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3D PRINTING AS A TOOL IN THE ARCHITECTURAL DESIGN PROCESS IN RELATION TO HISTORICAL BUILDINGS, AS EXEMPLIFIED BY WATER TOWERS FROM THE KUYAVIAN-POMERANIAN VOIVODESHIP

The article discusses the use of 3D printing technology in architecture, with particular emphasis on the renovation and reconstruction of historical buildings. The authors analyze how 3D printing enables accurate reproduction of architectural details, which is crucial when working with historic structures. The article presents the benefits of using this technology, such as increased precision, reduction of costs and working time, as well as the ability to create complex forms that would be difficult to produce using traditional methods. Examples of the use of 3D printing in practice were also discussed, including projects that used this technology to recreate destroyed elements of historical buildings. The article emphasizes that 3D printing is becoming an increasingly indispensable tool in the arsenal of architects and conservators, contributing to the preservation of cultural heritage for future generations.

Keywords: water tower, historical building, 3D printing, three-dimensional model

1. CHARACTERISTICS OF WATER TOWERS

Water towers are technical buildings where a water tank is placed at the top. A water tower consists of two main elements: a base and a head. The head is designed to enable the water tank to be raised to the desired height. By placing the tank above ground level, the appropriate pressure is achieved, which allows for gravity delivery of water to recipients. The second element is the head, which surrounds the tank, providing it with protection against adverse weather conditions, such as low temperatures, snowfall, rain or strong winds.

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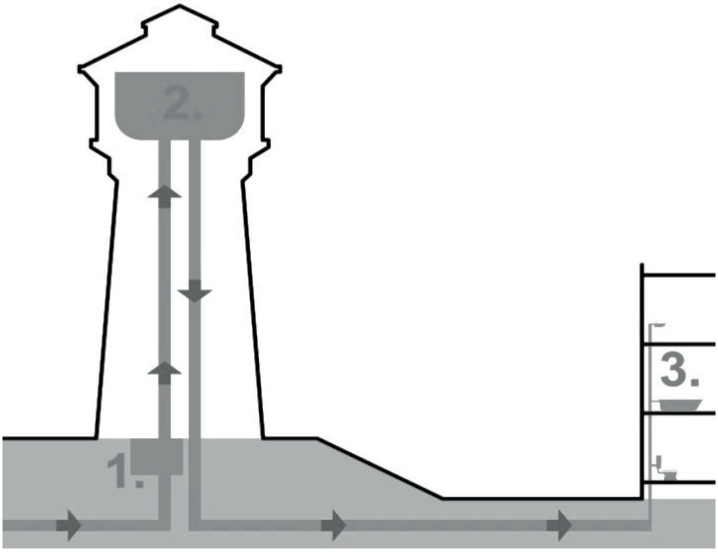

Fig. 1. Water tower operation diagram: 1. Water supply from the intake, 2. Water tank, 3. Recipient (user) [Piotr Brzeziński]

Despite their common function, water towers can be distinguished in terms of the recipient. "In principle, all water towers are water supply infrastructure facilities, but they should be divided into: water supply (municipal, also called urban), industrial (factory), farm (rural) and railway" [Brzeziński 2017: 31]. A water tower can also function as a surge tank, reserve tank, fire-fighting tank or additional supporting device in the water supply network.

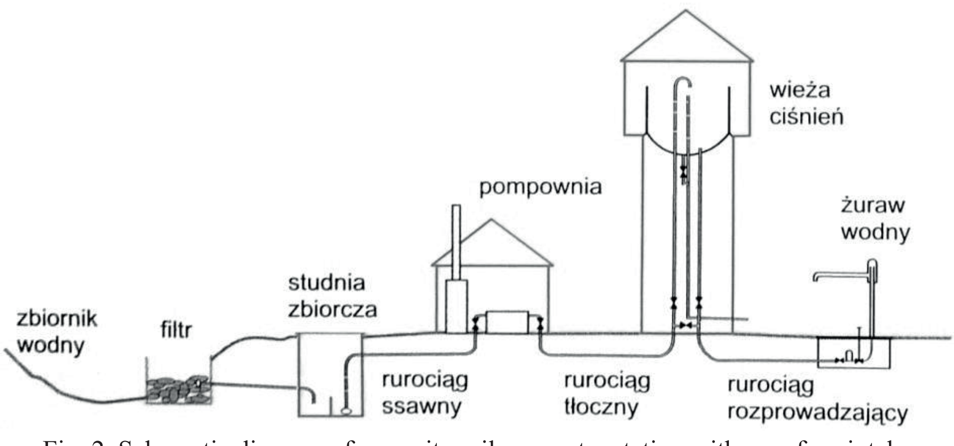

Fig. 2. Schematic diagram of a gravity railway water station with a surface intake [Jerczyński 2002]

