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TECHNOLOGY IS THE ANSWER. BUT WHAT IS THE QUESTION?

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Guest Editor: **Jelena Milošević**

TECHNOLOGY IS THE ANSWER.
BUT WHAT IS THE QUESTION?
- CEDRIC PRICE

Since architect Cedric Price (1934-2003) posed this provocative question to the audience during a lecture in 1966,[1,2] researchers and professionals, above all in the architecture, engineering, and construction (AEC) industry, have attempted to rethink our technology on numerous occasions. This Serbian Architectural Journal (SAJ) thematic issue aimed to reply to this challenge that remains pertinent owing to technological change (TC) by synthesizing artistic, theoretical, and technological positions. Authors were invited to continue the discussion on the more intelligent use of technology in building design, construction, operation, and assessment by questioning how it affects the future of societies and the environment.

Topics presented in this issue include technologically based practice, research, and education in the AEC industry, ranging from the methods and tools that enable the creation, simulation, and materialization to new ways of approaching the built-unbuilt and physical-virtual environment relationships. In this respect, Nestorović and Žujović in their article review digital fabrication of large-scale building elements using 3D printing (3DP), facilitated by the recent developments in additive manufacturing (AM) technologies. They discuss how potentials of 3DP can be exploited to produce customized, non-standard building elements, pointing on effective construction strategies that could enable more design freedom, complexity, and efficiency. In her study, Kosić Okanović address the topic of modularity contributing to the discussions of adaptive architecture and intelligent buildings. In addition to examining the prospect of automating the modeling process, her study discusses how modular architecture may be able to adapt to changes in the field of housing functions, particularly to the needs of the increasingly prevalent hybrid dwelling typology. On the other hand, Guzelis in his article discusses the socio-spatial impact of spatial computing technologies and SocialVR platforms on the space we inhabit, and transformation of our built environments into places of remote socialization. The article presents project that studies online modes of spatial production, including physical and digital objects in the physics/virtual overlap. In order to create a spatiotemporal and tactile mixed reality (MR) experience that transforms the built environment into a telecommunication medium where proprioceptive bodies and spaces are streamed across a spatial network, the project assembles a number of intelligent APIs (Application Programming Interfaces), such as Pose Estimation, Hand-Tracking, and Passthrough. This allowed author to explore the concepts of embodied telepresence, tactility, avatars, and sociality. In their article, Vuja and Milošević discuss application of bio-inspired patterns in generative design (GD). They propose deign strategy based on transferring complex behaviors of natural systems into patterns, their algorithmization, computational implementation, and application in production of design artifacts. Presented project designs produced by master architectural students at the University of Belgrade – Faculty of Architecture confirm the sustainability of the suggested design approach. Further, in their work Živković *et al.* focused challenge of sustainable urban planning using parametric design tools. They set themselves a challenge to answer the question of what sustainable urban patterns are and how a computer can help urbanists generate a range of urban patterns that can be evaluated for sustainability. Starting from the concept of transect urbanism, and urban density author defines parametric models which were evaluated using evolutionary algorithms. Case study conducted for urban area in Belgrade illustrates potentials of this approach.

Articles in this issue provided perspectives on architectural production in a creative setting where technology supports collaboration between scientists, artists, and designers, as well as human-machine collaboration, new methods and approaches. They give insights into the application areas in the AEC field for diverse emerging and growing technologies (including computational algorithms, artificial intelligence (AI), simulations, digital fabrication, extended reality (XR)) as they increasingly transit from experimentation to practical implementation. The efficiency of these technologies as creative forces, predictive mechanisms, design and craftsmanship tools, educational aids, or vehicles to understand and direct resource flow and fully explore the circular potential of the built environment could also be evaluated in terms of help they could provide for us to move beyond current exploitative and destructive models towards a symbiotic regenerative approach and healthy environments of cohabitation in the Anthropocene and possible coming age of hyperintelligence (*Novacene*).[3]

It is my great pleasure to present a selection of writings that I hope will challenge the reader to further rethink how technology could be instrumented to solve challenges of the environment and society. In the end, I am grateful for the vision of the Editorial Board of the Serbian Architectural Journal, the support of the Editorial staff, Arch. Desire Tilinger, Arch. Jelena Šćekić, Arch. Milan Ristić, and Arch. Jovana Stefanović, the insightful opinions of the elected Reviewers, and the time and effort put in by all authors to publish their research in this thematic issue.

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TOWARDS CONSTRUCTION OF CUSTOMIZED LARGE-SCALE ARCHITECTURAL ELEMENTS USING 3D PRINTING TECHNOLOGY

ABSTRACT

Recent advances in computational design and additive manufacturing have impacted the architecture, engineering, and construction industry, requiring a revision of common architectural design practices and processes. Rapid development and usage of digital fabrication, especially 3D Printing (3DP), has enabled the design and construction of more complex forms. This paper reviews different applications of 3DP for the construction of load-bearing architectural elements and the potential and limitations of these approaches. Starting from the hypothesis that 3DP facilitates the production of customized, non-standard, and complex elements, the research question of this paper is: How can the potentials of these technologies be fully exploited? This paper aims to identify relevant publications, collect and systematize 3DP methods, and then gather and analyze the present state-of-the-art in industry, using literature review methodology to illustrate the 3DP technology used in the industry. Relevant projects are then identified and categorized based on the element typology. Next, the advantages and disadvantages of the presented approaches are identified and systematized in relation to the level of design freedom, complexity and customization ability. Finally, the paper proposes a set of strategies for more efficient fabrication of customized architectural elements using 3DP technologies.

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1. INTRODUCTION: ARCHIVING THE INTANGIBLE

Computational design first gained popularity in the 1990s, changing the way many architects viewed the design process. The transition to 3D models of representation enabled designers to create free-form spaces with a level of geometric depth and complexity that has never been seen before. Since computational design has no economy of scale, meaning that the price isn't dependent on the total number of objects created or the number of variations, designers came to the idea of mass-customization. This meant that there was a possibility of using digital tools to mass-produce variations at no extra cost. This idea evolved over the past decades, and now, what Carpo[1] has referred to as the Second Digital Turn demands the revision of standard procedures and methods for architectural design. The development of computational design tools has opened up opportunities for designing more sustainable and optimized structures with outstanding geometric freedom. Meanwhile, recent advancements in additive manufacturing (AM), processes based on creating objects from digital data by adding material in successive layers, better known as 3D Printing (3DP)[2], have enabled the fabrication of such designs. Starting from the hypothesis that 3DP facilitates the production of customized, non-standard, and complex elements, the research question of this paper is: How can the potentials of these technologies be fully exploited?

This paper reviews different applications of 3DP for the construction of load-bearing architectural elements and the potential and limitations of these approaches. Many authors focus on the development of this technology, but their research is often focused on the advancement of technology through solving technical challenges, rarely prioritizing the design processes. As a result, many commercially available solutions for 3DP of architectural elements produce results that do not exemplify the geometric complexity of structural optimization but rather focus on the cost-time optimization of built structures[3]. Consequently, such examples were excluded from this research. Examples of 3DP large-scale architectural elements can more often be found in academia than in practice, with many research groups working in collaboration with companies to further develop project-specific technologies and fabrication methods[4].

The goal of this paper is to collect and systematically analyze the current state of the art by assessing the advantages and disadvantages of presented approaches and their relation to the level of design freedom, complexity and customization ability. A systematic literature review method was used to collect, analyze, and synthesize a selected body of research on the subject in order to answer the research questions and create new perspectives and frameworks.
A variety of sources, including the internet and other sources, were examined to acquire a complete picture of the state of the art in the field since it was thought that integrating non-scientific sources would provide a more comprehensive overview. Primarily, data collection was done by searching two main databases, Web of Science (WOS) and Scopus, using topic-relevant keywords. The search was only limited to the English language, and the publication period spanning ten years, as this timeframe was determined to be the most relevant for this study.

The analysis was conducted as a three-part process. First, current 3DP methods and technologies were identified. Next, methods and technologies used in those projects were systematized in order to determine their potential and challenges. Secondly, a wide range of projects was identified to recognize current trends and development directions in the industry. Finally, prominent research organizations and companies were recognized along with the most relevant research projects at the moment. Next, based on the literature review results, the potentials and limitations of different 3DP methods were observed and summarized. The results were then used to form a framework for more efficient design and fabrication of customized architectural elements using 3DP technologies.

2. LARGE-SCALE ADDITIVE MANUFACTURING IN AEC

Additive manufacturing, specifically 3DP technology, has been developing since the mid-1980s[5] and was introduced in the architecture, engineering, and construction industry (AEC) with the development of the first large-scale cement-based printer patented by Joseph Pegna in the late 1990s[6]. Even though 3DP refers to several AM processes, the most commonly used methods in the construction industry can be grouped into two main categories (1) Material Deposition Method (MDM) and (2) Binder-jetting (BJ)[7]. An overview of the methods discussed, as well as their properties and applications, can be found in *Table 1*.

	Method	Application	Structural Properties	Location	Materials
MDM	CC	Housing units, Walls	Load-bearing	On-site	Concrete, Ceramics
	3DCP	Structural elements, Panels	Load-bearing	Prefabrication	Concrete
	FDM	Building blocks, Panels, Formwork fabrication	Load-bearing	Prefabrication	Ceramics, Glass, Polymers
BJ	D-Shape	Walls, Panels, Formwork fabrication	Load-bearing	On-site, Prefabrication	Sandstone
	3DP	Formwork and mould fabrication	Not Load-bearing	Prefabrication	Sandstone, Ceramics, Polymers, Metals

TABLE 1: Overview of the main 3DP methods in AEC

2.1 Material Deposition Method

MDM is a layer-based method in which materials are extruded by a nozzle in layers on a predefined path, and then the material solidifies, creating the object. The two best-known MDM methods are Contour Crafting (CC) and 3D Concrete printing (3DCP)[8].

CC is an AM technology invented by Khoshnevis in 1998[9]. The technology was specifically designed for on-site construction. Despite their long development, on-site 3DP technologies still have a lot of limitations. The scale of the projects using this technology is still limited in size and possible geometric complexity that can be achieved[10]. Some companies have developed technologies similar to CC that are capable of 3DP entire housing units. For instance, there are printers that can produce construction elements at full scale, but unlike standard CC these methods are based on prefabrication[11].

3DCP is another extrusion-based method, but the main difference is that, unlike CC, this technology was designed for the prefabrication of concrete elements. The geometric complexity is limited by a maximal overhang that can be achieved using selected materials. As such it is more suitable for printing vertical non-standard architectural elements, especially columns or walls[12] Compared to CC, this method provides more geometric freedom, with the downside being a bigger layer height. This results in a coarser ribbed surface finish, where post-processing might be necessary, and weakening of the material's structural properties.

Another commonly used extrusion-based method is Fused Deposit Modelling (FDM), where the state of the material is controlled by a temperature difference. This technology can be used with different materials such as plastic, clay or ceramics and is often used for printing large-scale formworks[13].

2.2 Binder-jetting methods

BJ is a powder-based method where the liquid binder is selectively applied in thin layers over a thin layer of powder to create objects. The most common and well-known BJ method is D-shape printing developed by architect Enrico Dini[14]. Its significant advantages over MDM are its high printing resolution, almost complete geometric freedom, no need for support structures and large building volume[15]. This method of 3DP doesn't require any additional support structures, but powder serves as both; this allows the fabrication of complex geometries with a high level of detail. On the other hand, the disadvantage of this process is that it often requires postprocessing steps for cleaning loose powder and stabilizing the printed parts, which can be time-consuming[16]. The D-shape printer uses cement and can be used for printing large-scale architectural elements both on-site and prefabricated.

Three-Dimensional Printing (3DP) is a powder-based AM method that is able to print any powder material that can react with a liquid binder like cement, plastics or ceramics[17] Sand-printing, one of the 3DP techniques, has qualities that make it appropriate for fabricating architectural components, as it enables the manufacturing of precise and high-resolution large-scale parts. However, this technology still needs to be successfully applied for the fabrication of full-scale architectural elements due to the low structural strength of the sand-based 3D-printed material. For this reason, 3DP is more often used for printing formworks for non-standard structural concrete elements. A systematized overview of the discussed 3DP methods' limitations and potentials is presented in *Table 2*.

