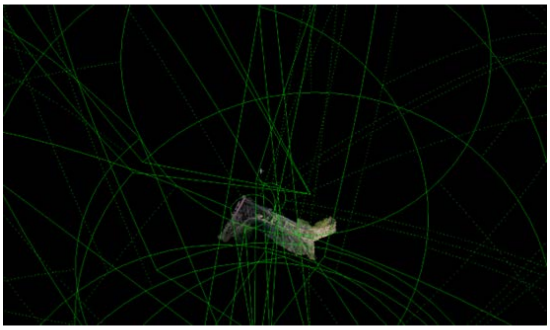


Fig. 10: Covering area of acquired scans at (a) Politsa and (b) Nonoulo bridges

The registration of all scans was performed in Cyclone software (Leica Geosystems) and alignment was achieved with a rms of the final model ranged from 1 to 1.3cm (Fig. 11).

Fig. 11: Registration of scans for the three stone bridges.

Due to the large volume of data, segmentation of the clouds was carried out for better and faster processing. Fig. 12 shows views of the final registered point cloud which was used in the hBIM.

Finally, it was necessary to export the point cloud file to an acceptable format via Autodesk ReCap software for later importing and editing into the Revit software.

Fig. 12: Final registered point clouds.

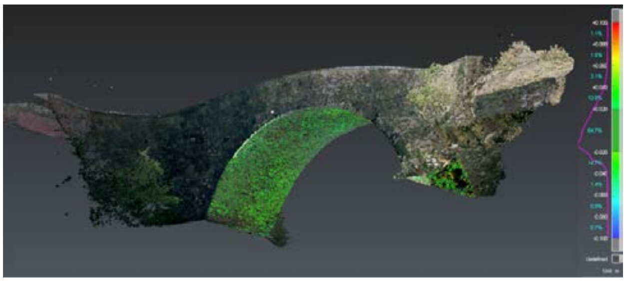
4.2 3D Modelling

The next step in point cloud analysis involves modeling of key elements of the stone bridges. The 3D modeling focused mainly on arches, decks and sidewalls of the bridges. The Cyclone 3DR software was used to model the point clouds and estimate all parameters for each element.

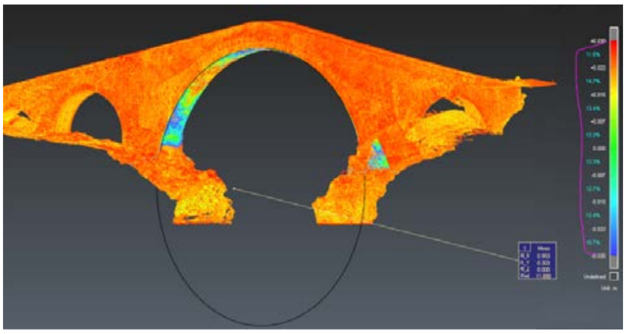
To represent each element, a cylinder or plane was appropriately fitted to the considered region. For each case, at least five fixed points of each surface were used, so that the algorithm locates the region with the same geometric parameters. Then the set of points is used to adjust a cylinder or a plane by estimating its parameters. The central axis of the cylinder, the inner and outer radius as well as the start and the end angles are estimated for each arc, always using a clockwise direction. In the three cases of the arch objects, the geometric fit by a cylinder provided residuals in the order of ± 0.03m (Fig. 13).

More specifically, for Dusan bridge the best fit in the arch is a cylinder with a radius of 6.73 m and the residuals for the set of points are ±2 cm (Fig. 13c). On the Politsa bridge, a cylinder with a radius of 11.76 m was adjusted with residuals of ±3 cm (Fig. 13b), while for the Nonoulo bridge the residuals are in the order of ±3 cm for the 90% of the points when a cylinder of radius 6.73m is developed (Fig. 13a).

