11TH INTERNATIONAL CONFERENCE

ON ARCHITECTURE – CHALLENGES IN DESIGN

PROCEEDINGS

strand
SUSTAINABLE URBAN SOCIETY ASSOCIATION

Impressum

Title
ON ARCHITECTURE — CHALLENGES IN DESIGN
Proceedings

Publisher
STRAND – Sustainable Urban Society Association
Belgrade

On behalf of the Publisher
Ružica Bogdanović
STRAND – Sustainable Urban Society Association

Editor
Ružica Bogdanović

Reviewers
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Cover Design
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Belgrade, 2023

ISBN 978-86-89111-34-7

Contents

IV **ART AND ARCHITECTURE**

V **NEW MEDIA AND NEW TOOLS IN DESIGN**

VI CONFERENCE POSTER SESSION

- *I Architecture – Design Challenges in Macro and Micro Scale*
- *II Technology and Architecture*
- *IV Art and Architecture*
- *V New Media and New Tools in Design*

RETHINKING CITIES: ARCHITECTS AS AGENTS OF CHAOS
POWER, PLANNING AND THE ROLE OF THE ARCHITECT IN THE DIGITAL ERA
Erez Ella

10.10 10-YEAR RETROSPECTIVE OF ARCHITECTURAL EDUCATION OUTCOMES IN 10 THEMES ON THE TOPIC OF *POSTINDUSTRIAL DEVELOPMENT OF THE AREA BETWEEN DUNAVSKA STREET AND THE DANUBE'S BELGRADE WATERFRONT*
Bojana Jerković-Babović

DEMOCRATIZING URBAN PLANNING: INSIGHTS FROM PARTICIPATORY FORUMS IN BELGRADE
Iva Čukić, Jovana Timotijević, Marko Aksentijević, Božena Stojić, Olga Andrić

URBAN EDUCATION FOR FUTURE TRAFFIC ENGINEERS – ALTERNATIVE TRANSPORT MODES, ECOLOGY AND SPACE PROBLEMS OF A LARGE CITY FACING CLIMATE CHANGES
Svetlana Batarilo, Ranka Gajić

DISTANT MOMENTS CONDENSED: MNEMOTECHNICS OF THE CITY.
CASE STUDY: THE WEDDING INSTALLATION
Nora Lefa

"SOUNDSCAPE OF FEMALE EXPERIENCE" – TRANSDISCIPLINARY ACOUSTIC ECOLOGY OF PALIĆ LAKE
Jasna Jovićević

THE ARCHITECTURE OF FLUIDITY
VISUALIZATION OF THE RESEARCH PROCESS OF FIGURATIVE AND NONFIGURATIVE INSTRUMENTALIZATION OF THE FLUIDITY PHENOMENON IN ARCHITECTURE
Bojana Jerković-Babović

Reimagining Materiality: Circularity Potential of 3D Printed Architectural Elements with Recycled Clay

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Abstract: This paper explores the application of 3D printing with recycled clay for architectural building elements, emphasizing its potential to contribute to a circular economy. The AEC industry has traditionally been associated with high material waste and environmental impact. However, the advent of 3D printing has revolutionized architectural design and manufacturing processes. Using recycled clay as a printing material, can address two challenges: reducing waste and promoting sustainability. Recycled clay, obtained from construction and demolition waste or other sources, offers advantages such as abundance, low cost, and a low environmental footprint, making it suitable for circular economy practices. Moreover, using recycled clay in 3D printing enables architects to create complex, customizable, and structurally efficient building elements, reducing the need for labor-intensive, resource-consuming traditional manufacturing techniques. The principles of the circular economy involve diverting collecting, processing, and transforming clay waste into printable material. Resource extraction and energy-intensive manufacturing processes associated with conventional building materials could be reduced by reusing and recycling clay. The paper examines case studies and ongoing research efforts in the field of 3D printing with recycled clay, demonstrating the potential of this approach to contribute to a circular economy in the AEC industry. This approach reduces waste, preserves natural resources, reduces carbon footprint, improves energy efficiency, and creates sustainable and aesthetically pleasing architectural structures. In conclusion, integrating 3D printing technologies with recycled clay presents a promising way towards creating a sustainable closed-loop circular economy system in architecture. By reimagining the construction process, designers and builders can contribute to an environmentally friendly and resource-efficient future while pushing the boundaries of architectural innovation.

