Technological modernization in window restoration: integration of 3D printing and digital modeling

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Abstract. Digital technologies are currently being actively integrated into design and construction practices. The process involves collecting and accumulating the necessary information, ensuring its orderliness and timely updating in accordance with the technical and managerial tasks to be solved at individual stages of the object's life cycle: during design, construction or reconstruction, and during further operation. This approach contributes to a significant increase in resource management efficiency and comprehensive safety in the field of construction and restoration. The purpose of the study is to analyze the potential of modern digital technologies in the restoration and manufacture of non-standard parts. In particular, the study examines the possibilities of 3D printing technologies for replacing elements of old structures, defines printing technology, and provides examples of the use of structures in real life. The potential for using BIM modeling for work planning is studied. The study identifies the main advantages of introducing digital technologies in the architectural and construction sphere, including acceleration of design and construction processes, project development and implementation; reduction of errors and shortcomings, improvement of design quality and accuracy, minimizing resources for corrections. The study highlights the main functions of BIM modeling and additive manufacturing in the context of improving characteristics, reproducing models of complex geometry, and simplifying the manufacture of individual elements of window structures during building restoration. It has been proven that the digitalization of the construction and architecture sector, which includes digital modeling and additive manufacturing, opens up wide opportunities for the potential development of the industry and its technological upgrade.

Keywords: digital technologies, additive manufacturing, BIM modeling, buildings, building operation, structures.

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Introduction

In recent decades, digital technologies have been increasingly used in construction and restoration practices, which inevitably leads to the need to adjust traditional algorithms of action. The introduction of digital technologies has revealed a number of positive aspects, including the ability to present models in virtual space, the creation of an electronic database for quick search of analog material based on the form of a 3D model, the ability to track any changes in the appearance and structure of the restoration object, and the ability to conduct analysis from several points of view.

The successful combination of new technologies and classic restoration techniques includes the reconstruction and restoration of lost elements or the creation of replicas using 3D printing methods, digital restoration and digital projection restoration, the use of augmented reality technologies for the reconstruction of objects, etc. Building information modeling (BIM) – a process that allows the creation of virtual models of architectural structures – shows significant prospects for application, including in the context of integrating various aspects of design, allowing the development of personalized architectural solutions through joint processes. At the same time, in existing restoration practice, the experience of using digital technologies is usually associated with a specific project, which does not allow for the formation of an objective approach to the use of modern technologies in restoration.

Literature Review

Contemporary scientific discourse in the field under study has been shaped by scientific research conducted by F. Cinquepalmi, V. Tiburcio [3], S. Mocerino [5], E. Pietroni, D. Ferdani [7], I. Trizio [11], and others. The publications of O. Soto-Martin et al. [10] and L. Wilson [13] highlight the need for active integration of modern technological solutions into the field of construction and restoration. The authors emphasize the key advantage of 3D printing for architects—rapid testing of numerous concepts and integrations in the early stages of a project, which allows for the prompt identification of potential problem areas that are difficult to predict through computer modeling.

At the same time, authors often position BIM modeling as the best choice for planning work. At the same time, L. Agustín, M. Quintilla [1], K. Siountri et al. [9], and E. Tsilimantou [12] draw attention to the environmental context of the problem, as construction and restoration processes have a significant impact on the environment. The authors conclude that the integration of digital solutions can reduce the destructive impact on the environment, which raises the question of the balance between innovative and traditional approaches to the restoration of window structures.

Particular attention should be paid to the studies by A. Khalil et al. [4] and C. Zhou [14], which substantiate the potential of additive manufacturing in the context of the “green” economy and the greening of the construction industry. According to the authors, 3D printing shows significant prospects in terms of implementing a local production model, in which products are manufactured on demand where they are needed, eliminating the need for large inventories and optimizing logistics processes.

Certain aspects of the issue under study are discussed in publications by contemporary researchers S. Musella [6], E. Sällström, L. Lidelöw [8], and a number of others. At the same time, despite the significant achievements of scientists, the search for rational concepts for the technological upgrade of window restoration systems using digital solutions remains open, which highlights the need for additional scientific research.

The purpose of the article is an analysis of the potential for using modern digital technologies in the restoration and manufacture of non-standard parts.

Research Results

The term "additive manufacturing" (3D printing) refers to technologies that create three-dimensional objects one ultra-thin layer at a time. Each subsequent layer is bonded to the previous layer of molten or partially molten material [1]. Objects are defined digitally using computer-aided design software, which is used to create stl files that essentially "slice" the object into ultra-thin layers. This information guides the path of the nozzle or print head as it precisely deposits material on the previous layer. A laser or electron beam partially melts the powdered material layer. As the materials cool or harden, they fuse together to form a three-dimensional object [12].