Method	Limitations	Potentials
CC	• Print size limited by the span of the printer • Intended only for on-site fabrication • Geometric complexity	• Small layer height • Good surface finish resolution • Used for load-baring elements
3DCP	• High layer height • Low surface finish resolution • Presence of cold bridges between layers • Geometric complexity limited by overhang angle	• Intended for prefabrication, • Suitable for printing vertical elements • Used for load-baring structural elements
FDM	• Usually used for small-scale objects • Requires support structure • Slow printing speed • Requires post-processing	• Suitable for formwork printing • High surface finish resolution • Uses wide selection of materials • Commonly available technology
D-Shape	• Post-processing of material needed • Structural performance of the printed element • Slow printing speed	• Good surface finish resolution • Greater form complexity
3DP	• No load-bearing properties • Post-processing of material needed	• Suitable for formwork printing • Uses wide selection of materials • Very high surface finish resolution • Scalable to larger build volumes

TABLE 2: Summary of the Characteristics of 3DP Methods

3. 3DP TECHNOLOGY APPLICATION OVERVIEW IN AEC

A significant number of projects focusing on the application of 3DP technology in the AEC industry were identified through the literature review. 3DP is currently used in a wide range of projects, from housing units[18] to space outposts[19] applied for both on-site and prefabricated elements. As this research focuses on customized architectural elements on-site technologies used for the fabrication of entire buildings are disregarded because of the limitations in terms of project scale and geometric complexity, focusing on prefabrication methods. Prefabrication is deemed more suitable for the fabrication of custom elements as it allows mass customization of large-scale architectural elements.

Regarding the variety of materials used for printing, it was observed that although there are studies based on the application of other materials, such as metal[20], concrete is the most commonly used structural material. As already mentioned, computational design tools allow complete design freedom in terms of geometric complexity and structural and material optimization of elements. However, in practice, most concrete structural elements are solid volumes, either linear (beams or columns) or planar (slabs). This is because the production cost increases with complexity, and materially optimized elements typically need unique formwork solutions, making them cost-inefficient as formwork can add up to 75% of construction cost[21]. One of the consequences of the broad application of concrete is its negative impact on the environment. Its carbon footprint is significant on a global scale, with 5% of the global CO_2 output[22] For this reason, a common goal of reviewed projects was raising sustainability through the reduced use of material and the need for formworks when using 3DP technology to produce bespoke elements.

3.1 Use of 3DP in bridge construction

Although bridges are not structural elements in architecture, they are specific structures that have the potential to develop and test new 3DP methods. Their freedom of design and necessary structural characteristics make them one of the most researched full-scale structures. This typology is important because it demonstrates that the application of 3DP technology is possible on larger scales and that it can meet construction industry regulations. This is something that is yet to be reached when implementing 3DP structural elements in full-scale architectural projects.

Loughborough University constructed Footbridge in Madrid[23] (*Figure 1*) assembled from U-shaped 3DP concrete elements that meet all state requirements defined for this structural typology.

Another notable example is the bicycle bridge from TU Eindhoven in 2017[24] (*Figure 2*). The bridge demonstrates the viability and security of 3DP concrete structures for public usage. TU Eindhoven later developed the largest 3DP bridge to date in Nijmegen, Netherlands, using similar technology[25]. This bridge also demonstrates advancements towards more complex geometric designs compared to the previous projects (*Figure 3*). To avoid the need for additional reinforcements the bridges are often designed as compression-only structures and divided into printable segments that are prefabricated and assembled on-site using concrete 3DP. Baoshan Pedestrian Bridge[26] from Tsinghua University is one such project (*Figure 4*). The project effectively demonstrates how 3DP has made it possible to produce materially efficient elements. Another example of a compression-only structure is the Striatus Bridge[27], a joint project between ETH Zürich and Zaha Hadid Architects (*Figure 5*).

FIGURE 1: Footbridge in Madrid, https://iaac.net/wp-content/uploads/2016/12/Puente-3D-002-1024x682.jpg, accessed on 09.06.2022

FIGURE 2: TU Eindhoven Bicycle bridge, Salet, Theo A. M., Zeeshan Y. Ahmed, Freek P. Bos, and Hans L. M. Laagland. "Design of a 3D Printed Concrete Bridge by Testing." Virtual and Physical Prototyping 13, no. 3 (July 3, 2018), 234, figure 20

As each type of architectural element poses its own challenges during the design and manufacturing process most researchers focus on a specific type of element. Used technology and design principles tend to be project-specific, and fabricated designs are often prototypes that are still to be implemented in real-life architectural projects. Consequently, to assess the advantages and disadvantages of available 3DP methods, this review focuses on the systematization of projects based on structural element typology and the classification of AM methods used in these projects.

FIGURE 3: Bridge in Nijmegen, Photo by Municipality of Nijmegen, https://assets.eu-central.w3.tue.nl/w/fileadmin/_processed_/e/6/csm_3d1_89ed9953ae.jpg, accessed on 07.12.2022

FIGURE 4: Baoshan Pedestrian Bridge, Photo by Professor Xu Weiguo, https://www.archdaily.com/909534/worlds-largest-3d-printed-concrete-pedestrian-bridge-completed-in-china/5c3f4e1b284dd125fd000102-worlds-largest-3d-printed-concrete-pedestrian-bridge-completed-in-china-photo, accessed on 07.12.2022

FIGURE 5: Striatus Bridge, Photo by Chiara Becattini, https://www.domusweb.it/content/dam/domusweb/it/architecture/gallery/2021/07/26/shajay-bhooshan-zaha-hadid-architects-striatus-bridge/gallery/domus_striatus_bridge_6.jpg.foto.rmedium.png, accessed on 07.12.2022

4. 3DP TECHNOLOGY APPLICATION IN THE CONSTRUCTION OF ARCHITECTURAL ELEMENT

Based on the literature review findings, discrete structural elements explored in this paper can be divided into four categories: (1) columns, (2) beams, (3) slabs and (4) construction blocks. There are two main approaches to applying 3DP for geometrically complex forms: the printing of formworks or the printing of structural material, which can be seen in all categories.

4.1 Columns

The most researched group of structural elements are columns. As columns usually carry compression loads, concrete is often a suitable material for their fabrication. However, because of their formwork complexity, columns are rarely made as bespoke elements but rather as simple forms with often uniform cross-sections. For that reason, many research projects focus on 3DP concrete as a method for fabricating geometrically complex columns that can be structurally optimized.

Most of the research still focuses on prototypes with only a few examples of their application in full-scale architectural projects as structural elements. The Future Tree pavilion project by ETH Zürich and Xtree company is one of the examples of the full-scale structural column projects[28]. This pavilion is a result of preceding Branching Column and Twisting Column projects as well as several prototypes (*Figure 6*). These projects are using Eggshell technology, a formwork printing approach with simultaneous digital concrete casting where a thin plastic outer shell is printed using FDM 3DP and later removed from the hardened concrete.

FIGURE 6: Columns printed using Egshell technology, Burger, Joris, Ena Lloret-Fritschi, Fabio Scotto, Thibault Demoulin, Lukas Gebhard, Jaime Mata-Falcón, Fabio Gramazio, Matthias Kohler, and Robert J. Flatt. "Eggshell: Ultra-Thin Three-Dimensional Printed Formwork for Concrete Structures." 3D Printing and Additive Manufacturing 7, no. 2 (April 1, 2020), 55-56, figures 5-6,8

This method allows for complex forms with a high-resolution surface finish. Scaling up a prototype for use in construction revealed one limitation, as reinforcement placement limits the possibility of cross-section variations.

The idea of 3DP formwork was tested in a few more ETH research projects, resulting in successful prototype structures. A similar approach to Eggshell was used in the Free Formwork project also by ETH Zürich[29] where BJ and FDM 3DP are combined to create a thin flexible outer shell that can be peeled off the cured concrete. Concrete with steel reinforcement cage is replaced by casted concrete[30]. Another approach was tested in Dissolvable Formwork[31] and Additive Archetypes[32] projects by casting concrete into FDM 3DP formworks made of water-soluble material. However, there have yet to be examples of the application of these technologies in architectural projects.

FIGURE 7: Concrete Choreography Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2019/06/fabrication-setup-1.

On the other hand, the printing of the structural material rather than formwork on a large scale can be seen in the Concrete Choreography project from ETH[33] (*Figure 7*). In this research, 3DCP was used as both formwork and structural material; the printed structure was later reinforced and filled with cast concrete. A series of twelve three-meter-tall columns were designed for a performing arts festival. The accent was put on the exploration of design possibilities using selected technology. Krypton project from XTree and Marc Dalibard also uses 3DP concrete as lost formwork for a column built in France[34].

There are also research projects focusing on the use of 3DP for the fabrication of column structures by printing structural materials with no additional support or formwork. A fossilized project from Bartlett combines 3DCP and BJ technology to explore the fabrication of complex forms.

The project focuses more on the design process and achieving form complexity using 3DP technology rather than on the structural properties of designed columns[35]. 3D printing Architectural expression[36] is another project developed as a part of the design studio at TU Eindhoven featuring three 3m high column prototypes. Cornell University led the project exploring the application of 3DP for architectural elements, especially columns in the Additive Architectural Elements project[37].

There are also researches focusing on materials other than concrete, one of them being metal 3DP led by Bologna University and company MX3D, although this technology still hasn't been tested in full-scale prototypes[38]. Another research by Blast Studio is exploring the use of live mycelium as a structural material for 3DP columns[39].

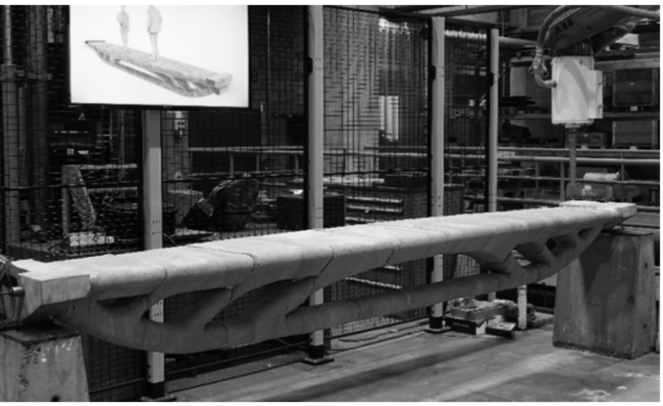

FIGURE 8
Ghent University Post-Tensioned Concrete Girder, Vantyghem, Gieljan, Wouter De Corte, Emad Shakour, and Oded Amir. "3D Printing of a Post-Tensioned Concrete Girder Designed by Topology Optimization." Automation in Construction 112 (April 2020), 7, figure 9

FIGURE 9
3D Printed Reinforced Beam from ETH Zürich, https://dbt.arch.ethz.ch/project/3d-printed-reinforced-beam/, accessed on 27.07.2022

FIGURE 10
COEBRO Ribbed Slab, Hansemann, Georg, Robert Schmidt, Holzinger Christoph, and Joshua Tapley. "Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling." In Fabricate 2020, 124–29. UCL Press, 129, figure 8

4.2 Beams

The beams are one of the least researched elements due to their more complex loads compared to columns, but also because they can be integrated into slab design, reducing the need for a beam as a structural element. However, there are two notable research projects focusing on beam fabrication. The first is Post-Tensioned Concrete Girder from Ghent University and company Vertico[40] (*Figure 8*). The project aimed to demonstrate how topological design paired with 3DCP can create a material-efficient structure. Topology optimization tools were used for form-finding during the design process. After the optimization pattern was created, the form was converted to the 3D structure. The prototype girder with a span of 4m was produced using 3DCP and it consists of eighteen prefabricated segments two end blocks that would need to be cast on site.

The second research is 3D Printed Reinforced Beam from ETH Zürich, which uses BJ technology to print topologically optimized beams in the sand (*Figure 9*). The beam has a complex geometric pattern and has been printed in seven segments with a 4.5m span[41]. There have yet to be any other prototypes from this research to show if scaling up the element to full architectural scale is possible using this technology and if the sand can be fully used as a structural material for larger spans.

4.3 Slabs

Although more materially efficient than solid, optimized ribbed slabs lost their popularity in architectural practice in the second half of the last century because of the high cost of formworks when they are not applied as a modular element. The same problem persists today, making bespoke slab design fabrication a point of interest for several researchers. One of the main reasons for researching optimized slabs is the possibility of better structural performance, material efficiency, and design aesthetics. Also, service ducts such as ventilation, heating or fire sprinklers can be integrated into the design eliminating the need for suspended ceilings[42].