Keywords: 3D printing, sustainable construction, circular economy, clay materials

1. Introduction

It has become apparent that the construction industry is responsible for a significant portion of global environmental concerns. In 2020, the architecture, engineering and construction (AEC) industry accounted for 37% of global greenhouse emissions (Renewables 2022 Global Status Report 2022). One of the major sources of CO_2 is the production and use of cementitious materials, as concrete is still the most used construction material, contributing to about 6-8% of emissions (Al-Noaimat et al. 2023; UNCCN 2017). Additionally, AEC is one of the main solid waste generators, producing around 25% of global solid waste (Benachio et al. 2020). Another important factor contributing to the environmental footprint of the building sector is resource consumption, and AEC is solely responsible for consuming around 32% of natural resources used annually (UNEP 2009). All of this shows that minimizing the carbon footprint of the construction industry is crucial in the present context. One of the ways to achieve this is to address all phases of the building process: construction, operation, and demolition through the use of novel building techniques, materials, or the recycling of construction-related wastes.

Additive manufacturing, or 3D printing (3DP) technology, has recently shown great potential for improving the sustainability and efficiency of the construction industry by reducing waste output, construction time, and material consumption (Ning et al. 2021). From the architectural standpoint, 3DP also enables the fabrication of geometrically complex bespoke elements that cannot be efficiently produced using traditional building methods. Due to the growing need for decarbonatization, most research is currently focused on the concrete 3DP in order to reduce its consumption (Buswell et al. 2018). However, 3DP technology can be used with a variety of different materials, including sand, metal, plastic, or clay. The clay and other earth-based materials can be printed using adapted extrusion-based printers that form objects by depositing layers of paste material. The main benefit of the use of clay and other earth materials for printing is that they are abundant, natural materials that can be recycled (Alonso Madrid et al. 2023). Also, clay is traditionally used in the construction industry for brick manufacturing, thus attributing to construction waste. Such waste can be recycled and reused as 3DP material, creating a closed-loop consistent with the circular economy practices.

For this reason, the main goal of this study is to discuss the use of clay and other earth materials in 3DP of architectural elements and their potential for reducing the environmental footprint of the industry. To achieve this, the case study methodology is used to examine ongoing research efforts in the field of 3D printing with recycled clay, demonstrating the potential of this approach to contribute to a circular economy in the AEC industry. Finally, based on the case study results, this paper provides an overview of the challenges and potentials for future research.

2. Circularity potential of clay 3D printing

Traditionally, construction industry is based on a linear economic model (i.e., make-use-dispose) that is closely associated with growing environmental concerns, especially with growing resource consumption and waste generation. For this reason, another economic model has gained significant attention in recent years (Hossain et al. 2020). The circular economy model aims to preserve and enhance natural resources by creating a closed-loop system through maintenance, long-lasting design, repair, reuse, or recycling (Geissdoerfer et al. 2017). The application of circular economy principles in AEC can help the industry mitigate some of the negative environmental impacts and become more sustainable by improving the use of sustainable materials, recycling and reusing construction materials, and avoiding unnecessary waste generation and disposal. Based on the study by Benachio et al (2020), this can be achieved through the implementation of several main principles of circularity, including:

- *Reuse of materials* - Salvaging and reusing materials from demolished buildings can significantly reduce the demand for new resources. Previous can be achieved by allowing the manufacturers to reuse the materials after the end of the life of the first building for new construction, reusing secondary materials in the new production cycle, reducing the need for virgin materials.
- *Prefabrication and modular construction* - Prefabrication involves assembling building components in a factory before they are transported to the construction site. This approach can reduce construction waste, improve quality control, and speed up construction, all of which align with circular economy principles.
- *Circular economy in the project design* – Implementing BIM and other digital tools at the early stages of a project can help optimize construction processes, reduce errors, and enhance resource efficiency. It also allows simulations of disassembly processes and material reusability.
- *Life Cycle Assessment (LCA)* - Conducting an LCA analysis of construction materials and techniques helps identify their environmental impact throughout the entire life cycle. Also, including practices such as design for disassembly can help guide decisions to choose more sustainable options and reduce embodied carbon and energy in buildings.