The technology adds value to the product by increasing the productivity of the restoration process itself. One of the advantages of 3D printing is also the rapid testing of new concepts and iterations in the early stages of a project. This makes it possible to quickly identify various potential problems that would be much more difficult to identify using computer modeling [9].

In addition, designers can print inexpensive architectural models simultaneously at different stages of the project, which are used as research models, with different designs and scales, to evaluate space, volume, and overall structure. Models are produced faster, easier, and cheaper at any time during the design process, and any new changes made to the design are adapted and printed simultaneously, which is a rather effective technique. Models can be updated quickly and without significant expense, allowing for real-time changes and corrections based on previous designs [4].

It should be noted that 3D printing is currently positioned as an energy-efficient technology that can ensure environmental efficiency in terms of the production process itself, creating less waste, which gives it additional advantages in the context of prioritizing sustainable development principles [11]. In addition, the additive approach reduces anthropogenic pressure on the environment throughout the entire life cycle of the manufactured product, thanks to a lighter and more durable design that leaves a smaller carbon footprint compared to traditional products. In the long term, the optimal solution in this area appears to be the synergy of additive and traditional manufacturing processes, which will allow for greater sustainability.

In modern conditions, 3D BIM modeling provides the most comprehensive solution to this problem. For successful testing of the developed system, its functionality, and practical applicability, it is necessary to use specialized software (in particular, Autodesk Revit), into which all parametric information and related metadata are integrated. Next, a management system support database (e.g., in Microsoft SQL Server) is developed, where the model will support all information exported from the BIM model [9]. A web application is being developed separately, which works through an application programming interface that provides communication between the web application and the BIM model, allowing not only to interact with the parametric information of this program, but also providing constant access to the data management system (drawings, verification reports, specifications, etc.) [1; 12].

One of the key practical advantages of the BIM modeling methodology is the ability to integrate parametric objects into a 3D model, ensuring their direct interaction. Some of the above methods, in particular additive technologies (3D scanning and 3D printing), are currently widely used in the work of restorers. Along with additive technologies, augmented reality technologies have also become popular. Although new technologies can provide new solutions for the restoration of objects, the choice of method requires prior assessment and adherence to the basic principles of restoration [6].

In cases where part of the structure is destroyed or has suffered serious damage, a number of traditional methods are used, based on the laws of restoration and the nature of the defects:

- physical restoration – reconstruction of lost elements to fully restore the condition;
- digital restoration – restoration of the original appearance by reconstructing lost details in digital space using multimedia technology;
- digital projection restoration – the process of restoring decor, color, or texture by projecting an image onto the surface of objects;
- AR restoration – the use of augmented reality (AR) technologies to reconstruct objects and digitally restore them on smart devices;
- template-based restoration – restoration of incomplete artifacts to their complete state by using prototypes (templates) that are placed behind the object, creating a visual effect of the object's integrity [2; 9; 14].

The above-mentioned option for using digital technologies should be considered as an auxiliary option for their use in the restoration process. In practice, new technologies can be effectively implemented in the process of modeling individual lost elements in the form of a virtual 3D model. The resulting models can then be used for digital restoration using augmented reality technologies or for further 3D printing.

Depending on the field and purpose of use in construction and restoration, there are different types of 3D printers:

1) portal 3D printers, consisting of a frame, three portals, and a print head, which are quite effective for construction but are limited to printing three-dimensional models;
2) Delta printers, which involve the installation of vertical guides on the construction site, on which the print head is suspended; this form is not limited to printing three-dimensional models, and modeling errors are minimal;
3) Robotic printers equipped with a crane arm and a computer control system; this model is quite easy to use, as the process follows a predetermined algorithm, which virtually eliminates the risk of errors and inaccuracies, making this printer model the most popular.

The manufacture of parts for the restoration of window structures using a 3D printer opens up a huge number of new opportunities for the construction industry. In particular, 3D printing has many advantages over other methods:

- reduction of the duration of work due to high printing speed;
- virtually unlimited possibilities for the implementation of designers' and architects' ideas;
- minimization of errors in the construction process due to full automation;
- low energy consumption of equipment;
- economic effect and conservation of resources, including labor;
- minimization of waste and leftovers of building materials.