Although water towers in Poland were built in the 16th or 17th century, such as buildings in Lublin, Frombork, Głogówek or Biała, the authors focus on buildings related to the period of the industrial revolution. In simple terms, it can be assumed that the time frame for the construction of water towers in Poland is the period from the first half of the 19th century to the mid-20th century.

The industrial revolution, being a process of social, economic and political changes, which was connected with the transition from manufacturing to large-scale factory production. The popularization of the use of steam engines implied the development of water supply and sewage systems, including water towers. The greatest development of water supply networks took place in the 19th century, also known as the age of steam. Steam, which Julian Tuwim called "water in inspiration", played a significant role in the period of industrialization and technical progress. "Since the invention of printing and gunpowder, no idea has become so widespread and has not caused such extensive work and excellent undertakings as the invention of steam and the invention of railways" [Kolberg 1844: 1].

At the turn of the 19th and 20th centuries, the railway was unrivaled and wherever it reached, it was a success. It connected entire countries, cities and villages, shortened distances and opened windows to the world. The railway changed people's lives because it made it possible for almost everyone to start traveling for the first time in human history [Dominas 2013: 5].

The first water towers, which have not survived to this day, were wooden or sheet metal vats with a capacity of several to a dozen or so cubic meters. They were placed either on the first floor of a building or on an openwork support structure or a stone pedestal [Jerczyński 2002: 18].

It is difficult to estimate the size of the water tower resource, both in Europe and in Poland. Referring to the area analyzed by the authors, it is estimated that in the Kuyavian-Pomeranian Voivodeship alone, over seventy water towers from the turn of the 19th and 20th centuries have survived to this day.

It should also be added that many of these objects have similar parameters, which makes it possible to define strong typological features in the case of both railway and water towers. "Typologies allow for determining, for example, what features an object with a given function should have or what type of aesthetic solutions dominated in a given historical period" [Niezabitowska 2014: 270].

Due to their characteristic form, water towers constitute a recognizable point in the space in which they are located. Representative features of these objects influence their important role in space. The characteristic slender form narrowing upwards, topped with a head that housed a water tank, creates distinctive features. Additionally, specific styling, representative of the period in which they were built, identifies water towers and distinguishes them. These buildings are clear spatial signs, they have individual features that are easy to remember. "The factors that determine the emotional impact of the spatial environment are: its form, and more broadly speaking, the structure, individualism, distinctiveness of a given environment and the function and social significance of individual objects of a spatial complex or its entirety” [Wejchert 1984: 50].

2. WATER TOWERS – STRUCTURE AND ORNAMENT

When considering the structural and material solutions used in water towers in the Kuyavian-Pomeranian region, it is necessary to consider the chronological development of the structures, which was influenced by the type and method of using individual materials. Initially, wood was used as the main building material, as was the case with railway water towers from the mid-19th century. At the end of the 19th century, brick became the most commonly used construction material. Brick appears in each of the more than seventy towers. In most of them, it is the main construction material, and in some, in the later ones, it appears as a structural element together with reinforced concrete or steel elements. The decorative elements of water towers are related to the building materials used in their construction.

Fig. 3. Entrance area of the water tower in (from left): Nowe, Toruń, Chełmża, Lniano [photo: Piotr Brzeziński]

The oldest preserved buildings located in the Kuyavian-Pomeranian region were made of wood, brick and steel/cast iron decorative elements. Later buildings from the mid-20th century were equipped with more modest artistic decoration, the reasons for which can be sought in the use of reinforced concrete under the influence of modernist trends. “Architectural details did not arise suddenly, nor simultaneously, nor in one place, nor were they invented by one man. Some of them are associated with the oldest civilizations of Asia and Africa, others with younger ones of Europe” [Mączeński 1956: 5].