The use of 3DP in the construction industry can have a significant impact on promoting all of these principles. First, 3DP enables the customization of building elements and allows for the creation of complex and optimized geometries, reducing material consumption and improving cost-effectiveness. Most research on 3DP in the construction industry focuses on 3D printing concrete (3DPC) as an alternative to standard in-situ concrete casting. Traditionally, concrete casting requires formworks, which can account for about 50% of total fabrication time and cost, as well as considerable amounts of waste if non-reusable formworks are used (Hurd 2005). As an answer to this problem, 3DPC can be used as a structural material for printing architectural elements, as explored in a study by Anton et al. (2021) or more commonly for printing formworks (Hack et al. 2020). Using 3DP technology coupled with optimized design strategies for prefabricated construction can lead to a significant reduction in material consumption (Mata-Falcón et al. 2022). For example, when comparing a 3DP prefabricated bathroom element with a traditionally fabricated one, Weng et al. (2020) found that a digitally fabricated one had 85.9% lower CO_2 emissions during construction, mostly due to the reduced need for material and formworks. Additionally, 3DP can help reduce production chains by localizing production and, therefore, reducing the need for long-distance transportation of construction materials and components, leading to lower carbon emissions and reduced environmental impact (Khan et al. 2023).

Although 3DP shows considerable potential in terms of circular practices, there are still some concerns regarding 3DP in AEC. Printable cement-based materials tend to be more expensive and have higher levels of cement content and additives harmful to the environment compared to regular concrete mixes in order to achieve the necessary structural properties for large-scale construction (Faleschini et al. 2023). As a response, there is a considerable amount of research focusing on improving material properties for 3DP either by formulating new mixes (Bedarf et al. 2021) or by replacing their parts with recycled materials (Pasupathy et al. 2023; Sangiorgio et al. 2022). As construction and demolition waste (CDW) is an important environmental factor in the building industry, its use for 3DP can contribute to increased sustainability of construction and the creation of a closed-loop system (Ponis et al. 2021). Masonry waste consisting of brick, tile, and other clay-based waste represents a significant portion of CDW. These materials are often researched for their natural composition and recyclability, which makes them suitable partial substitution for cement (Pasupathy et al. 2023). There are multiple examples of research into more sustainable material mixes for 3DP using brick, ceramic, and porcelain waste that demonstrate the potential of recycled geopolymer mixes for construction (Christen et al. 2022; Faleschini et al. 2023). However, even though this approach can reduce the use of virgin resources, the production processes of these mixes tend to be energy-intensive, and it is still unclear how they compare to traditional methods regarding sustainability (Khan et al. 2023).

Another alternative to cement-based 3DP is using other more sustainable materials, such as clay and earth-based mixes, as they naturally have high adaptability to different climates, a low carbon footprint, and renewability. Earth-based materials have a long history in the construction industry, but the traditional method of building using earth, such as cob (earth, water, and straw mix), usually lacks the structural properties needed for large-scale construction. As a wet building technique, cob is actually similar in logic to 3DP – the object is created by depositing material paste. However, the mixture has to be reformulated to fit 3DP technology requirements and to improve structural properties. Several research projects are exploring the potential of 3DP with earth-based materials for both in-situ fabrication and prefabrication of architectural elements, such as customized building blocks (Faleschini et al. 2023).

Aside from earth-based mixtures, clay is another natural raw material suitable for 3DP. One of the main potentials associated with it is that clay can be used for 3DP in its raw state without any additives, and it can also be reused even after drying just by adding water to achieve printable consistency. This reusability was tested on a small scale in a study by Alonso Madrid et al. (2023) and, it was concluded that this property could reduce waste generation during the production process stemming from failed or inadequate prints. The main challenge of clay 3DP is the lack of structural properties, making it difficult to scale up the application of this method. For this reason, clay is mostly suitable for fabricating discrete building elements such as building blocks, as demonstrated by Peters (2013) or Kontovourkis (2020). Another challenge regarding clay 3DP is material afterlife, as clay needs to be fired in order to gain structural properties. Baked clay cannot be directly reused but needs to be recycled the same way as any other clay-based CDW. However, despite challenges, clay and earth-based 3DP shows great alignment with circular economy principles addressing some of the most pressing issues in AEC industry, such as waste management and resource protection.