COEBRO[43] project from TU Gratz uses 3DCP for the prefabrication of the optimized ribbed slab. Concrete elements were printed, then reinforcements were placed between the elements, and concrete was cast on top (*Figure 10*). The use of concrete as built-in formwork eliminates the need for a large number of different formwork pieces, which traditionally represent the biggest limitation in the production of ribbed slabs, and enables efficient construction. This way, 3DP concrete can be seen on the bottom side of the slab, and it has specific aesthetic qualities.

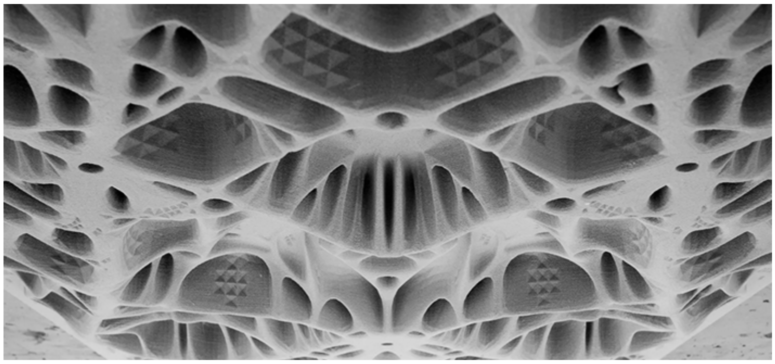

FIGURE 11A:
3D Printed Slab Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/02/dbt-eth-Topology-Optimization-for-3D-Printed-Slabs-andrei-jipa-mathias-bernhard-0.jpg?fit=3840%2C1645, accessed on 27.07.2022.

FIGURE 11B:
Topology Optimisation for a Concrete Slab Project, source: https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/02/dbt-eth-Topology-Optimization-for-3D-Printed-Formwork-andrei-jipa-mathias-bernhard-0.jpg?w=1920&ssl=1, accessed on 27.07.2022.

ETH Zürich realized a series of projects during recent years developing structurally optimized slabs. 3D Printed Slab[44] explored the possibilities of using topology optimization as a design method for floor elements. This research focused on achieving a high level of detail of surface geometry. As a result, a 2 m^2 prototype was printed using sand printing (*Figure 11* (a)). Scaling up of the prototype was done through Topology Optimisation for a Concrete Slab[45] project where sand 3DP was instead used for formworks that were later filled with conventionally cast concrete. This method was tested on a smaller-scale demonstrator slab (*Figure 11* (b)). These two projects were further developed through the Smart Slab[46] project. Sand 3DP formwork was used in combination with concrete casting and spraying to produce a complex non-standard ribbed slab with highly detailed geometry. This is the only project tested on an architectural scale as part of the DFAB HOUSE, where eleven 7.4m long segments were joined into a single prefabricated slab (*Figure 12*). This time, post-tensioning ducts and electrical and sprinkler systems were integrated into the slab structure.

Funicular Floor[47] and Fast Complexity[48] projects from ETH are also combining structural optimization with the integration of functional elements into the design. The Funicular Floor uses a 3DP for formwork elements on top of which are placed reinforcements and cast concrete. The usage of 3DP formwork results in a highly detailed surface where the cooling and heating systems are integrated inside the voids in the structure. This design method can result in a 70% reduction of concrete compared to the standard monolithic slab. Fast Complexity addresses the issue seen in previous projects such as Smart Slab where multiple different fabrication methods are used to manufacture a single element. The project proposes a combination of the BJ method for formwork and 3DCP extrusion for the loadbearing part directly on top, as BJ gives precision and 3DCP speed. The proposed method was tested on a 2 m^2 prototype, representing a 1:1 excerpt of a larger slab. The structure is divided into modules of reusable BJ 3DP formwork with extruded 3DP concrete on top of it. The structure above can differ for each module, allowing for structural optimization and integration of functional elements (*Figure 13*). Also, after removing the formwork, only the bottom side has a high-resolution surface finish, while the other sides have a coarser finish, as there is no need for a detailed finish on all sides of the slab.

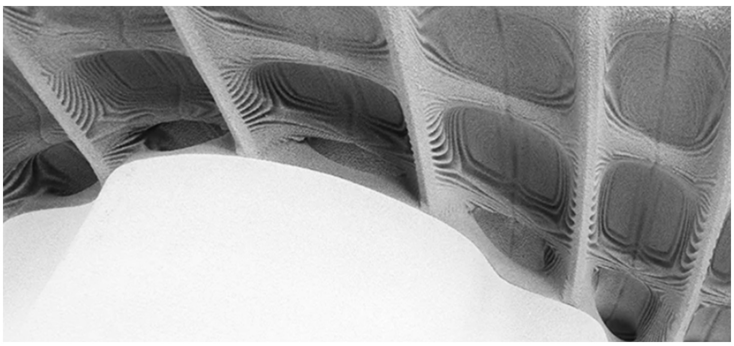

FIGURE 12: Smart Slab Project, https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2018/06/DBT_NEST_DFAB_HOUSE_ETH_EMPA_Smart_Slab_005b.jpg, accessed on 27.07.2022

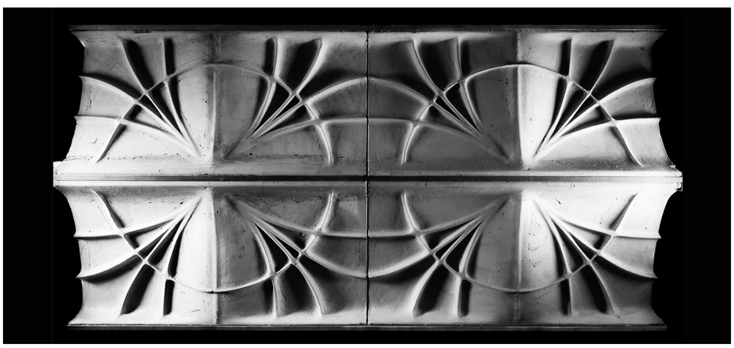

FIGURE 13: Fast Complexity Project, https://i0.wp.com/dbt.arch.ethz.ch/wp-content/uploads/2020/06/Fast-Complexity_7.jpg?w=1280&ssl=1, accessed on 27.07.2022

4.4 Construction Blocks

The final group of elements are construction blocks prefabricated using AM technologies. While most research focuses on large-scale 3DP for building elements, some authors directed their research towards the discretization of elements by using 3DP for small-scale building blocks. Building Bytes[49] project explored the use of small-scale 3DP ceramic printing for non-standard construction blocks, customized with variable characteristics and shapes that can be used as façade components or structural elements (*Figure 14*). The study explores ceramic brick formations with irregular three-dimensional features and interlocking joints. With this method, it is possible to include the essential mechanical or electrical infrastructures inside the bricks. This type of construction block still hasn't been tested in full-scale construction, only as part of outdoor installations or interior screens. Another research project with a similar approach is Digital Adobe from IAAC[50]. The main goal of the research was to produce architectural solutions using AM technologies and natural materials. Local clay is used as 3DP material for interlocking blocks. This was tested on a series of smaller-scale prototypes before building full-scale prototypes in an attempt to test the possibilities of its use in architectural objects. The test structure was a self-standing clay wall made of 3DP blocks (*Figure 15*). Modular 3DP blocks were further explored in Knitting Concrete[51] research by KTH Royal Institute of Technology and company XTree. In this case, concrete is used as a material for 3DP, and the main goal of the research was to create a database of different toolpath patterns for printing concrete when designing architectural elements.

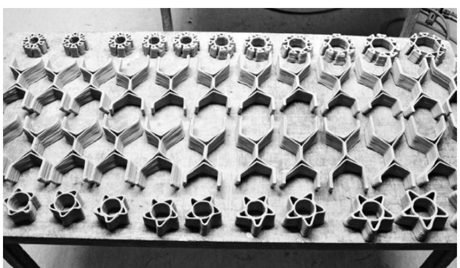

FIGURE 14:
Building Bytes Project, Peters, Brian. "Building Bytes: 3D-Printed Bricks," 2013., 115, figure 6

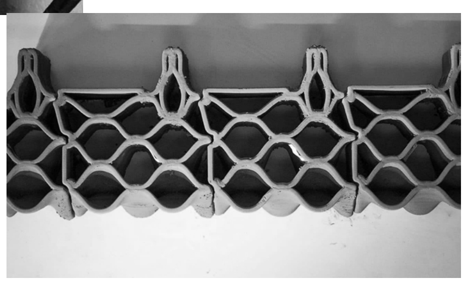

FIGURE 15:
Digital Adobe Project, https://iaac.net/wp-content/uploads/2019/03/09-prototype-09.jpg, accessed on 27.07.2022

Depending on a pattern, the element can have different surface qualities and aesthetic properties, or it can change its structural properties. Several patterns were tested on different scales and full-scale prototypes were produced by XTree company.

5. RESEARCH PROJECTS

Analysis showed that research projects focused on the design of custom prefabricated elements are currently primarily done in the academic setting. Currently, the most significant percentage of projects is being developed by Digital Building Technologies at ETH Zürich. Additionally, ETH has built a full-scale test building where they have implemented several researched AM methods for fabricating 3DP elements including a prefabricated Smart Slab system. TU Eindhoven is another research center that has left had a significant impact in the field of prefabricated 3DP elements in recent years, although their research is mainly focused on the development of bridge structures with only a few projects relating to structural elements used in architecture. In addition to academic research, another important factor that contributes to progress are construction companies, which often partner with academia to further develop AM technology. *Table 3* provides a comprehensive summary of all reviewed projects. It maps each project according to the element typology, name of the project, institutions and category of the 3DP system.

Element type	Project	Participants	Method
Column	Concrete Choreography[52]	ETH Zürich	3DCP
	3D printing Architectural expression[53]	TU Eindhoven + Vertico	BJ (D-shape)
	The Future Tree[54]	ETH Zürich + XTree	FDM
	Branching Column, Twisting Column[55]	ETH Zürich + XTree	FDM
	WAAM Columns[56]	Bologna University + MX3D	Metal 3DP
	Fossilized project[57]	UCL Bartlett	3DCP + BJ (D-shape)
	Free Formwork[58]	ETH Zürich	BJ + FDM
	Additive Archetypes[59]	ETH Zürich	FDM
	Dissolvable Formwork[60]	ETH Zürich	FDM
	Krypton[61]	XTree + Marc Dalibard	CC
Beam	Post-tensioned concrete girder[62]	Ghent University + Vertico	3DCP
	3D-printed reinforced beam[63]	ETH Zürich	BJ
Slab	Fast Complexity[64]	ETH Zürich	BJ + 3DCP
	COEBRO[65]	TU Gratz	3DCP
	3D printed slab and Topology Optimisation For A Concrete Slab[66]	ETH Zürich	BJ (Sand-printing)
	Smart Slab[67]	ETH Zürich	BJ (Sand-printing)
	Funicular Floor[68]	ETH Zürich	FDM
Construction Blocks	Knitting Concrete[69]	KTH Royal Institute of Technology + XTree	3DCP
	Building Bytes[70]	DesignLab Workshop	FDM (Ceramics 3DP)
	Digital Adobe[71]	IAAC	FDM (Clay 3DP)

TABLE 3: Comprehensive summary of all reviewed projects

6. DISCUSSIONS

6.1 Potentials and Limitations in Fabrication of 3DP Architectural Elements

This part of the paper presents a systematized overview of the detected challenges and potentials related to the design and fabrication processes of selected element typologies based on the literature review findings, as presented in *Table 4*.

Element type	Challenges	Potentials
Column	• Reinforcement integration • Difficult to achieve necessary structural properties • Design scaling up • Building codes requirements	• Geometric complexity and aesthetic qualities • 3DP used for structural material or formwork • Different methods and materials are researched
Beam	• Reinforcement integration • Limited research • Obsolete as a prefabricated element • Difficult to achieve necessary structural properties • Requires element discretization	• Form optimization for material efficiency • Use of 3DP structural material
Slab	• Reinforcement integration • Complex case-specific loads • Multiple fabrication methods needed per element • Requires element discretization • Design scaling up • Building codes requirements	• Geometric complexity and aesthetic qualities • Form optimization for material efficiency • 3DP used for structural material or formwork • Integration of infrastructure ducts • Possible high surface finish resolution • Formwork design and production
Construction Blocks	• Limited research • Limited structural performance • Fabrication time	• Geometric complexity and aesthetic qualities • Material efficiency • Use of local materials • Wall and panel design • Use of small-scale equipment

TABLE 4: Summary of potentials and challenges in the fabrication of 3DP architectural elements

All of the discussed element types have limitations in terms of reinforcement integration, which affects the choice of the 3DP method and the geometric complexity of the design. Another common limitation is the need for the practical testing of the designed models, as building codes generally don't recognize 3DP fabrication methods and custom designs. Despite said limitations, research shows a great potential for the reducing of the material consumption thus lowering of CO_2 emission for concrete structures through the use of the 3DP methods and form optimization, especially for the 3DP slabs.