It should be noted that, at present, 3D printing is used not for printing complete elements, but for manufacturing casting molds, which is an extremely important area in restoration. Additive technologies can also be used for complete printing of individual lost elements. In this case, polymers (SLA, FMD, FFF, etc.) or metal powder (SLM) can be used in the printing process. In this case, the principle of restoration will not be implemented due to the difference from the original, and the method of digital restoration will be introduced as restoration using a template that allows you to create a visual effect of the integrity of the object [9; 12; 13].

There are two approaches to creating a digital twin of a building object: the first involves compiling a large number of files in various formats using specialized computer-aided design software (e.g., Autodesk Revit, USA), which represent the architectural or engineering model of a specific element, which provides a holistic perception of heterogeneous information about the object, since its formation is produced in accordance with the program code of a single complex; the second approach implements the procedure for forming digital models based on the manipulation of information from databases compiled in text files, which allows working with 3D graphics in conjunction with databases.

The complexity of the second approach is associated with the integration of architectural, design, technological, and organizational solutions obtained using various software complexes into a single environment [2; 10]. It is worth noting the potential problems of such information assimilation: the issue of the correctness of displaying various information, as well as the lack of unified approaches to the formation of models for these databases [5].

For the successful development of information modeling technologies, it is necessary to develop a general methodology for building models, which includes the following main stages:

- determining the list of project participants;
- forming a research program and development environment;
- conducting research and processing the results in accordance with a unified data presentation format in the model using open formats;
- creating a conceptual model that includes visual processing of the object and reflects approaches to planned interventions, as well as determining the main technical and economic indicators of the object after restoration;
- forming a detailed model in accordance with the approved conceptual parameters – in the model being created, materials and products must be presented with the possibility of visualization, contain physical and mechanical characteristics for performing the necessary structural calculations, and be accompanied by a technological map of their application;
- forming the technical and economic parameters of the restoration process;
- refinement of the model during the restoration work;
- formation of the operational stage of the model to ensure the necessary parameters of current content.

A striking example of the creation of a new urban environment that preserves historic buildings or recreates them, thereby shaping a modern environment with the help of digital design, can be found in the projects of two Dutch architectural firms: Crystal Houses Amsterdam (MVRDV) and The Looking Glass (UNStudio) on one of the most expensive streets in Amsterdam, P.C. Hooftstraat.

The architects reconstructed the Crystal Houses complex, almost completely recreating the historic facades of the old building using glass structures manufactured using special technology. The combination of real terracotta brickwork with green-tinted glass blocks creates a visual illusion, dissolving the walls into space. To implement the project, a new technical development department was opened in the architectural bureau: experts worked with lasers, special lamps, and digital models.

The main idea behind the reconstruction of the historic facade in the Mirror project was the authors' desire to combine the idea of architecture and textiles, expressed through glass. Terracotta bricks were used as the main material, which allowed the facade to retain its authenticity, characteristic of the three-tiered structure of buildings in the center of Amsterdam. The most memorable part of the reconstructed facade is the windows, which are three glass structures that “hang” from the second floor and create the feeling of curtains fluttering in the wind. The glass structures were carefully designed and verified using digital models, which helped to solve both artistic and engineering tasks.

In conclusion, it should be noted that 3D printing and BIM modeling currently offer a relatively fast, simple, and cost-effective approach to creating detailed models directly from digital data, which opens up broad prospects for further technological improvement of approaches to restoration work.

Conclusions

The construction and restoration industry is currently undergoing a significant impact from digital technologies, which involves the introduction of new approaches to collecting and processing information, as well as updating methods for solving technical and management tasks. The use of innovative technological solutions in 3D printing and BIM modeling not only allows for the creation of accurate copies of complex elements or the implementation of unusual solutions, but also forms a reliable system for monitoring and forecasting.

The results of the analysis of the potential for using modern digital technologies in the restoration and manufacture of non-standard parts make it possible to update the capabilities of 3D printing technologies to replace elements of old structures while preserving their authenticity, while summarizing their accuracy and preventive protective function in terms of preventing errors in operation.

The key vectors for the use of digital technologies in the window restoration process – 3D scanning and BIM modeling – allow for the creation of accurate virtual copies of window frames and decorative elements even before the start of installation work, which significantly optimizes the restoration process and reduces the risk of errors when installing new elements. It can be argued that digital technology upgrades will simplify restoration processes, as they are less labor-intensive and resource-intensive, more environmentally friendly, safer, and more economical. This highlights the significant potential of innovative technologies in the development of the construction industry.

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