Fig. 4. The heads of the water towers in (from left): Bydgoszcz, Szubin, Żnin, Serock [photo: Piotr Brzeziński]

The solutions found in water towers can be found in other structures, both representative and industrial or technical, belonging to the era in which they were built. Moreover, their range of occurrence does not cover only one region, but is independent of national borders. Brick details, to a large extent, were formed based on developed decorative detail [Liebolda 1891] patterns intended for architects and master bricklayers.

Undoubtedly, water towers are a group of valuable, although special architectural objects. Their specific value results from their original purpose. As long as they served this purpose, their survival was not threatened, but after being decommissioned and due to the lack of functional activation, they are increasingly treated as problematic objects. This is related, on the one hand, to the fact that their original function has been irretrievably lost, and on the other hand, to the specific form of the building and often the lack of an idea for its further life.

"The utility value of a monument therefore depends to a large extent on whether it meets modern requirements from a technical and operational point of view and whether it is functional" [Frodl 1966: 50]. It should be remembered that in the case of water towers we can mainly talk about their utility potential, which assumes the possibility of introducing a function other than the original one, mainly for inactive facilities.

Considering that most of them are not functional (these are mainly railway towers), and restoring their original function is not possible, this is the only possibility for their survival in the local space. Form and structure do not have such a strong impact on the social field as function. Changes that occur in the function in a natural way are much more significant and impossible to eliminate. Therefore, in my opinion, the protection of the function cannot be identified with the protection of a monument [Barełkowski 2014: 63-64].

Detale charakterystyczne dla zdefiniowanego typu budynków **na przykładzie kolejowych wież ciśnień** – Typ 01	
Opis detali reprezentatywnych	Rysunek detali reprezentatywnych
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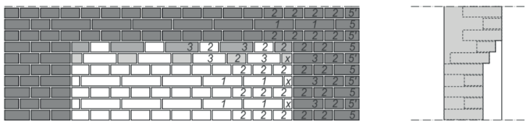
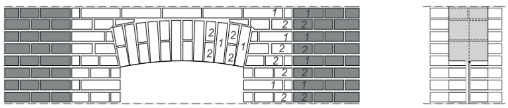
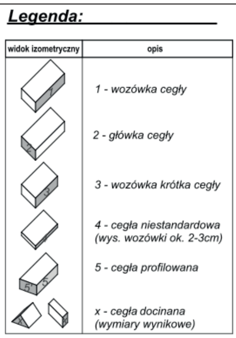
Blenda elewacyjna (Kcynia):	 Widok, przekrój
Okno w blendzie (Kcynia):	 Widok, przekrój
 	**Parametry szczegółowe (TYP 01):** *1 - wozówka cegły* *Wymiary: 24,2-26,2 cm na 6,1-6,8 cm* *1' - wozówka cegły (cięta)* *2 - główka cegły* *Wymiary: 11,2-12,4 cm na 6,1-6,8 cm* *2' - główka cegły cięta (sklepienia/nadproża)* *3 - wozówka krótka cegły* *Wymiary: 17,8-19,6 cm na na 6,1-6,8 cm* *x - cegła docinana (wymiary wynikowe)* *szerokość spoiny: 1,0-2,2 cm* *obrys cegły w murze (orientacyjny)*

Fig. 5. Characteristic details on the example of one of the types of railway water tower buildings [Piotr Brzeziński]

3. WATER TOWERS – CATALOGING METHODS

Knowing that water towers are valuable historical objects and their fate is uncertain, it is worth taking care of the possibility of documenting them for the purpose of their protection. In order to catalog water tower objects, which will be helpful in further activities with objects such as cataloging the resource, reconstructing the object or its part, design work and others, the given object should be inventoried using available methods.