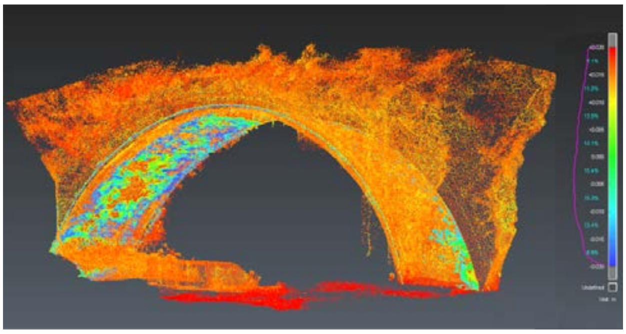
The same procedure was also carried out for the sidewalls and deck of the three bridges. As an example, Fig. 14a presents the modeling both for both the arch and the deck of the Nonoulo bridge where the residuals vary between ±4 cm for 90% of the points. Additionally, Fig. 14b shows a plane fit on the north sidewall of the Politsa bridge where the residuals are ±4 cm for the 88% of the region points.



(a)

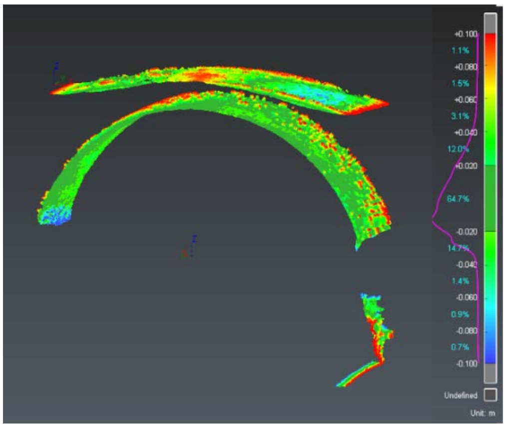


(b)

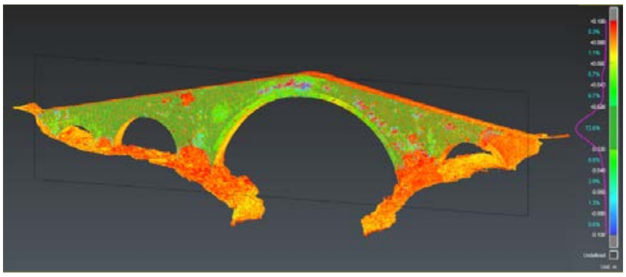


(c)

Fig. 13: Adjusted cylinders and residuals for (a) Nonoulo (b) Politsa and (c) Dusan Bridge



(a)



(b)

Fig. 14: (a) Arch and deck modeling of Nonoulo Bridge. (b) Plane adjustment (north façade of Politsa Bridge)

4.3 Development of smart object libraries

Using an object library is essential for the creation of an hBIM in stone bridges documentation. An important advantage of it, is the way the features and the materials of the bridge are given.

The model of the bridge can be created through predefined components, each one of them has its own customed properties. All this information is contained in an object library. A stone bridge, has complex characteristics and properties. These have to be transferred to the model with accuracy and consistency.

Moreover, the use of an object library in the creation of an hBIM, makes time-effective the construction of the model. The pre-defined objects can incorporate in the bridge model, reducing the time needed, and increasing the accurate representation of the model.

Another crucial parameter of an object library is the improvement of the teamwork of the people dealing with the same project. Having pre-defined components with specific properties, makes it easier to communicate, collaborate and finally gain more time.

Some characteristic components of a stone bridge, that could be used as object libraries for hBIM could be:

- Stone masonry: A library, containing the different types of stones used for the masonry. Objects could contain properties such as material, porosity, bonding motive, thickness, etc.
- Arches: Different types of arches have been used for the construction of stone bridges. Such a library, can contain these types (e.g. segmental, pointed, horseshoe) as objects and the properties of its may be the radius of curvature, the height, and the span.
- Piers and Abutments: They are used to support the bridge and transfer loads to the foundations with different ways and materials. Each object could have its own properties (e.g. material type, dimensions etc.).
- Joints: They are used for connecting the stone bridge. The most common was the keystone, but also pattress plates or tie rods were used. The properties of these object may contain the material type, dimensions, and loading capacity.
- Decks and Parapets: An object library containing the forms of decks and parapets used, including information for materials used, their dimensions, load capacity and their conditions.