3. 3D printed clay architecture

The case study approach is used to examine built prototypes and existing research areas addressing the issues and opportunities associated with the given technology, building on the subjects mentioned in the previous section. The environmental impact of the technology was studied, along with the technical difficulties encountered during the construction process. The first case shows a dwelling prototype constructed as a large-scale building suitable for passive building function inspired by nature. The second example focuses on the phenomenon of 3DP earth architecture in scales ranging from pavilion-type structures, which test out different configurations of the 3DP earth elements, to 3DP prefabricated construction of urban furniture building blocks. The last subsection presents several cases of novel techniques and methods from recent studies, showcasing different areas of interest for future research.

3.1 3D printed TECLA house

Technology and Clay (TECLA) house by the Mario Cucinella Architects is the first full-scale 3D printed dwelling prototype built from raw earth material, which reinstitutes low-carbon building concepts (Figure 1). The sustainability-related value of the project is seen in several of its characteristics:

- *Optimized massing and self-supporting shape* – in the initial design phase, the authors identified challenges related to the chosen earth material, such as its null bending resistance. The final dome-like shape of the building was produced through a from-finding process, resulting in a structure that withstands compression forces, therefore resisting loads through its geometry. No additional support or formwork was needed, bearing in mind that the limitations of the 3DP process have also been considered.
- *Adaptive and performative building envelope* – the innovative approach is also seen in the design of the building envelope as an active contributor to the building's low carbon footprint. In its two-layer clay configuration, thermal mass, sufficient insulation, as well as, shading and infill ventilation have been included. Depending on the climate parameters, such as air temperature and relative humidity, the envelope design is reconfigured to present the optimal results in line with the specific location. Since earth-based materials cannot resist prolonged water exposure, the wave-like envelope was also created to effectively evacuate it.
- *Life cycle assessment* – the building is biodegradable, using natural materials, with a small percent of artificial materials such as additives (less than 5%), frames, plumbing, shelves, and sanitary ware, which need to fulfill various safety, mechanical, and hygienic requirements not suited for clay. The life phases

that can be measured include the printing period (about two weeks with two printers for 250 m^2), the use phase (estimated at 75 years), and the disassembly and biodegradation of the house (estimated at 50 years). The building allows for recycling and reuse of the dismantled material, which greatly reduces the amount of energy needed to excavate it from the beginning. The specific design for the disassembly method is used to reduce the waste to as low as 5% (Cucinella 2022).

Figure 1 TECLA built prototype (source: https://static.dezeen.com/uploads/2021/04/tecla-3d-printed-home-mario-cucinella-architects_dezeen_2364_hero_7.jpg, accessed: 18.09.2023)

The building process was multidisciplinary and involved several stakeholders. An Italian firm, World's Advanced Saving Project (WASP) managed the printing process through a system of hexagonally distributed printing heads held by cranes and metal braces, which allowed more movement freedom for the printers (Figure 2). The structure was fully printed on-site, reducing transportation needs and CO$_2$ emissions generated that way. Mixture design represents another important aspect in which the firm Mapei was involved. The engineering team from the firm tested out different mixtures, settling on the one with the optimal buildability and best mechanical properties. One of the issues that was encountered included the question of non-existent regulations when it comes to the use of natural materials such as clay for large-scale printing. The project was developed in the hopes of showcasing a new building paradigm for the housing of people seeking shelter all over the world. The building possesses adaptability, where concepts for temperate climate, cold climate, hot and humid, and hot and arid climate vary in the building skin design and the distribution of openings (Moretti 2023). In conclusion, this project demonstrates the potential of clay 3DP by implementing several circular economy practices such as waste reduction, optimized use of natural materials, and use of LCA analysis combined with optimization of the entire design process.

Figure 2 WASP technology printing process (source: https://www.3dwasp.com/en/3d-printed-house-tecla/, accessed: 18.09.2023)