Research showed that even if not yet at full-scale 3DP is a suitable technology to consider for the fabrication of all of the analyzed structural elements in non-standard geometries.

By using 3DP methods it is possible to fabricate custom elements with optimized forms without the need for traditional formworks making this process much more time-cost efficient. However, the biggest problem is encountered when trying to scale up the prototypes to architectural scale. Another significant challenge across all categories is fabricated elements' structural properties. The structural properties are dependent on two factors: applied AM methods and used material. As was previously shown each technology has its weaknesses in terms of the structural properties of the end product. Limitations in structural strength and aesthetic qualities can be mediated by improving material properties and choosing the most suitable fabrication method. However, further research is still needed in both areas to substantially improve the current state of 3DP technology.

6.2 Strategies for optimizing the construction of customized architectural elements

Taking into the account said limitations of currently available technology, this paper proposes a strategy for more efficient design and fabrication of customized architectural elements. Computational design tools allow us to create complex optimised forms; however, the limitations set by the technology must be taken into account to form the most efficient process. This chapter discusses several strategies whose implementation can optimize the design process of architectural elements so that it integrates the potentials and limitations imposed by technology.

1 Design by Testing Implementation

Based on the literature review, it can be concluded that optimization tools must be used from the early stages of the design process to achieve structurally efficient constructions. Namely, topology optimisation has shown great potential, especially in slab design as it allows optimised material distribution leaving room for the integration of other functional elements inside the structure. Design and fabrication need to be part of a single process that cycles between the two phases iteratively. Since most national construction standards do not yet recognize 3DP fabrication, one option is to use design by testing to construct full-scale structures, demonstrating their ability to adhere to legal criteria, ensuring the possibility of their application in standard practice.
This method can be seen in the Smart Slab project, which was the result of

several separate types of research where developed prototypes t focused on different aspects of the application of the technology and which results served as input parameters for each subsequent step, up to the final slab model that could be implemented in a real-life setting.

2 Using the prefabrication methods

Analysis of different large-scale 3DP methods' potentials and limitations confirmed that the use of prefabrication methods is a more suitable approach to mass customization than any currently available on-site fabrication method. CC and other similar methods used for on-site 3DP, proved to be too limiting for exploring the full potential of digitally designed forms. Such technology is limited both in terms of the size and complexity of an element that can be achieved. For this reason, other technologies, such as BJ or 3DCP, are more suitable for the direct printing of architectural elements. Demonstration of these limitations can be found in projects of 3DP houses and are discussed in the article. Approaching 3DP technology as a tool for prefabrication would realize one of the main potentials of this technology, which is the possibility of producing variations without the additional costs that are characteristic of standard prefabrication methods. That is why 3D printing can be seen as the next step in the development of twentieth century prefabrication methods.

3 Printing Formworks

Even though the printing of architectural elements can be achieved by directly printing structural material using MDM methods, there are still limitations regarding the structural and aesthetic characteristics of such printed structures. For this reason, the proposed approach for more efficient fabrication of full-scale structural elements is printing formworks and not the element itself, or at least the combination of the two approaches. This approach allows for a much greater potential for achieving geometric complexity as a result of optimisation procedures, as can be seen in the number of analysed slab projects from ETH Zürich, where 3D sand printing was used in combination with classical concrete pouring methods. Another example of this approach is the Eggshell system, in which the application was tested on a full scale. Aside from geometric complexity, this approach results in a smoother and more detailed surface finish, opening new design possibilities. Finally, printing formworks, either removable or staying in place, enables the application of structural materials in more traditional ways to accomplish higher structural strengths. At the present moment, the authors consider this approach to have the highest potential to fully exploit the benefits of both computational designs and AM fabrication processes to produce custom architectural elements efficiently.

7 CONCLUSIONS

This paper offers a systematic state-of-the-art review of current modes of 3DP technology application for the fabrication of large-scale architectural elements. Following the research goal, various possibilities for applying 3DP technology in the construction industry have been identified and presented. The different types of available 3D printing methods are also identified and analysed to gain insight into their potential and shortcomings. Next, selected projects were systematized based on the typology of the element, through which potentials and challenges relating to each project and the specific use of fabrication methods were assessed.

Based on the literature review results and identified challenges, this paper proposes a set of strategies for more efficient design and production of structural elements through the use of 3DP technology. By putting it into practice, the potential of 3D printing would be realized. The proposed strategies address the entire production process by proposing the integration of design and fabrication processes. They also discuss the approaches to 3DP that authors consider to have the most potential for use with mass-customized structural elements. The proposed framework is intended as a guideline and possible directions for further research which should focus on integrating proposed design strategies and their practical testing. This paper doesn't address one of the main challenges present with all 3DP methods: the printed element's structural and material properties. Because of that, future research is still needed to improve structural qualities through material research or modification of the 3DP methods for 3DP structural elements to become more commonly used in large-scale projects.

NOTES

1 Carpo, *The Second Digital Turn: Design Beyond Intelligence.*

2 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

3 García-Alvarado, Moroni-Orellana, and Banda-Pérez, *Architectural Evaluation of 3D-Printed Buildings*.

4 Jipa and Dillenburger, *3D Printed Formwork for Concrete.*

5 Ali, Abilgaziyev, and Adair, *4D Printing.*

6 Pegna, *Exploratory Investigation of Solid Freeform Construction.*

7 Tay et al., *3D Printing Trends in Building and Construction Industry.*

8 Perkins and Skitmore, *Three-Dimensional Printing in the Construction Industry.*

9 Khoshnevis and Dutton, *Innovative Rapid Prototyping Process Makes Large Sized, Smooth Surfaced Complex Shapes in a Wide Variety of Materials.*

10 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

11 Naboni and Paoletti, *How to Build (Almost) Anything Customized.*

12 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns.*

13 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

14 Lowke et al., *Particle-Bed 3D Printing in Concrete Construction – Possibilities and Challenges.*

15 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

16 Jipa and Dillenburger, *3D Printed Formwork for Concrete.*

17 van Woensel, *Printing Architecture: An Overview of Existing and Promising Additive Manufacturing Methods and Their Application in the Building Industry.*

18 García-Alvarado, Moroni-Orellana, and Banda-Pérez, *Architectural Evaluation of 3D-Printed Buildings.*

19 Colla and Pambaguian, *The Design of a Lunar Outpost: 3d Printing Regolith as a Construction Technique For Environmental Shielding on the Moon.*

20 Gardner et al., *Testing and Initial Verification of the World's First Metal 3D Printed Bridge.*

21 Hack et al., *Structural Stay-in-Place Formwork for Robotic in Situ Fabrication of Non-Standard Concrete Structures.*

22 Bos et al., *Additive Manufacturing of Concrete in Construction.*

23 de la Fuente et al., *Structural Fibre-Reinforced Cement-Based Composite Designed for Particle Bed 3D Printing Systems. Case Study Parque de Castilla Footbridge in Madrid.*

24 Salet et al., *Design of a 3D Printed Concrete Bridge by Testing.*

25 *Nijmegen Has the Longest 3D-Printed Concrete Bicycle Bridge in the World.*

26 Xu et al., *Fabrication and Application of 3D-Printed Concrete Structural Components in the Baoshan Pedestrian Bridge Project.*

27 *Striatus 3D Concrete Printed Masonry Bridge.*

28 Burger et al., *Design and Fabrication of a Non-Standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork.*

29 *Free Formwork - Dbt.*

30 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

31 *Dissolvable Formwork - Dbt.*

32 *Additive Archetypes - Dbt.*

33 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns.*

34 *Krypton, a Column in Aix-En-Provence.*

35 *Design Computation Lab - RC4 - Amalgama.*

36 Bekkering et al., *Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.*

37 *Elements.*

38 Waldschmitt et al., *3d Printing of Column Structures for Architectural Applications.*

39 *Blast Studio. 3D Prints Column from Mycelium.*

40 Vantyghem et al., *3D Printing of a Post-Tensioned Concrete Girder Designed by Topology Optimization.*

41 *3D Printed Reinforced Beam.*

42 De Schutter et al., *Vision of 3D Printing with Concrete — Technical, Economic and Environmental Potentials.*

43 Hansemann et al., *Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling.*

44 *3D Printed Slab.*

45 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone.*

46 Graser, Baur, and Norman, *DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

47 *Functional Formwork For a Funicular Floor.*

48 Anton et al., *Fast Complexity.*

49 Peters, *Building Bytes: 3D-Printed Bricks.*

50 *Digital Adobe* - *IAAC.*

51 Westerlind and Hernández, *Knitting Concrete.*

52 Anton et al., *A 3D Concrete Printing Prefabrication Platform for Bespoke Columns; Graser, Baur, and Norman, DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

53 Bekkering et al., *Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture.*

54 Burger et al., *Eggshell.*

55 Burger et al.

56 Waldschmitt et al., *3d Printing of Column Structures for Architectural Applications.*

57 *Design Computation Lab - RC4 - Amalgama.*

58 *Free Formwork - Dbt.*

59 *Additive Archetypes - Dbt.*

60 *Dissolvable Formwork - Dbt.*

61 *Krypton, a Column in Aix-En-Provence.*

62 *Krypton, a Column in Aix-En-Provence.*

63 *3D Printed Reinforced Beam.*

64 Anton et al., *Fast Complexity.*

65 Hansemann et al., *Additive Fabrication of Concrete Elements by Robots: Lightweight Concrete Ceiling.*

66 Nicolas et al., *Complex Architectural Elements from HPFRC and 3D Printed Sandstone,3; 3D Printed Slab.*

67 Graser, Baur, and Norman, *DFAB House: A Comprehensive Demonstrator of Digital Fabrication in Architecture.*

68 *Functional Formwork For a Funicular Floor.*

69 Westerlind and Hernández, *Knitting Concrete.*

70 Peters, *Building Bytes: 3D-Printed Bricks"; Naboni and Paoletti, "How to Build (Almost) Anything Customized.*

71 *Digital Adobe - IAAC.*

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HYBRID HOUSING IN THE CONTEXT OF MODULAR ARCHITECTURE AND THE POTENTIAL FOR MODELING AUTOMATION

ABSTRACT

The complexity of the present moment requires intense adaptation to different models of living, work, production, consumption, transportation, and social interactions. Adaptability, transformability, resilience, economy, and accessibility, as well as the sustainable disposal of resources, are the key concepts for navigating future challenges and are of crucial importance within the framework of the architectural profession. This paper deals with the possibilities of modular architecture to respond to changes in the sphere of housing functions, especially to the requirements of the increasingly common typology of hybrid housing, as well as to examine the possibility of automating the modelling process. In this work, under the term of hybrid housing, we understand an architectural typology of housing, which includes the parallel functioning of residential and business contents (i.e., work) within the same household and whose users own and manage both functions simultaneously.

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KEY WORDS
HYBRID HOUSING
TRANSFORMABILITY
MODULARITY
AUTOMATION

1. INTRODUCTION

We are witnessing that modern global society faces a series of problems, such as energy and political turmoil, pandemics, climate change, recession, and social conflicts, resulting in mass displacements. However, the crisis that has had a profound influence on the architectural scene in the last three years and significantly influenced the entire architectural discourse is the Covid-19 pandemic: the permanent fear of contamination, to a greater or lesser extent, defines the kind of spaces we want to live and work in today. Following the destructive impact of this pandemic on health systems and world economies, the architectural community has been dealing with a series of questions, such as how to convert airports into hospitals or make overburdened hospitals safe, but also how to transform our homes into hybrid spaces, in which it is possible to live and work at the same time. The profession, however, remained undivided on the necessity of flexibility of the architectural program and adaptability of the space in general. Dictated by the urgency of the situation, these approaches were first tested during emergency sanitary measures - temporary, mobile, easily foldable sanitary units and newly built hospitals, as well as during adaptations of already existing structures (e.g., sports halls and schools). As expected, modularity proved to be an irreplaceable tool, making the transition to ambulatory care faster and healthcare more efficient[1]. However, unlike the design of new or expansion of existing facilities for the care and treatment of the infected, the profession's response to the need to transform the living space did not have more noticeable results. This is mainly due to insufficient needing more time for extensive research, but also because our homes are considered safe spaces during the pandemic.