All proprietary BIM software provide a number of ways to create objects.

The most common way is standard native AEC objects such as walls, floors, and other predefined elements. For example, in Revit software, one can model pillars as foundation walls, wing walls and parapets as walls, and flat decks as floors by configuring the shape of the face.

For curved elements like the bow of the arch, the roof by extrusion tool can be used. The relief is modeled as a toposurface based on the points of the point cloud. As an alternative technique, the various parts of the bridge can be modeled as solid shapes (in place components) with different categories assigned to them, such as walls or floors.

Then, the entire bridge can be modeled as a single solid (generic mass). These objects are unique without repeatability, which means each component is a single family and a single type.

As an alternative technique, smart parametric objects can be used, which are custom families with specific geometric forms and parameters that can be used for various cases by adjusting parameter values. This approach enables the creation of different types/instances based on the parameters defined for each family, allowing for greater flexibility and efficiency in the modeling process. In this case, the modeling methodology involves defining an ontological scheme for the object of study, which includes analyzing the object into parts and determining the different forms - types that these parts have in different views - instantiations of the object.

For traditional single-arch bridges, the parts typically include the pedestal, bow, tympanum (wing wall), abutment, and deck. Different types of spare parts may include piers, arches of different shapes, wing walls with various features, decks of different shapes, and parapets of different designs.

Types of parts are in general:

Piers: abutments, intermediate piers (in bridges with more than one arch), no piers (rock foundation)

Arch: raised (elliptical), semicircular, lowered, pointed
Wing wall: with / without relief arches, with curve, straight, polygonal end
Deck: curved, consisting of one or more flat sections
Parapet: with / without parapet, with single or clustered arches

Specializing the types of components for the specific bridges being studied is the next step. For these three bridges, there are no piers as they are founded on rock on either side of the bed. The arch is part of a circle, which is probably stepped down with a full semi-circle.

On the bridge of Nonoulos, the wing wall has an arched ending consisting of three tangential arcs, while the flat surface of the central part curves at the edges to adapt to the natural terrain. On the bridge of Politsa, the wing wall has an end consisting of two straight sections and three relief arches. On the bridge of Dusan, it has a straight ending, or a form of an arch with slight curvature. The deck of the bridge on Nonoulos has a concave shape, whereas on the bridge of Politsa it follows the shape of the wing wall, meaning it consists of two flat sections parallel to the end of the wall. On the bridge of Dusan, the deck is flat and horizontal. The first two bridges have their parapet united with the wing wall, while the third bridge currently has no parapet.

First, an analysis is conducted on the geometric forms of the bridge components and the determination of the parametric quantities that influence these shapes. Based on these data, parametric objects are identified for modeling corresponding elements in the Family editor environment of the Revit software. These objects can be adjusted to different dimensions based on their parameter values.

Once the individual families for the bow, wall, and deck are completed (Fig. 15, 16, 17), an overall family is created for the entire bridge by assembling the different parts appropriately. Using the scanned digital data, the parameter values are adjusted to match the cases under study, and then a comparison is made with the point cloud.

For parts of the model that cannot be described geometrically or parametrically, other techniques mentioned earlier are utilized, such as native AEC objects or in-place components. In the three cases being studied, the arc has a common form that can be described using parametric objects. The deck and wing wall of the Nonoulos bridge are described by a section, whereas native AEC objects are used to describe these components in the other two bridges.