3.2 Scales of 3D printed earth architecture

One of the advanced laboratories for earth-based architecture explorations is situated in Barcelona. The Institute for Advanced Architecture of Catalonia (IAAC) recently added a new prototype pavilion to its resume, created with large-scale printing WASP technology. The TOVA pavilion is Spain's first 3DP earth-based prototype, built from local materials, also aiming at nearly zero carbon emissions (Figure 3). All the material was collected within a 50m radius of the building site, not generating any transportation-induced environmental pollution. The building's volume responds to the local climate characteristics: it is compact, protecting the users from cold winter weather, while perforations allow natural airflow through its interior, providing sufficient passive ventilation, which helps during the humid and hot weather cycles. The walls are injected with cavities for heat loss prevention and solar radiation protection, providing the needed insulating capacity. The structure's material mix was injected with organic compounds such as aloe and egg whites, which serve as surface protection from external weather conditions. The overall construction time was reduced to seven weeks, which could place this prototype among the solutions to the emerging housing crisis. The follow-up pavilion built after the TOVA was created on the same site, using the same material (IAAC 2022). The VOLTA pavilion is characterized by a more complex and curved shape, resembling a rugged shell-type structure, demonstrating the possibility of using a single material for the whole project, unlike TOVA, which had a wooden roof structure (IAAC 2023). The project was a multidisciplinary collaboration between several industrial partners and research groups, CITA from the Royal Danish Academy in Copenhagen and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart. These projects were built showcasing circular economy principles in practice, most notably by redirecting and localizing supply chains, thus considerably reducing energy consumption during construction.

Figure 3 TOVA pavilion in Spain (source: https://prizes.new-european-bauhaus.eu/application/9773, accessed: 18.09.2023)

3DP technology using clay is also effectively researched in the domain of smaller-scale elements used for the aggregative assembly of larger structures. One novel example is a project done by the IAAC and their partners, CO-MIDA (IAAC 2020), which resulted from the competition launched by the BIT Habitat Barcelona Municipal Foundation. The restricted horizontal surfaces in densely populated metropolitan areas that could be used as gardens for growing food plants can be considered as the project's context. As a potential solution, a vertical modular garden was designed (Figure 4).

The sustainability values of the intelligent garden prototype are seen through:

- *The use of natural materials* – clay as a material itself has a low carbon footprint. The 3D-printed clay elements were additionally exposed to low temperatures to transform them into ceramic.
- *Installation on existing building walls* – the fact that building facades could be covered with additional layers of the vertical garden, which could enhance the thermal inertia of the building, leading to less energy being used for the heating.
- *Bio-Photovoltaic concept* – the soil used for growing plants is inhabited by various bacteria that transform the nutrients from the plants to hydrogen protons and electrons. These free electrons are transferred from the anode to the cathode situated in the clay elements, creating electricity that powers the vertical garden's built-in sensors.

This project demonstrates the potential of clay 3DP on a smaller-scale, enabling modular construction of elements that can be applied to further enhance the energy performance of buildings. The production process of the smaller scale elements also has fewer technical challenges, as opposed to full-scale printing logistics. The elements are produced in a controlled environment, with the ability to adjust the printing parameters according to the design intent.

Figure 4 CO-MIDA vertical garden prototype (source: https://iaac.net/project/co-mida/, accessed: 18.09.2023)

3.3 Clay 3D printing research domains

To further explore the many challenges and potentials in the topic of clay 3DP in architecture, relevant recent studies and applications have been discussed. The goal was to scope the research field and inform future research in the 3DP of clay and earth materials.

One of the main advantages of 3DP technology is its ability to print out complex geometries created in the modeling software and directly transferred into slicing software to adjust the printing parameters. An example is the research of 3DP artificial ceramic marine habitats using eco-friendly materials and imitating the morphology of the nature-found reefs (Berman et al. 2023). The printing of complex internal geometries has been assessed regarding the challenges faced by 3D clay printing technology. The mentioned challenges include the long printing time, geometries collapsing without added supports, and the question of control of the material extrusion (Sangiorgio et al. 2022). Similar topics are explored in the context of free-form ceramic vault systems, which relate to material mechanical behavior in the drying and firing stages, purposely for use in printing large-scale structures (Figure 5). The main constraint of the paste-like printing materials is seen in their retraction in the printing process, as well as the appearance of surface cracks (Carvalho et al. 2019). Precision in the 3DP process is seen as a large contributor to the quality of the product, as highlighted in the study exploring different morphologies enabled by paste-based 3DP (Seibold et al. 2018). A parametric-integrated design method is explored in the design domain, which highly relates to the geometrical and morphological characteristics of the 3DP structures (Kontovourkis and Tryfonos 2020).