During the lockdown, people have become more familiar with their homes, shortcomings, and limitations. Spending a lot of time in one place required a space that can be freely and easily changed, not just rearranged - the need for a more integrated, functional, and ergonomic private space became evident. It was also observed that our modernist homes and offices, made of airy, untouched, empty spaces, lose their qualities in quarantine conditions: the necessity of physical distancing, setting up barriers, and changing the spatial routine has become the requirements for this new reality. It was also noted that in pandemic and post-pandemic conditions, the spaces of so-called secondary importance, such as roof terraces, balconies, and courtyards, have gained importance, primarily through their inclusion in the functions of a home office or exercise space. Even this brief review leads us to one safe conclusion: the pandemic reaffirmed the concept of hybrid housing[2], globally and at all levels, and paved the way for more serious research in this area.

A review of the other challenges listed above shows us that the several-decades-spanning superposition of crises has determined some of the specifics of today's moment, which are manifested as a chronic and omnipresent need for housing (especially for smaller- and micro-apartments, as per Marchand), the inability of the younger population to afford housing in cities (as per Wendler), but also a growing trend of suburbanization and individualization. According to di Pasquale, profoundly changed working habits and extreme mobility of the labor market also contributed to the rise of the sharing economy and fundamental changes in the very concept of property: renouncing the right to exclusive possession in favor of common resources or sharing one's own resources with others (*Figure 1*). This concept represents a significant change in the cultural paradigm, which faced the architects with a not-at-all-simple task: to design a residential space, in terms of architectural language, uncompromisingly dedicated to the modern urban environment, which offers the possibility (but not the obligation) to live in a community, where social interaction is possible but never imposed, while at the same time achieving a high degree of individualization and simultaneously anonymization of the tenant's profile. The same author claims further that this concept initially prevents thinking in the direction of clearly defined residential typologies, such as apartments, to the extent that it can still exist, rather as the result of a particular project, but not its starting point.
Accordingly, one of the assumptions that will be examined in this paper is the relevance of the modular approach, which is inherently flexible and variable, as a solution for perhaps the most significant characteristic of this new, hybrid typology: a transformable and informal spatial-building structure, suitable for different levels and types of adaptations and constructive adjustments.

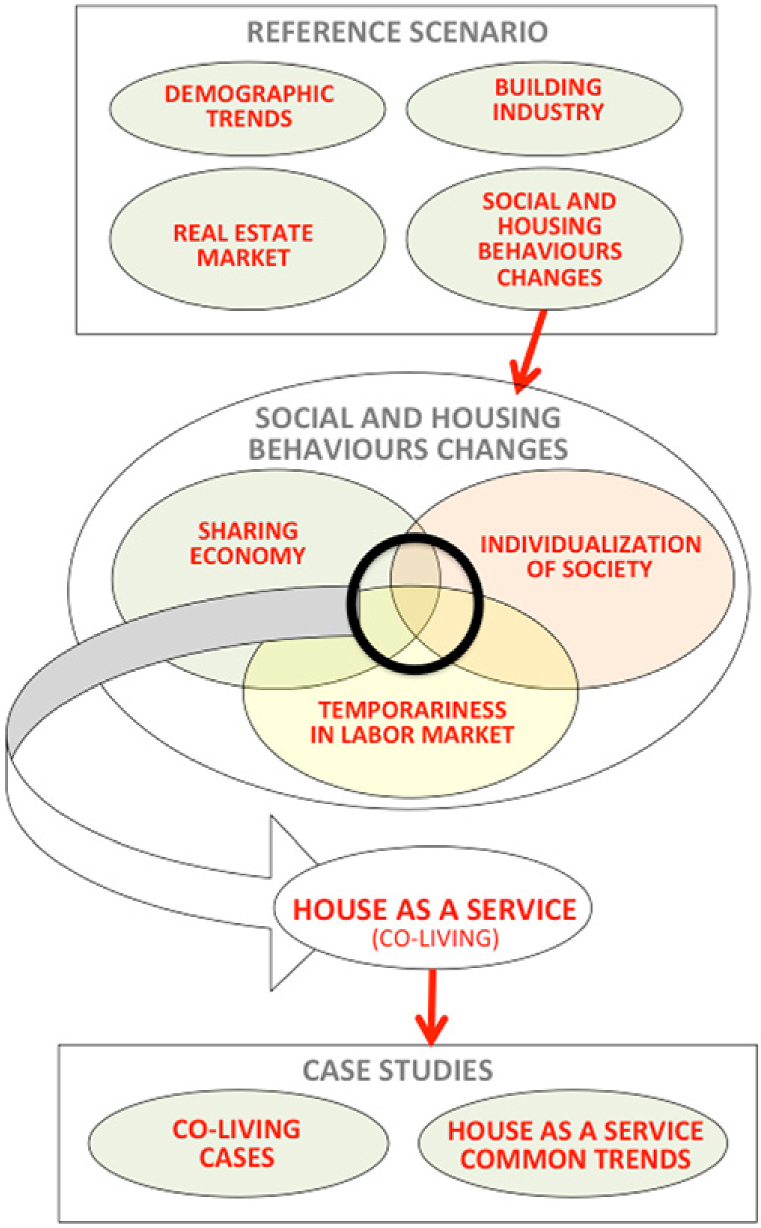


FIGURE 1:
Changes in social and economic patterns and new hybrid residential typologies conditioned by them - concepts of co-living and 'house as a service' (Source: di Pasquale)

This paper will deal with the issue of hybrid housing in five chapters. After the introductory considerations, in Chapters 2 and 3, we will examine the modular approach's conceptual and typological advantages and limitations, analyzing representative architectural examples. The goal is to derive basic physical and functional parameters that can be used to define and regulate the relations between the areas of residence and work within a hybrid space. In Chapter 4, we will examine the possibilities for automating the modelling of hybrid housing based on the parameters identified in previous chapters, as well as from the literature. In the last chapter, we present concluding considerations and directions for further research.

2. HYBRID HOUSING IN THE CONTEXT OF MODULAR ARCHITECTURE OF THE 20TH CENTURY: THE POTENTIAL FOR TRANSFORMABILITY AND ADAPTABILITY OF RESIDENTIAL SPACE

The first, more significant, steps in the development of modular architecture took place in Western Europe in the period between the two world wars, when the centralized, state-coordinated design of prefabricated structural systems and rationalized urban solutions was only one of the ways to deal with complex socio-political and epidemic circumstances - cheap and high-quality mass housing was supposed to transform society and improve the quality of urban life as a whole[3]. Bauhaus functionalists prioritized buildings suitable for mass production, where the architectural form should follow the functional logic of the building, and the use of materials should be rational. Seen in the wider context of post-war reconstruction and industrialization in the second half of the twentieth century, the need for mass housing construction showed that conventional construction methods were inadequate for post-war circumstances and led to the expansion of prefabrication and modular construction technologies. Multi-family buildings conceived in this way were placed in a strictly geometrized, almost utopian urban matrix, in which the functional city zoning mostly meant a surgically precise separation of the functions of living and working. In this sense, hybrid housing during the twentieth century mainly was not implemented - except for examples such as Unité d'Habitation[4] in Marseille, which can be called a kind of experiment, hybrid housing in this context can be viewed mostly from a phenomenological point of view.

Parallel to innovations in the field of prefabricated building modules, and also motivated by rationalization of design and development of cheaper and faster construction, the theme of functional modularity was developed, initially through the functionalist concept of Existenzminimum, i.e., 'minimum of space, air, light and heat, necessary for men to develop their own vital functions without restrictions due to lodging, namely a minimum modus vivendi, instead of amodus non moriendi' (as claims Gropius). The architectural approach for the implementation of these requirements consisted of combining continuous horizontal surfaces with double floor heights, which resulted in a larger volume of living space and, in the end effect, maximum architectural quality with a minimum usable area.

The concept mainly focused on the fact that the size of rooms depends on the dimensions of furniture and explored the theme of flexibility of living spaces through the use of pieces that can be removed or transformed, as well as through a better organization of storage space.

Rethinking this approach to housing, i.e., criticizing the rigidity of functionalism and not accepting the reduction of human existence (and therefore living) to only the most basic human needs, was introduced by structuralists in the second half of the twentieth century - they went further in their efforts to humanize the architectural rationality reinforced by modernism. Their leitmotif of infinite reconstruction and adaptability (also known as open-ended design) was intended for flexible and authentic social mechanisms. It found its expression primarily in the structures of the Japanese metabolism, composed mainly of plug-in flexible modules, as well as in brutalist residential architecture, which applied modularity in visually rich and astonishing structures. The formal aspects of structuralism can also be expressed through terms such as growth and coherence, as well as change and articulation of the built volume.

FIGURE 2: Prefab modular building Dubiner in Ramat Gan, Israel by Zvi Hecker (1963). The 'conversation pit' can be today repurposed as a home office or a hobby corner. (Source: Atelier Adam Nathaniel Fuhrman)

The analysis of some of the representative examples of modular residential architecture of this era, which were far ahead of their time in terms of design, transformability, and even potential for hybrid housing, brings us to the conclusion that the full capacity and advantage of modular design compared to others concepts are manifested only when the flexibility of the living space and the richness of the functional program are the absolute priorities of the architect[5], while a formalistic approach opens up space for misinterpretations and a wide range of further problems. One example is the design of the residential building, Dubiner, by Zvi Hecker (1963), which is based on the dynamic growth of the structure made of hexagonal concrete modules. A special quality of this design is the internal communication space, in which freely arranged stairs and bridges lead to the apartments and enable visual privacy and physical distancing (modular, honeycomb terraces of apartments have similar qualities). The same care that makes the exterior aesthetically and functionally successful has been transferred to the interior space as well: the furniture is integrated with the floors and walls, which, along with interesting spatial overlapping, results in zoning without the necessary use of physical barriers and/or the possibility of individual interpretation and use of the living space – the flexibility of the living space directly derives from the modular concept itself (*Figure 2*). On the other hand, Hecker's residential complex Ramot Polin (1972), composed of modular prefabricated dodecahedrons, is a lesson on the capacity of modular architecture to respond to authentic human needs (*Figure 3*).

As Merin concludes, the living space inside concrete dodecahedrons turned out to be inflexible to the extent that the tenants spontaneously and arbitrarily expanded their apartments with rectangular cubic annexes using conventional construction methods, although it is intended to be inventive and provocative - due to the inability to transform the living space within the boundaries of their apartments, they have redefined the complete external structure of the building.

An icon of modular brutalism, Moshe Safdie's Habitat 67 (1967) was designed as an organic, living system composed of concrete modules, arranged in various geometric configurations, so as to combine the qualities of urban garden housing (enough open space and natural light per housing unit) and high-density housing in the form of modular high-rise buildings, but also as a hybrid housing complex, which combines apartments, shops, and a school. Due to increased costs, the final project had only 158 apartments of various sizes and structures [5].

FIGURE 3: Prefab modular building Ramot Polin in Jerusalem, Israel by Zvi Hecker (1972). (Source: Tsur, S.)

FIGURE 4: Habitat 67, Montreal, Canada by Moshe Safdie (1967). One of the renovated apartments displays the fluidly integrated qualities of individual housing and the modular concept, which derive directly from Safdie's modernist approach and eliminate the usual use of walls, allowing each room to be arranged on different levels and coordinated with individual needs. (Source: Williams, A. and Fazli, G.)

Corbusier-inspired apartments are spread over at least two floors, contain at least one terrace each, and allow an effortless circulation of air and inhabitants. According to Baker, over the turbulent decades of exploitation, the apartments underwent numerous transformations: inhabited mostly by the lower- rather than the middle-class urban population, for which they were initially intended, some of the two-modular apartments were expanded differently. For example, glazed gardens were rearranged into bedrooms and terraces into storage areas. Nowadays, the potential for hybrid housing is reflected in the possibilities for forming micro-units and reformatting the space in order to isolate and/or repurpose the premises (*Figure 4*).