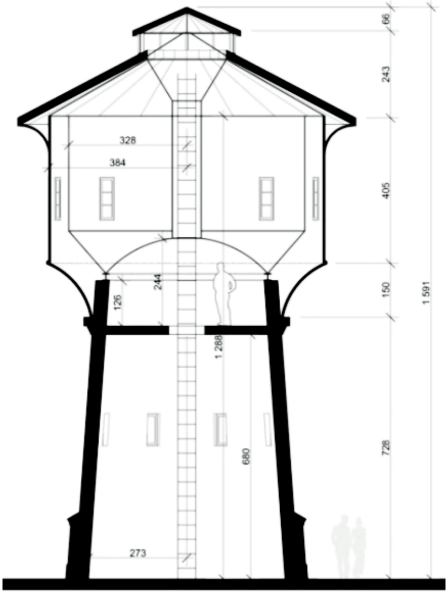


Fig. 6. Inventory. Cross-section of the railway water tower in Żnin – existing condition [Piotr Brzeziński]

Fig. 7. Computer model of the railway water tower in Żnin [Piotr Brzeziński]

Traditionally, the inventory is performed in the form of physical measurement of the building or the use of newer methods such as inventory using P2P (point-to-point) technology or LIDAR. "The use of modern tools such as P2P and LIDAR technologies allows for a significant reduction in the working time needed to build a three-dimensional model of the analyzed structure. The measurements and preliminary analysis of the model are carried out practically during the visit to the facility. […] Classic solutions would require much more time in this case, which would include: alpine work, difficult lighting conditions, low temperature, many hard-to-reach places, the age and condition of the wooden structure elements, taking measurements of individual wooden elements, taking notes or the need to take many photos, from which a model of the truss would then have to be built. In addition, when using classic solutions, several visits to the facility are usually necessary, which significantly increases the costs and extends the process of developing documentation" [Domagała, Domagała, Undas 2023].

After taking measurements, it is possible to develop a detailed three-dimensional computer model of the building, which can be used for further activities, including: further design work or preparation of 3D printing, which will be discussed in detail.

4. WATER TOWERS – 3D MODELING PROCESS

The preparation of a 3D model for historical objects, such as water towers, follows a structured process that closely aligns with standard 3D modeling practices, particularly when the final model is intended for 3D printing using technologies like Fused Deposition Modeling (FDM) or Stereolithography (SLA)/Digital Light Processing (DLP). However, when dealing with historical structures, special attention must be given to preserving the authenticity of the object, while ensuring the model is optimized for modern fabrication methods.

At the core of this process is the need to create a faithful digital representation of the object, starting with detailed data collection. Typically, this involves the use of inventory drawings, archival photographic documentation, and direct on-site inspections. These sources provide critical insights into the object's original form, dimensions, and architectural details. The combination of these materials forms the basis for developing the initial 3D model, which aims to replicate the structure with as much precision as possible.

Once the data has been collected, the process moves to the preliminary 3D modeling phase. Here, a computer-generated model of the water tower is constructed, integrating all available information. The goal is to reproduce every visible element of the structure, paying close attention to its scale and proportions. However, unlike general 3D modeling projects, in the case of historical buildings like water towers, particular care must be taken to ensure that non-original or modern alterations to the structure are identified and removed.

This brings us to one of the most critical steps in the process: ensuring historical accuracy. Often, historical buildings undergo various modifications over time, with new elements being added that were not part of the original design. These modern features may include alterations made for functional reasons, repairs, or aesthetic updates. To achieve an accurate historical reconstruction, it is essential to carefully analyze each component of the structure. This analysis is based on the original documentation and photographic evidence, and any non-original additions are removed during the early modeling stages. For example, windows, facades, or architectural details that were altered in recent renovations must be carefully assessed, and only those elements that belong to the original historical fabric of the building are retained.

Following this, the model enters a verification and refinement phase. At this point, the preliminary 3D model is scrutinized in detail, comparing every architectural element to the original data sources. Any discrepancies or mistakes that are discovered are corrected, and further refinements are made to ensure that the model accurately represents the historical structure. This step is particularly important for architectural heritage preservation, as the resulting model may later be used for various purposes, including educational presentations, virtual reconstructions, or physical reproductions using 3D printing.