Figure 5 Ceramic 3D printed shading vault prototype (source: (Carvalho et al. 2019)

The main identified research areas in the field at the moment with the prospect for further development include:

- **Material properties research** - Research by (Faleschini et al. 2023) aims to explore different components in the material mix, their role in the final material compressive strength, and embodied carbon to analyze the environmental impact. Materials such as cob have been researched in the domain of their 3DP parameters adjustment, such as extrusion rate, continuity, consistency, and mobility (Gomaa et al. 2021). Another paper deals with the application of mycelial growth within 3DP clay structures, with the goal of enabling fiber connections on a microscopic scale, increasing the material's tensile strength (Jauk et al. 2022). Different sets of additions to the earth-based mortar have also been considered, such as natural textile material for reinforcement purposes (Tarhan and Perrot 2023).
- **Clay recycling** – This type of research mostly focuses on mixing concrete 3DP technologies and recycled clay materials to create a more sustainable system with better mechanical properties (Chen et al. 2021; Christen et al. 2022; Faldessai et al. 2023; Zhao et al. 2023). A comparative analysis of the environmental impact of different circular materials and construction techniques showcases that the CDW-based geopolymer materials for 3DP have the lowest global warming potential compared to ordinary Portland cement-based 3DP construction processes or conventional masonry construction of the equivalent structure. The only downside to this type of material production is the amount of electrical energy needed for the mechanical processing of waste materials (Khan et al. 2023). Another experimental study concludes that the eco-friendly geopolymer containing brick waste could reduce embodied energy and carbon emissions by up to 60-80% compared to regular Portland cement concrete (Pasupathy et al. 2023). The use of recycled clay for 3DP material mixes is a current topic but it is only in the beginning stages of research with extensive potential for further development.
- **Sustainability assessment** – Despite the emerging research concerning the circularity potentials of earth-based 3DP, there is a notable lack of systematized research focusing on the sustainability aspects of this construction process. For example, presented case studies have demonstrated how different aspects of clay 3DP can promote sustainable practices in the construction industry, mainly through the reduction of the carbon footprint and changing the production chains. There was even an LCA conducted for TECLA house highlighting significant sustainability improvements compared to the industry standard (Cucinella 2022). However, these findings are still project-specific and often derived from small-scale prototyping as this type of construction is still in the early phases of development. Construction 3DP in general faces the overall lack of regulations and building codes relating to this novel construction method. This challenge is also present in the sustainability assessment of 3DP buildings. This technology demonstrates significant potential in terms of material recyclability, reduced material consumption, and waste generation, but on the other hand, it comes with additional challenges and risks that need to be addressed (El-Sayegh et al. 2020). To better understand the sustainability potentials of 3DP structures it would be beneficial to conduct more comprehensive sustainability assessments based on the building specifications of certification institutions as no such research was identified.

4. Conclusion

This paper examines the opportunities of 3D printing with clay and other earth-based materials in relation to circular economy practices. As one of the sectors with the highest environmental impact, the construction industry must reconsider traditional processes and practices. For this reason, implementation of the circular economy principles can lead to more environmentally friendly and sustainable construction. Using 3DP technology proved to be a promising way of reducing labor costs, construction time, and material consumption. However, printing materials must also be reconsidered as the most commonly used cement materials still have considerable environmental impact. To answer this problem, this study focuses on 3DP of clay and earth materials, which can be locally sourced and are renewable natural materials. Through the analysis of current research trends and industry examples, some of the main advantages of the clay 3DP are lower CO2 emission, low waste generation, and recyclability of the material. Clay can even be directly reused during printing, eliminating production waste. Another important circularity potential of clay 3DP is the localization of production, helping to create closed-loop resource paths. From the circular economy standpoint, clay 3DP has a strong potential to further circular practices in the construction industry through the recycling and reuse of materials, construction localization, and the design of modular optimized architectural elements. While 3DP offers many advantages for the circular economy, it is essential to consider its environmental impact, particularly in terms of the energy required for printing. Sustainable material choices and energy-efficient printing processes are critical to maximizing the circular economy benefits of 3DP. Additionally, issues related to intellectual property, quality control, and regulatory compliance need to be addressed in the future as the technology becomes more widespread in the industry.

Acknowledgements: This research was funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia, grant number 451-03-68/2020-14/200090. The research was done under the research lab of the University of Belgrade, Faculty of Architecture—Laboratory for Innovative Structures in Architecture (LISA).

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