FIGURE 5: Prefab Modernique Home, Mar Vista Tract, Los Angeles by Gregory Ain (1948). Movable partitions transform a modern living space into a one-, two-, or three-bedroom. (Source: Mar Vista Tract)

In this context, it is important to mention the efforts in the field of prefabricated, single-family housing, which also expanded, especially in the USA, in the period after the Second World War. Architects such as Gregory Ain made prefabricated houses flexible so that the rooms could be adapted to the different needs of different household structures and at different times of the day. His Modernique Homes of the 1940s, with functional areas of about 100 m^2, were based on a primary module with eight variations of house-garage and house-street spatial relationships. Modernly designed and with an open floor plan, they optimized the use of living space. The living room was removed from the main communication line and directly connected to the garden area through a large glass wall. Sliding partitions provided the flexibility of the interior space and increased the feeling of openness and functionality (*Figure 5*). Built-in furniture was also used: fixed locations for the kitchen and bathroom, as well as the depth of the plot, made it possible to change the house's dimensions and reconstructions without changing the street facade. The tenants were given the opportunity to intervene, i.e., changing the physical structure of the house, but this was foreseen and regulated in advance. Combined with the flexibility of the entire approach, this resulted in only a small number of houses having been changed to date - Ain's functional solutions have not lost their relevance and still inspire after more than 70 years.

3. CONTEMPORARY MODULAR ARCHITECTURE AND HYBRID HOUSING - MODERNIST CONCEPTS AS INSPIRATION FOR DEFINING NEW TYPOLOGIES

Around the year 2000, digital transformation and the general acceptance of modern technologies allowed architects to shape and visualize previously unimaginable objects and environments, resulting in significant progress in the field of prefabrication and modular construction. Unfavorable economic and environmental circumstances, as well as the aforementioned rapid development of computer modelling technologies, allowed a new generation of architects to tackle the concept of modularity and prefabrication on a significantly higher level.

In recent decades, robots and 3D printing of architectural objects have also contributed immensely to the modular concept, making the prefabrication process gradually more efficient. Technological advances in all engineering fields have allowed modular building components to be much more functional and better integrated. Similarly, increasingly strict requirements in the field of ecologically sustainable construction (not only in terms of regulations but also due to increasing social acceptability) make prefabrication an inevitable, even desirable factor because greater control of the assembly process has a positive effect, both in the realization of the designed performances and through material optimization and waste minimization. It is particularly noteworthy that the characteristics of modular construction significantly extend the lifespan of buildings through flexibility, transformability, and reuse of components.

The problem area that could be summed up by the question 'How to quickly produce an affordable and lasting living space, which can amaze with the quality of life?', in recent decades, has initiated numerous works in research and in collaboration between architects, other engineering fields, and the construction industry, culminating in very interesting and high-quality solutions. One of them is undoubtedly a prefabricated mobile module of solid (concrete or wooden) construction, which combines the qualities of a classic container and a solid-built building. Some other successful examples are based on the complete recyclability of the construction - without composite materials, with structural elements that can be removed without residue, and with the use of construction products based on their CO_2 neutrality, as well as the use of the newest techniques of modular construction and computer modelling.

Important for this research is the fact that, motivated by these goals and supported by the mentioned technologies, modularity ensured high quality and a significant degree of transformability of the living space and thus enabled hybrid housing, even within the framework of traditional housing typologies, such as single-family houses, row houses and multi-family residential buildings (*Figures 6, 7, and 8*).

Although the trends mentioned in the Introduction have revealed the limits of the usual typologies in meeting current social and housing needs, contemporary architectural practice still largely adopts these typological solutions without essential changes. In addition, as di Pasquale claims, the available housing stock is largely unsuitable for providing "housing solutions specifically designed to fit the ongoing mutations of social and interpersonal urban relationships". New fluid housing behaviors are usually placed within a rigid and outdated building heritage. New needs and novel residential behaviors have unquestionably conditioned the re-evaluation of the existing and the consideration of the introduction of new typologies.

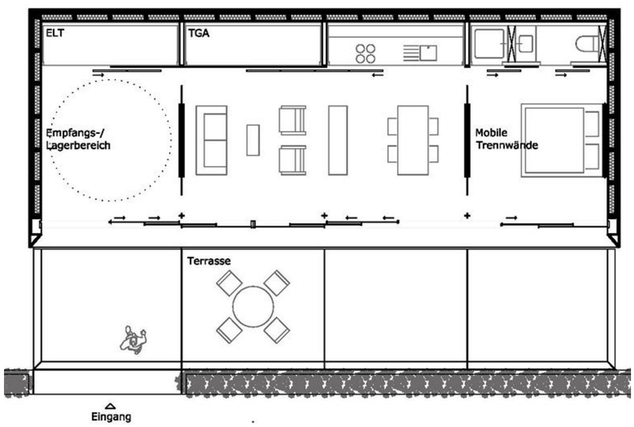


FIGURE 6: A SINGLE-FAMILY HOUSE:
Werner Sobek: Modular prefabricated Active house B10, Weissenhof, Stuttgart, 2014. A prefab structure of the minimalistic design developed on the basis of a modular system: assembled in one day and equipped with technical solutions that are not revolutionary by themselves. The transformability of the interior is achieved by easy sliding partitions so that the house can be used exclusively for living/working or a combination of these two functions. (Source: dds Online)

As Marchand and Brysch conclude, almost a century later, we can notice that Existenzminimum is present again and that a new, redefined minimum housing standard responded to the need for new housing typologies, mainly a growing number of one- and two-member households[6] - primarily for professionals, who have ever shorter periods of living in one place, as well as the need for workspace within a household[7].

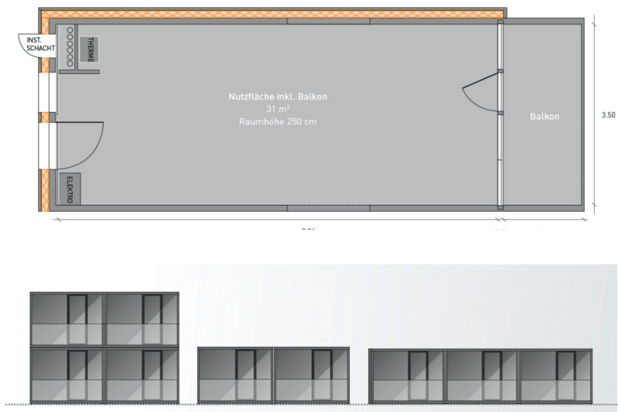
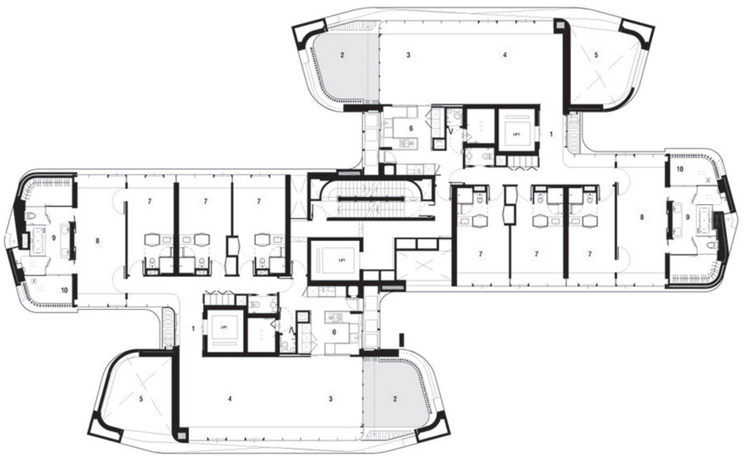


FIGURE 7: A ROW HOUSE:
Concrete Rudolph, Weiler-Simmerberg + Studio Sachner, Stuttgart: MobileCube module. The basic module has an area of about 30 m2 and a free layout, equipped only with installation leads. It provides inexhaustible design possibilities, both within a free-standing unit and in terms of combining modules, up to a maximum of three floors in height. With a lifespan of over 50 years, this module can be adapted to current needs: it remains flexible, ready to use, and can be recombined quickly. It is especially well applied in case of the need for additional residential, home-office, or quarantine space. (Source: Concrete Rudolph)

FIGURE 8: MULTI-FAMILY HOUSING:
UNStudio: Ardmore Residence, Singapore, 2013. The 36-story modular residential tower provides a 'living landscape' concept, connecting indoor and outdoor spaces, and offering the possibility for versatile space functionality. An indoor-outdoor experience is being achieved through the introduction of large windows and double-height balconies in all apartments. The apartments are designed to increase the amount of daylight and enable a visual connection between different parts of one apartment. This concept allows for the privacy of the bedrooms and adds a four-dimensional aspect to the layout, as the two wings can be used separately, serving different needs and being active at different times of the day. (Source: Ardmore Residence)



Today, Existenzminimum still focuses on the reduction of the usable area of the living space, but in a more versatile and flexible way: the concept is no longer related only to the spatial dimension, but also to services, resources, and finishing, and a new understanding of the quality of life, which, above all, implies a lower consumption of resources (*Figure 9*). Residential spaces conceived in this way are no longer seen as reduced conventional housing units, but as spaces that create new qualities due to their compactness - therefore, spaces like this, together with communal spaces, which enrich the social dimension, as well as community-oriented housing models (e.g., co-housing and co-living) belong to new housing typologies. From a purely technical perspective, this new Existenzminimum strives for environmental protection and sustainable construction methods. At the same time, modularity and prefabrication continue to play an irreplaceable role in reducing costs and increasing the efficiency of construction and exploitation (*Figures 10 and 11*).

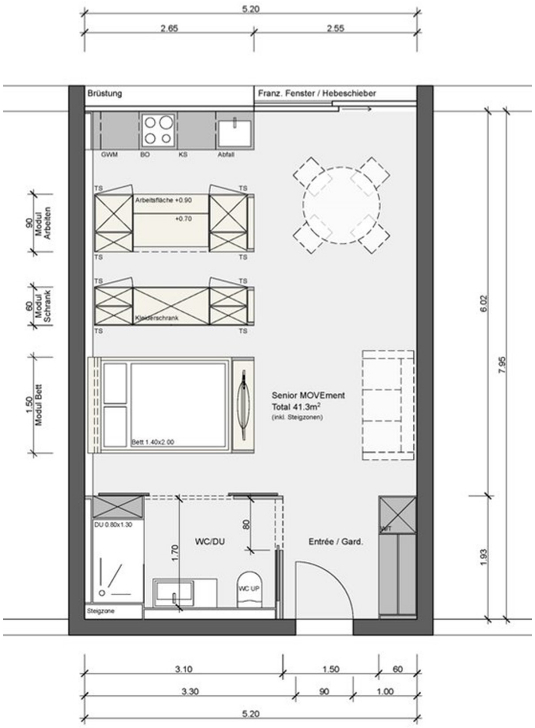


FIGURE 9: HYBRID LIVING IN THE CASE OF AN APARTMENT - Space flexibility is achieved by using modular and movable interior elements: Modul MOVEment. The approach to the ideas of minimal and hybrid housing here is based on the application of specific sliding modules for beds, wardrobes, and workspace, while the bathroom and kitchen have fixed positions. (Source: Marchand)

FIGURE 10: HYBRID DWELLING WITHIN A RESIDENTIAL BUILDING:
EMI Architekten: Glattpark residential and commercial building, Opfikon, Switzerland, 2016. The MIN 1 residential unit (image right) gives off the impression of fluid space, resulting from the continuity of horizontal surfaces and the establishment of diagonal views. The compact construction of the internal common courtyard contains a separate laundry room, a common kitchen, and meeting spaces, with each apartment having only the necessary contact with them. (Source: Glattpark)

FIGURE 11: HYBRID HOUSING AS AN EXAMPLE OF STUDENT HOUSING:
WilkinsonEyre: Dyson Institute of Engineering and Technology, Malmesbury, UK, 2019. This student village consists of clusters of modules, with each of 32 m2 modules manufactured off-site and delivered to the campus, before being placed in its final position. Each such module (or 'capsule for living') has an open plan and consists of an entrance area with a shower and a toilet, a bedroom, and an integrated workspace. For every six units, there is a shared kitchen and laundry area, as well as an entrance area with reception and storage. Green areas and paths determine the movement of users through the campus and connect residential accommodations and the common clubhouse in the center. (Source: Dyson Institute of Engineering and Technology)

Co-living (or cooperative living) is a typology that combines private living space with shared communal facilities. Unlike sharing and other types of shared living arrangements, co-living explicitly seeks to promote social contact and strengthen the community. Co-living covers a wide range of models, from co-housing to different rental options, and is guided by the principles of the sharing economy within the framework of urban multi-family housing. It combines individual and shared spaces with services, networking the community (e.g., with the help of digital platforms) and providing affordable apartments in privileged, central parts of cities (*Figures 10, 11, and 12*).