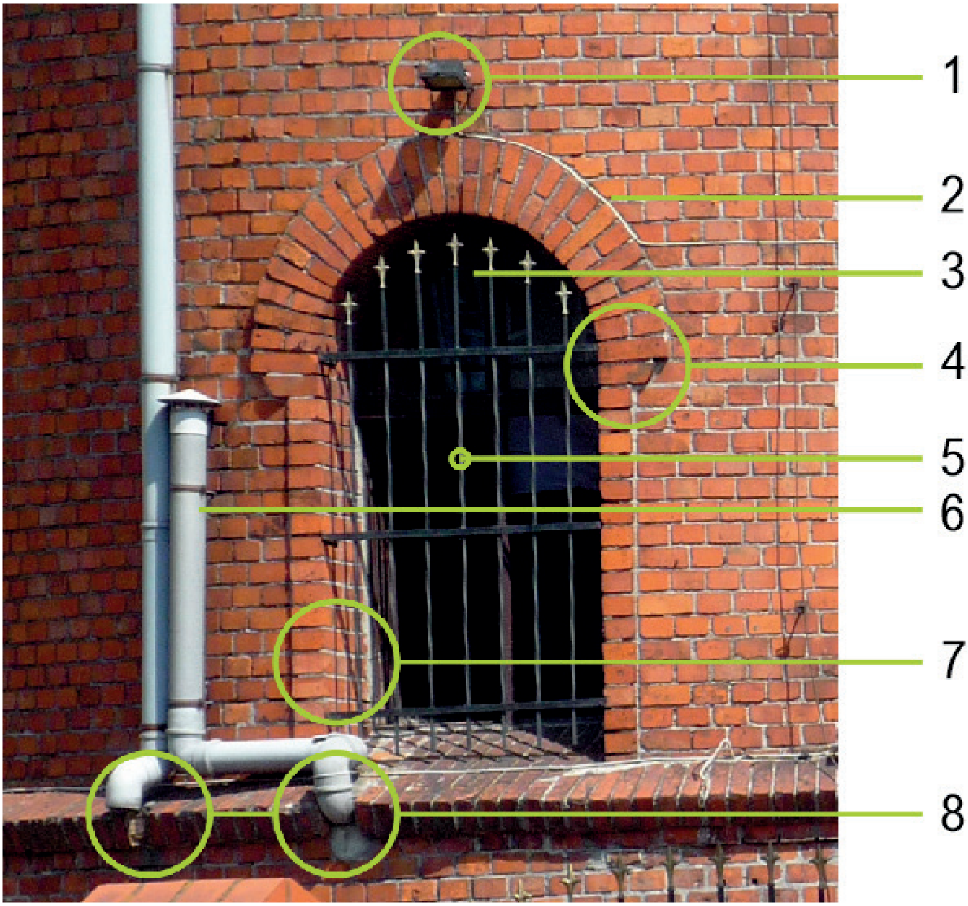


Fig. 8. Elements to remove from 3D model (1, 6, 8)
and elements to preserve with special care (2, 3, 4, 7)

The graphic includes elements that must be removed before continuing with the design process, as well as those that require special attention during 3D modeling. At this stage, it is crucial to clarify the final scale of the print or prints, or architectural models. The scale will significantly affect how individual elements are modeled in 3D. For instance, the element marked as "7" in the graphic may become completely indiscernible in scales of 1 : 100–1 : 200 if insufficient emphasis is placed on it during the 3D modeling phase. This is where scale plays a critical role in determining the number and size of compromises made, such as optical adjustments. If the primary focus of the final print is to highlight element "7" and ensure its visibility in a 1 : 200 scale, it will be necessary to adjust its dimensions according to the chosen 3D printing technology and its ability to replicate such details. It might turn out that in the selected scale, this element will not be perceptible at all. In such cases, there are two possible solutions. The first is to modify the scale until the object is clearly visible in test prints. The second option, when the final scale cannot be altered, is to adjust the physical dimensions of the element. While this adjustment may not be true to the original object's real-world dimensions, emphasizing the element by altering its size will enhance the overall perception of the model or architectural mockup, making it appear to faithfully showcase architectural details, even if the dimensions are slightly compromised.

Before beginning the creation of the digital model for 3D printing, it is necessary to understand the technological limitations and decide how the entire object will be processed. Depending on the chosen printing technology – whether FDM or SLA – specific technological constraints will arise. For SLA prints, these include the presence of supports and the challenges associated with their removal, as well as a much smaller working area. In FDM printing, it will be necessary to divide the model into smaller sections to improve the accuracy of the process and allow for easier corrections. Correcting errors or oversights in a 3D model is much simpler when working with smaller sections of the whole object. In such cases, replacing an individual module of the physical model is relatively easy, and working on a smaller digital model fragment allows for faster identification and resolution of any issues. The printing process itself is not quick, particularly with additive manufacturing technologies, so the ability to work on a single fragment instead of redoing the entire project is economically justified, both in terms of cost and labor time.