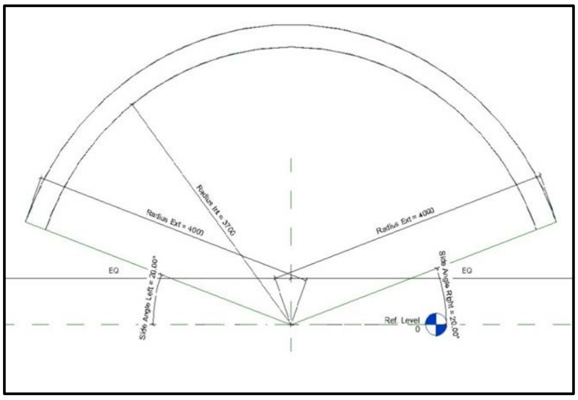


Fig. 15: Family bow. Parameters: inner and outer radius, arc start and end angles

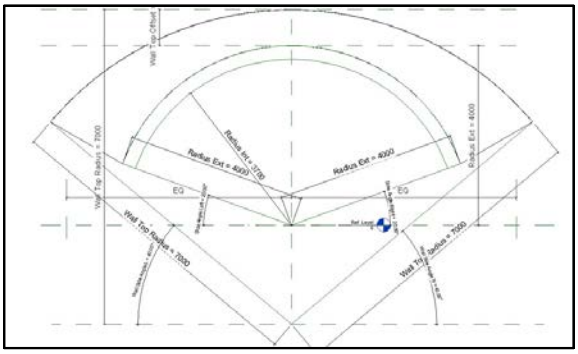


Fig. 16: Family wing wall. Parameters: outer arc radius, parapet radius, parapet height, parapet start and end angles

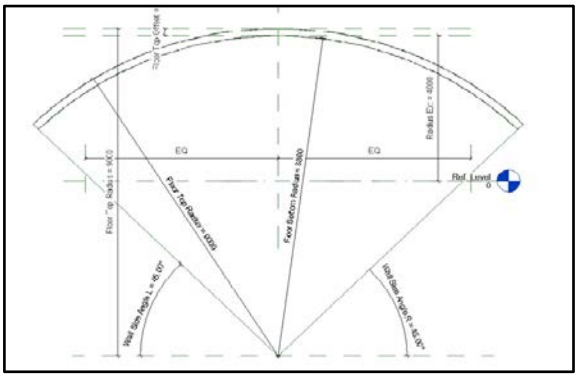


Fig. 17: Family deck. Parameters: top face radius, bottom face radius, deck start and end side angles

5. Concluding remarks

The use of hBIM for the digital documentation of stone bridges provides many benefits in terms of accuracy, efficiency, and serves as a valuable tool for a more comprehensive and reliable documentation of these significant cultural heritage structures.

This study demonstrates the use of BIM technique and the development of 3D models for the historic bridges of Nonoulo, Politsa and Dusan Bridge. The 3D survey produced precise point cloud data to create a model of each bridge, despite the structure's complex geometric architecture. The accuracy of the final models ranged from 1-1.3cm.

The libraries of parametric items available in the most popular BIM-based modelling systems are insufficient for accurately representing the architectural geometry and construction solutions utilized in historic structures. **An important step in the study was the creation of a comprehensive BIM library resulting in families for the bow, the wing wall and the deck, each with unique details.**

Throughout our research came out that the available libraries are not sufficient to describe a stone bridge. Representing the different components of such a bridge is often difficult, because of the complexity of the structure. The creation of new object libraries is necessary, in order to be implemented for Heritage Building Information Modelling (hBIM).

The custom-oriented object libraries ensure that all desired characteristics, that describe a stone bridge are represented. Using a custom library not only certifies that the final model becomes more accurate, but also all objects can be reused for a similar construction.

The objects the we developed for this study are easily adaptable and the users can rapidly add the materials and components needed for their projects into BIM models, saving time and effort, while creating models.

The quality of the bridge model is increased, as custom objects are added. Both of our case studies gave accurate models.

An important aspect is the availability of the built smart object libraries for stone bridges. These can be made available to other users, in a variety of ways (online platforms, open-source repositories etc.).

An object library has to remain applicable throughout time, so it has to be maintained or even updated.

In this study, the developed objects are available but the users should be given explicit usage instructions and rules to ensure that the libraries are utilized ethically and responsibly.

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