As di Pasquale writes, the typological characteristics of co-living would be as follows:

1. Complete abandoning of classification based on the number of bedrooms (one-bedroom, two-bedroom, three-bedroom, etc.).

2. Floor plans are composed of an aggregation of individual micro-units (in literature known as 'capsules', 'individual microcosms', 'residential pods', or 'living pods', as they can be considered integral cells providing housing services), which are variously combined with typical contents (*Figure 13*). Individual units - modules have different dimensional and typological characteristics and can be completely independent. They are equipped with everything an individual needs for living, without using common spaces and services to spaces (*Figure 13*).

3. Potential independence *(Figure 12*), in the sense that individuals have everything they need to live within their unit, makes the use of common spaces become a choice based on their will to share the housing experience rather than a necessity driven by their practical needs. Therefore, these spaces can be considered optional and additional services. The levels of sharing of these spaces largely depend on their proximity to individual units or their accessibility from the city area. In some cases, the common areas of the floors, e.g., the kitchen, have close connections with the residential modules of each floor. In other cases, these shared spaces should be understood as public, open to all in the building, and optionally to external visitors. This bivalence, therefore, represents the dual nature of these spaces: common spaces near these residential units can be considered hotspots of a cluster, and the spaces open to the city as peripheral spaces. Therefore,

4. Individual living spaces become a fundamental typological element for every possible configuration. In other words, free and individual choices of included contents dynamically define types. This typological structuring through the aggregation of individual living pods constitutes a permanent typological character in the modular hybrid building. At the same time, their eventual physical interchangeability and reconfigurability represent their temporary character.

Fig. 06. Floor plan layout 1

Fig. 07. Floor plan layout 2

FIGURE 12:
HYBRID HOUSING WITHIN A FRAMEWORK OF CO-LIVING TYPOLOGY:
Common Space, Syracuse, USA. The figure represents a model of shared living, from the aspect of its place in a central urban context, as well as the proximity of centers of professional interest and studies (Syracuse University). The model foresees the possibility of co-working service within the same building. There are also common areas on each floor that relate to individual floor users. (Source: di Pasquale)

FIGURE 13: HYBRID LIVING WITHIN A FRAMEWORK OF CO-LIVING TYPOLOGY:
Individual living space (capsule) as the basic typological element for every possible configuration. (Source: di Pasquale)

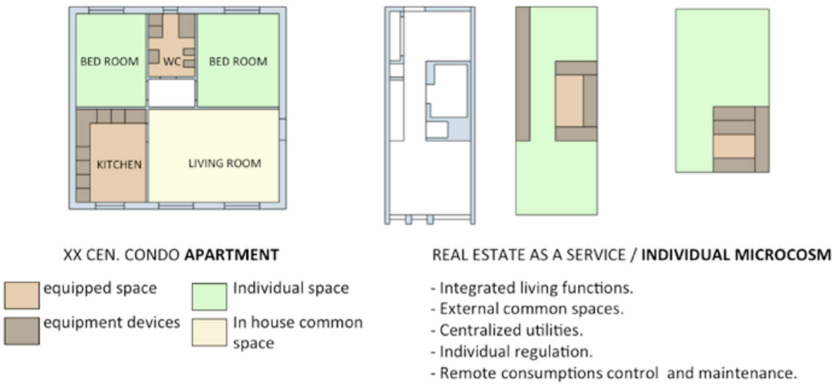
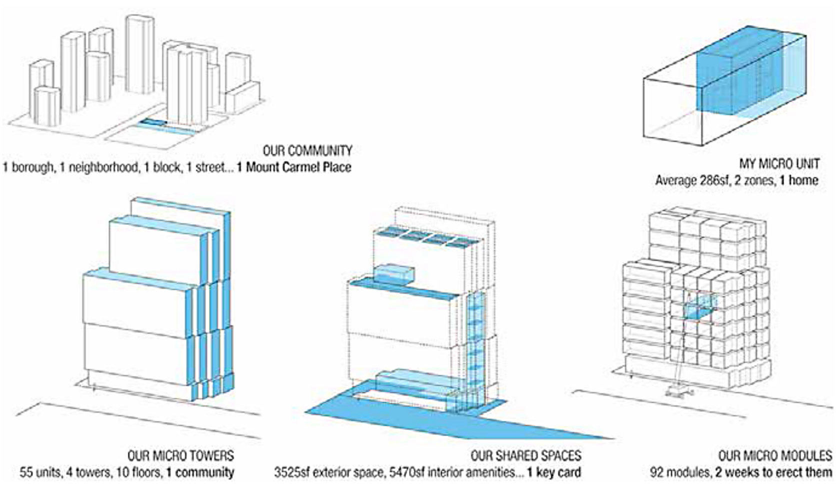


FIGURE 14:
HYBRID HOUSING WITHIN CO-LIVING – STRUCTURAL HYBRID:
nArchitects: Carmel Place, New York, 2016. This project tests the potential of reducing the size of an apartment from 37 m^2 to 28 m^2, while balancing the need for a larger common space. These rental (micro-)units are complemented by generous common facilities distributed throughout the building, encouraging social interaction between neighbors. The interior of the apartments offers plenty of light, fresh air, high ceilings, and significant storage space, demonstrating new possibilities for micro-living. Their design and construction were entirely carried out using a hybrid modular technology: the basement and ground floor were built using traditional on-site construction technologies, while the floors were realized using modular technology off-site. (Source: di Pasquale)



A step further in the direction of modular, hybrid, multi-family housing construction are high-rise buildings that reduce land consumption and promote energy sustainability and socially aggregative functions (both among tenants and between tenants and the urban context) (*Figure 14*). This combination of the autonomy of a housing module and the possibility of social proximity as an opportunity to exchange experience is the basis of the attractiveness of this housing model. Finally, per di Pasquale, the fundamental characteristic of this typology is the ability of the system to reconfigure and reorganize its basic typological elements (housing units) according to changing users/aggregations, both in terms of composition (typological flexibility) and size (dimensional scalability). Different modification needs that may arise during the life cycle of buildings are a consequence of the needs of different users or the evolution of the needs of the same users over time[8].

4. THE ROLE OF RELATIONS AND AUTOMATION IN THE MODELING OF HYBRID HOUSING SPACE

A typology of hybrid housing could be defined by grouping and classifying living spaces of certain inherent structural similarities, thereby establishing a typological scheme that emphasizes common forms and themes among individual configurations. In the conclusions presented so far and the listed architectural examples, it can be observed that the accessibility, the distance of the workspace in relation to other (residential) rooms, as well as the visual exposure of each of the functions could play crucial roles in that process - typologies of hybrid housing would be based on the relationship between working and living space, as well as on the general system of communications and connections between them.

Some authors, such as S. Ahrentzen in ‘Hybrid Housing: A Contemporary Building Type for Multiple Residential & Business Use’ derive typologies of hybrid housing from a relational plan, i.e., relations between the working space and the residential part – “the fluidity and rigidity of these connections will determine the dynamics and quality of processes and contacts within the home”. By analyzing that typological division, it can be concluded that for the smooth functioning of a home office, additionally to structural issues that need to be considered (such as sufficient natural light and air, adequate surface area and volume and a satisfactory level of sound insulation), of essential importance are also the existence of a separate entrance, separate sanitary facilities, separation by levels or with the help of mobile walls, avoiding the so-called transitional rooms and differences in interior solutions and the like.

The aforementioned physical characteristics increase, while shared spaces, mixed-use spaces, and a visual connection (within an open space or through interior or structural solutions) reduce the privacy of the workspace. In addition to the limitations mentioned earlier, the pandemic crisis also revealed new directions in which it is necessary to think in attempts to conceive and standardize new standards of housing, which would respond to newly created conditions and needs, primarily due to the necessity of partial or complete distancing, i.e., limiting the social dimension of housing.

It can be concluded that the typologies listed in the work provide different levels of privacy for the work function within a hybrid residential unit. Ahrentzen suggests some possible solutions for separation, i.e., isolation of the workspace/home office in relation to residential functions:

a) separate street access for residential and working areas

b) primary street access that leads to a neutral space from which there is separate access to the residential and working parts of the house

c) separation by levels/floors

d) long thin plan (long corridor with office space at one end)

e) doors

f) circulation loop (circular path circulation through rooms with a neutral by-pass corridor)

g) absence/avoidance of transit rooms

h) minimum length of common walls between business and residential space

i) a possibility of spatial sub-division, e.g., with movable walls

j) separate storage areas

k) different interior design

l) noticeably different facades or dimensions of each area

m) separate toilet facilities in each area

n) independent heat regulators and thermostats in each area

o) sufficient acoustic insulation between areas.

If there is a necessity for intensifying of connections between the two areas, some of the solutions that can be applied are:

a) common spaces for gathering (outside the work and living areas),

b) walls between areas extended to create shared spaces,

c) workspace shared by two or more households,

d) attics or windows that allow a visual connection with other parts or the surroundings of the house.

In the design process, if we consider individual functions as modules (work module, living module, ...), the above solutions can be seen as ways to connect those modules. This group can be further expanded by adding a temporal component - a predefined time for using the rooms/spaces, which could be one of the directions for further research. For the purposes of this work, the focus will be only on the first set of solutions, i.e., separation solutions.

A. Expansion of the existing model with project forms for implementation

The solutions mentioned above are relatively easy to define in verbal communication, with the next step being the implementation of those requirements in a project. The introduction of these solutions complicates the design process, so the question arises whether it is possible to automate this process. Examples of automation, such as the algorithm described in the work 'New Comfort: Towards the Post-pandemic Living', are more concerned with the geometry of the units rather than the specific function of rooms and the nature of their relationships. In this sense, the question becomes: how can we introduce solutions from Chapter IV as algorithm parameters, i.e., how to present them in a form acceptable to the computer so that the generated models satisfy not only geometric (dimensions, compactness) but also functional requirements? Based on the ideas of Christopher Alexander, the listed solutions could be viewed as templates or design patterns, which in the next step could be applied to different stages of modelling algorithms, e.g., as an extension of the scheme that defines certain initial requirements (input rules) or as a restriction that would exclude a particular set of generated variants (*Figure 15*).

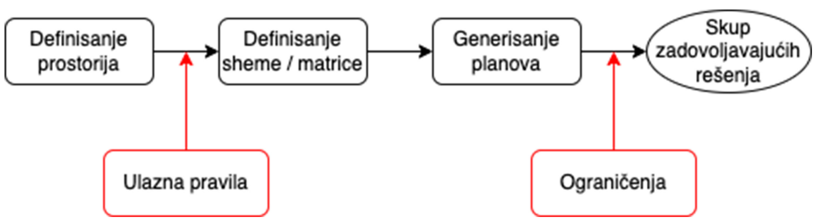


FIGURE 15:
Stages in the design algorithm and possible places where patterns can be applied (boxed in red)

In the following text, we will discuss how we can extend the process of modelling housing units from Atanacković Jeličić et al. to model hybrid housing units using the solutions in Chapter IV.

We will present several additional rules for defining the patterns, as mentioned earlier, which can be used to extend the existing model. The goal of the experiment is not to create a comprehensive pattern-definition language that would cover all possible cases - such a thing would not even be possible - but to check feasibility and determine possible directions for further research.

B. Case study and examples of rules and limitations

As a case study, we will take Scheme 02 (*Figure 16*), which represents a residential unit with two bedrooms (with accompanying sanitary units) and two glazed balconies that should serve as workspaces.