The graphic below presents a proposed method for dividing larger elements into smaller sections. These divisions should not be arbitrary and must be carefully planned. When assembling the whole object from individual parts, each technology and material will exhibit specific characteristics. For example, the shrinkage behavior of materials like PLA or ABS filaments will differ significantly from that of UV-curable resin. Even within a single material, it is not always possible to maintain consistent printing conditions (temperature, airflow, etc.), which can lead to deformation. "In FDM, the final resolution is influenced by the consistency of the filament diameter and the material parameters. Variations in the quality of the material or filament diameter can lead to uneven layer deposition, which can compromise overall precision. Achieving great precision with 3D printers requires regular calibration and maintenance. It's necessary to carefully control elements like temperature control, nozzle alignment, and bed leveling" [Lodhi, Gill, Hussain 2024: 129-138].

Achieving perfection in printing can be hindered by time constraints or economic factors. To account for such situations, the model should be designed in a way that minimizes the impact of these divisions on the overall structure. In the case of water towers, architectural details can be used to conceal joints between different sections, thereby mitigating the visual impact of these connections.

Fig. 9. Visible line (3) shows possible place of connection between two separate 3D prints

Incorporating architectural elements as natural connectors between individual sections of the final 3D print can significantly enhance the overall perception of the architectural model. By aligning the divisions of the model with existing architectural features, such as cornices, columns, or decorative moldings, the seams between parts can be effectively hidden or minimized. This approach not only preserves the visual integrity of the model but also contributes to a more cohesive and aesthetically pleasing final product.

Architectural elements, which are naturally part of the design, serve as optimal locations for these connections, as they allow for the seamless integration of individual parts without disrupting the overall structure. When employed thoughtfully, this technique ensures that the joints between sections are less noticeable, maintaining the model's fidelity to the original design and enhancing its realism. This method is particularly advantageous in the creation of complex historical models, where maintaining architectural continuity and accuracy is essential.

Moreover, using these elements as connectors reduces the risk of structural weakness that might arise from arbitrary or poorly placed divisions. By integrating the seams into the architectural design, the final printed model not only looks more authentic but is also more durable, as the structural load is distributed more evenly. Consequently, this approach positively impacts both the aesthetic and functional aspects of the 3D printed architectural model, making it a preferred strategy in architectural visualization and historical reconstruction projects.

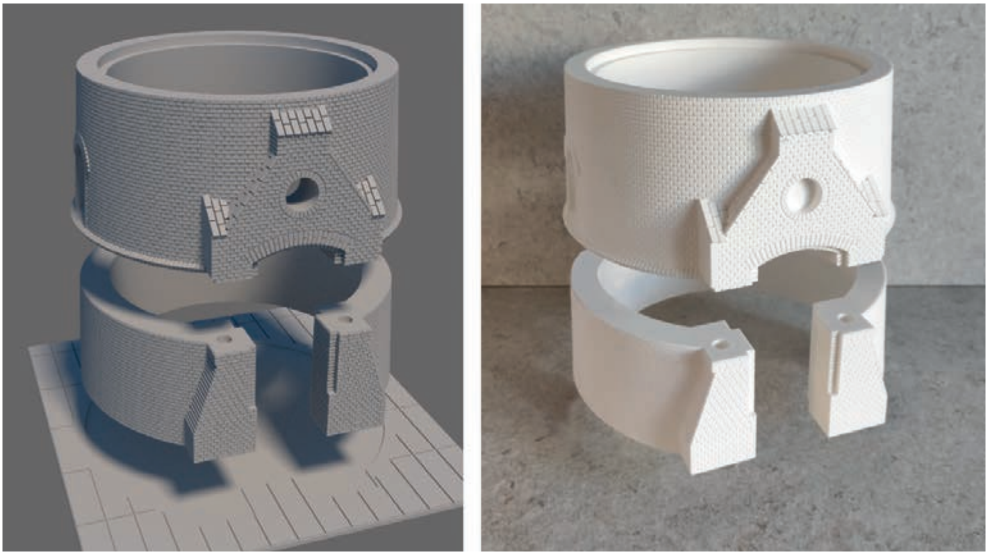


Fig. 10. Comparison between prepared 3D digital model (left) and final result of 3D print in FDM technology [photography and 3D model by Dawid Fischer]

As illustrated in the graphic above, proper file preparation during the digital design phase allows for a thorough analysis of the assembly process for individual components. Special attention should be given to concealed mounting elements, such as the recesses visible in the graphic, which will significantly facilitate the precise alignment of parts after printing. This thoughtful design consideration ensures that the components fit together seamlessly, as demonstrated in the graphic below.

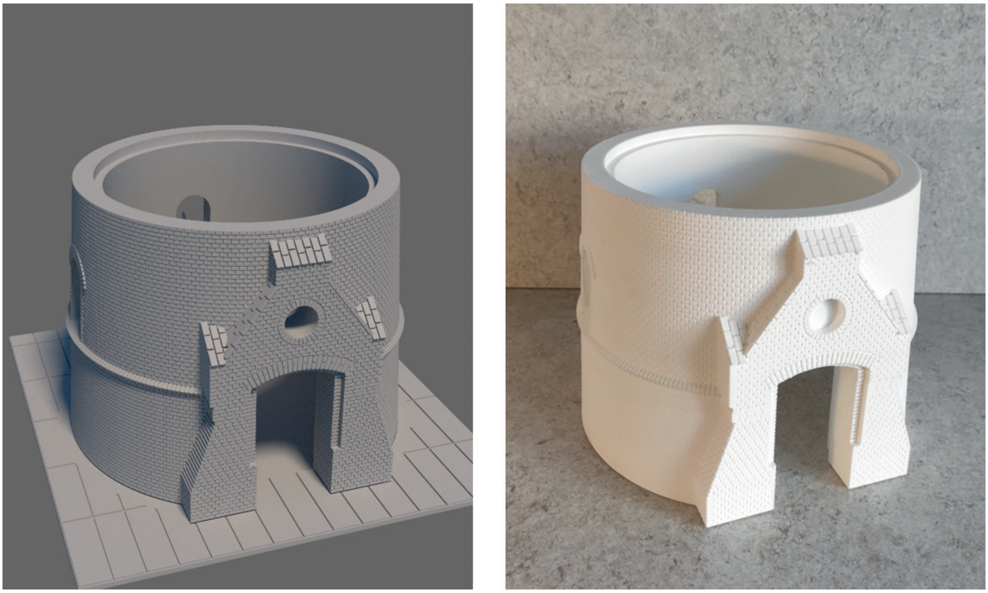


Fig. 11. Comparison between prepared 3D digital model (left) and final result of 3D print in FDM technology [photography and 3D model by Dawid Fischer]

Individual elements of water towers may lose their characteristics during scaling. Unfortunately, architectural details modeled at a 1 : 50 scale will behave quite differently when scaled down to 1 : 200, especially when printed using the same technology and settings, as demonstrated in the graphic below.

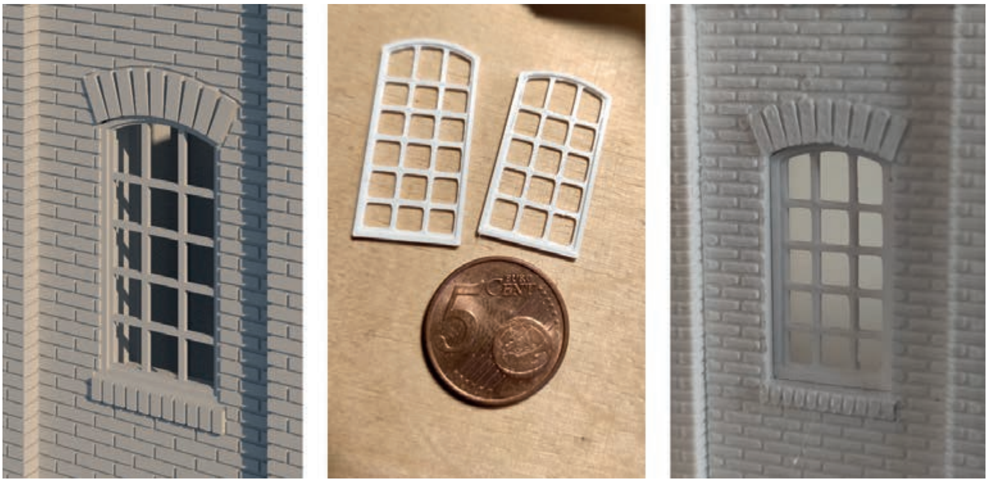


Fig. 12. Visible deformations on bricks ater rescaling digital model using FDM technology to print [photography and 3D model by Dawid Fischer]

5. CONCLUSIONS

3D printing represents an exceptional method for presenting historical structures in their original form. Its primary advantage over traditional modeling techniques lies in its ability to quickly replicate work results and its seamless integration with digital design methods. While the time required to develop a digital model and produce a 3D print may, in some cases, exceed that of conventional modeling, 3D printing offers distinct benefits in terms of flexibility. Corrections and modifications to individual components can be made rapidly, allowing for greater adaptability during the design process. Also very important aspects of 3D printing is availability as mentioned: "In architecture, building a model used to require a significant amount of time, often weeks or even months, and the result depended heavily on the skills of the person carrying out the work – a task that was, without a doubt, purely artisanal. In 3D printing, this dependency no longer exists, as the outcome is not tied to the need for a specialist whose expertise determines the materialization of the design. With this new form of printing, it is possible to obtain virtually any shape, no matter how complex. We can create sets of simple volumes that can be printed quickly, aiding in our design process" [Molina-Siles, Maruenda, Costa et al. 2018: 797].

Additionally, the durability of objects produced through 3D printing is significantly higher compared to traditional materials used in physical models. This increased durability ensures the longevity of the printed models, making them suitable for long-term display or educational use. Moreover, depending on the selected printing technology, 3D printing allows for an exceptionally high level of detail and historical accuracy in reproducing architectural features. This capability is particularly important when reconstructing intricate details of heritage sites, as it ensures that the models remain faithful to the original design and construction of the historical objects.

In summary, while the time investment for 3D printing may initially seem higher, the technology offers unmatched advantages in precision, flexibility, and durability. These factors make it a highly effective tool for the preservation and presentation of historical architecture, offering new possibilities for both researchers and the public to engage with cultural heritage in more accurate and accessible ways. As mentioned by Antreas Kantaros: "Three-dimensional printing, on the other hand, has the potential to create highly detailed replicas of cultural artifacts and sites. This can be useful for research, education, and even for creating new exhibits, without the need to handle delicate and fragile original artifacts. Three-dimensional printing can also be used to repair damaged artifacts, as well as for creating casts for molding and reproduction purposes" [Kantaros, Ganetsos, Petrescu 2023: 19].

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WYDRUK TRÓJWYMIAROWY JAKO NARZĘDZIE W PROCESIE PROJEKTOWANIA ARCHITEKTONICZNEGO W ODNIESIENIU DO BUDYNKÓW HISTORYCZNYCH NA PRZYKŁADZIE WIEŻ CIŚNIEŃ Z TERENU WOJEWÓDZTWA KUJAWSKO-POMORSKIEGO

Streszczenie

W artykule omówiono zastosowanie technologii druku 3D w architekturze, ze szczególnym uwzględnieniem renowacji i rekonstrukcji budynków historycznych. Wyjaśniono, jak druk 3D umożliwia dokładne odwzorowanie detali architektonicznych, co jest kluczowe w pracy z zabytkowymi strukturami. Przedstawiono korzyści płynące z wykorzystania tej technologii, takie jak zwiększenie precyzji, redukcja kosztów i czasu pracy, a także możliwość tworzenia skomplikowanych form, które byłyby trudne do wykonania tradycyjnymi metodami. Omówiono również przykłady zastosowania druku 3D w praktyce, w tym projekty, w których wykorzystano tę technologię do odtworzenia zniszczonych elementów budynków historycznych. Podkreślono, że druk 3D staje się coraz bardziej nieodzownym narzędziem w arsenale architektów i konserwatorów zabytków, przyczyniając się do zachowania dziedzictwa kulturowego dla przyszłych pokoleń.

Słowa kluczowe: wieża ciśnień, wydruk 3D, model trójwymiarowy, obiekt historyczny