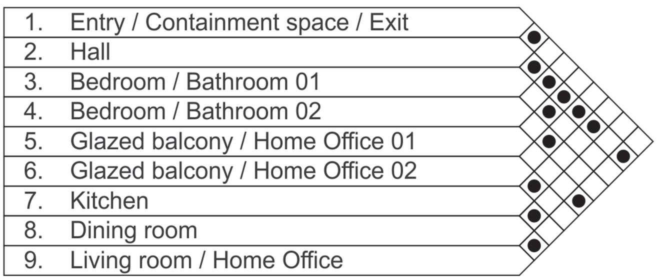


FIGURE 16:
The basic case under consideration - Scheme 02 from Atanacković Jeličić et al.

```
touch = [ [ 9, 1, 0, 0, 0, 0, 0, 0, 0, 0],
          [ 1, 9, 1, 1, 1, 1, 1, 0, 1, 0],
          [ 0, 1, 9, 0, 1, 0, 0, 0, 0, 0],
          [ 0, 1, 0, 9, 0, 1, 0, 0, 0, 0],
          [ 0, 1, 1, 0, 9, 0, 0, 0, 1, 0],
          [ 0, 1, 0, 1, 0, 9, 1, 0, 0, 1],
          [ 0, 1, 0, 0, 0, 1, 9, 1, 0, 0],
          [ 0, 0, 0, 0, 0, 0, 1, 9, 1, 0],
          [ 0, 1, 0, 0, 1, 0, 0, 1, 9, 0],
          [ 0, 0, 0, 0, 0, 1, 0, 0, 0, 9] ];
```

FIGURE 17:
Expanded matrix for Scheme 02

Example of an input rule: separate street entrances for residential and working areas. This solution requires the expansion of the starting matrix with one rather fictitious room - Outside.
Before entering the modelling process, the application of this rule would add a new column and a row in the matrix, i.e., a new node in the schema with which only the workspace is in contact. Assuming room 6 is designated as a workspace, the new matrix for Scheme 02 would be as in *Figure 17*. The same matrix can also be displayed using the visualization from Atanacković Jeličić et al. as follows (*Figure 18*):

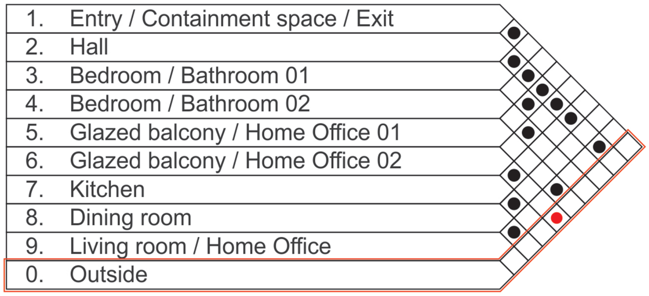


FIGURE 18: Visualization of the extended matrix in accordance

Note 1: Although Room 1 (Entry/Containment space/Exit) should technically also have contact with this additional room, adding an additional room (Outside) gives more freedom in generating the scheme. Also, the dimensions of this fictitious room can be completely arbitrary. However, it would be best if they were minimal (e.g., matching the dimensions of the entrance door) so that it is easier to avoid contact with other rooms and leave more room for varying the model in the following step.

Note 2: The implementation of the rule for 'primary street entrance leading to a neutral space from which there is separate access to the residential and commercial part of the house' can be carried out in a similar way: it is necessary to add a new room, which should have contact with the room marked as a workspace, as well as a room (or rooms) leading to the rest of the residential unit.

An example of a constraint: Does the generated workspace have enough usable area?

The purpose of this constraint is to verify that the generated room has sufficient dimensions to meet the needs of the workspace, and for this purpose, we will define the constraint O_1. For example. whether the base of the room has both dimensions greater than 2 m and whether it has more than 10 m^2 of surface area.Taking the nomenclature from [13], this constraint could be represented mathematically by:

$$O_1\colon \Delta\mathrm{w} > 2 \wedge \Delta\mathrm{h} > 2 \wedge \mathrm{P} > 10$$

where $\Delta\mathrm{w} = \mathrm{w} + \Delta$ are the width and its variation, $\Delta\mathrm{h} = \mathrm{h} + \Delta$ are height and its variation, and P is the area. The constraint would be applied in the last step of the algorithm. After the algorithm generates possible variants based on the input matrix, this constraint would eliminate those that do not satisfy the constraints.

C. Additional considerations for implementation

The previous section shows how certain design patterns can be implemented. As for the others, further analysis is needed. In this section, we will consider some more, for example:

Forms for Separate sanitary units or for Separation by floor would represent, similarly to the form for entrance from the outside, adding new items to the scheme. As for the separation by floors, a modified type of connection - stairs - would be required to connect two rooms on two floors. On the other hand, the Separation of sanitary units, although it seems trivial - adding another room for the wet room, which is connected to the work area - can be expanded with additional requirements. One such requirement is that due to savings/optimization during installation, two rooms with wet nodes can be connected by a new type of connection: 'a common wall'. Thus, the generated layout would connect those two rooms, but it would be clear that they are physically separated. A long, thin plan form should be implemented to check the geometry of a particular room. On the other hand, a form to eliminate transit rooms would have to make interventions in the scheme by adding new nodes and connections.

Further analysis also shows that there are forms where (currently) automation is impossible. Such an example is Separation through interior solutions or the possibility of sub-division. In those cases, an architect's intervention is required.

5. CONCLUSION

Looking back at some of the experiences of residential architecture of the twentieth century, we confirmed that the architectural scene in crisis and post-crisis times, as well as in periods of great social turmoil, repeatedly turned to modularity, i.e., the advantages offered by this concept, which (unfortunately) was also confirmed later, in this century. Also, we noticed that although the modular concept has been a subject of architectural interest for a relatively long period of time and, very justifiably, developed mostly outside the architectural mainstream - the mentioned projects of Zvi Hecker could rather be called avant-garde than the usual approach to the mass-housing design. The roving, hybrid metropolises of Archigram went even further: embracing techno-culture and negligibly relying on traditional tectonics, they took the structuralists' dream of modular and spontaneous ever-changing architecture in a perhaps unexpected direction.

Furthermore, we have seen that the roots of hybrids in architecture are related to the critique of modernism and the functionalist' urban zoning. It also remained largely under-researched during the twentieth century. As a product of technological progress from the beginning of this century and contemporary culture, the architectural and urban hybrids are based on overlapping structures, spatial programs, and functions on different scales. What defines them and makes them special in the urban fabric is the interweaving of private and public space - their intrinsic transformability and adaptability combine particularly well with modularity, more or less in the case of all residential typologies. The possibilities and advantages of using the modular concept grow with the housing process's complexity and the living-work relationship's complexity, and the need for prefabricated modularity grows with the constructive requirements of hybrid structures.

Regarding the possibility of including hybrid modelling in the design automation process, we have shown how some of the solutions for separating and combining functions can be implemented as design patterns and then included in one of the existing algorithms. In this way, the existing algorithm no longer takes into account only the connection of rooms but also the type of those connections, as well as the function of the rooms, which in the previous work was only declarative. Further work on the implementation of the patterns from Chapter IV has already been partially discussed in the Additional Considerations of Pattern Implementation section. As already mentioned, in a similar way, it would be possible to introduce a time component into consideration, where, in addition to the generation of possible solutions, it would be necessary to introduce the simulation of those solutions as an additional form of their evaluation. Furthermore, while this paper deals more with the automation of the design process of apartments with a home office, it would be interesting to examine the same process for co-living spaces. In this sense, it would be necessary to formulate additional rules for intensifying the links between the area of residence and work, as described in Chapter IV.

NOTES

1 An especially interesting example of modular construction is the Huoshenshan Hospital in Wuhan, which has a capacity of 1,000 beds and was built in just ten days in March 2020 from prefabricated container-type units. Several studies have shown that the modular approach to the design and organization of the construction of this hospital enabled a record-short construction period and a very high functionality.

2 The term 'architectural hybrid' can be considered in a structural, when buildings consist of different structural and spatial systems, or functional sense, when housing is mixed or combined with work or public facilities. Therefore, the term can be used not only for individual objects but also for complexes, as well as parts of urban space. In contrast to multifunctional spaces, hybrids offer richer experiences - they are not a simple sum of different functions and elements of the program, but following the principles of synergy, create completely new spatial and functional relationships, generating new activities. (Gyurkovich, M.)

3 The construction of affordable, serial apartments did not only satisfy existential needs but also had openly socio-political goals: modernist and functionalist architecture did not represent only neutral, apolitical spaces in which life would flow according to a traditional pattern. They were newly built environments which shaped and rearranged interactions and relationships in houses and therefore, in society. Architects of this period, above all those involved in large housing projects in Germany (Siedlungen), created a design that was in line with modern, technological society, contrary to historicism and conservatism.

4 Perhaps the most successful and certainly the most famous example of a residential hybrid of the 20th century is Le Corbusier's Unité d'Habitation in Marseille (1952): with a combination of functions and private and social spaces, it unequivocally ranks among the most influential predecessors of contemporary hybrid multi-family buildings. It offers 337 residential units of 23 types for all social groups. The inner street on the seventh and eighth floors enriched the functional program with shops and services, creating the equivalent of a traditional public space within the building. The roof terrace plays a similar role.

5 'Instead of separate houses, whose design is standardized according to an antiquated pattern, and which are therefore wasteful and monotonous and ugly, we can have truly standardized parts which will be adjusted for harmonious arrangement as much as human requirements require.' (Ain, G.)

6 Data show an increase in the number of households in Western societies mainly due to a decrease in the average number of members and an increase in the number of single people. Progressive ageing is also visible in the population and a longer life expectancy of people after the death of a spouse. From a sociological point of view, many scientists share the idea that the process of 'individualization' summarizes all the specific characteristics of the variety of family relationships that exist today. (di Pasquale, J.)

7 In 2019, about 26.7 million (23.7%) Americans worked from home. Due to the Covid-19 pandemic, even 44% of them now work from home - especially in the IT sector. (Gyurkovich, M.)

8 Research showed that hybrid urban structures solve numerous problems of modern cities and societies: natural and man-made disasters and economic crises, help form 'neighborhoods within walking distance' or achieve an appropriate level of physical and/or social distancing. It can create a refuge within dense urban spaces and an alternative to exploding suburbs. An appropriate density of mixed-use urban residential environments could make cities more resilient to the spread of infection and help solve the post-pandemic economic and social crisis. (Gyurkovich, M.)

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BODIES WITHOUT ORGANS
TACTILITY OF NETWORKED BODIES

ABSTRACT

Spaces and bodies are not what they used to be. They are no longer merely isolated and static in their physicality but extended, plastic, virtual, augmented, mixed, and networked. When physical spaces lost their accessibility during recent critical times, spatial computing technologies and SocialVR platforms have not only entered and transformed our built environments into places of remote socialization with their ability to stimulate telepresence but also afforded new online modes of experiencing spatiality and spatial production strategies which build upon the notions of telepresence, and sociability. Consequently, the socio-spatial impacts of SocialVR platforms fundamentally redefine the spaces we inhabit.

Following this, the paper introduces the mixed reality experience of Bodies Without Organs, which investigates online modes of spatial production, including physical and digital objects in the physical/virtual overlap. The project examines the notion of embodied telepresence, tactility, avatars, and sociality through assembling a series of intelligent API (Application Programming Interface) such as Pose Estimation API, Hand-Tracking API, and Passthrough API as building blocks that constitute a spatiotemporal and tactile mixed reality experience which turns the built environment into a telecommunication medium where proprioceptive bodies and spaces are streamed across a spatial network.

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KEY WORDS
VR/AR CHANGING PHYSICAL SPACE
SOCIAL DISTANCING VS PHYSICAL DISTANCING
EMBODIED TELEPRESENCE
HERE AND THERE
GAMING AS DESIGN TOOL
AVATARS AS POSTHUMAN BODIES
BECOMINGS

1. INTRODUCTION

This paper contributes to generative research and addresses a readership on the effects of new media, theory, and spatial telecommunication on architecture. In juxtaposing XR installations (e.g. IoT, API, VR, AR, Spatial Web, Motion Tracking) with spatial design, social media studies, and posthuman theory, the thesis seeks to extend the disciplinary boundaries of architecture by practising its assimilation of new media technologies.

The title of this paper, Bodies Without Organs, refers to a philosophical concept by Deleuze and Guattari. The notion of 'body without organs', or 'BwO', is hereby adopted as a philosophical point of departure while trying to demonstrate how this could open up a reading for understanding our contemporary experience of embodiment with social media technologies, a condition in which the human subject is increasingly inhabiting new spatial productions that continuously entangle online and offline materialities.

As a result of the COVID-19 pandemic outbreak and the ensuing physical limitations, isolation, and lockdown measures, our interactions with one another and our real-world and virtual environments have been significantly impacted. The migration of our social lives online has been one of the most transformative aspects, compelling us to experiment with new modes of coexistence in the digital realm. Because of this, our premise of space has been profoundly altered in a world where physical distance is the norm. In response to this, a new form of social interaction has emerged in human subjects' communication and social constructs: Social VR.

Social VR represents a fundamental shift in our perceptions of ourselves, our identities, and the architecture of our social lives. In other words, it has a significant impact on how we portray our social selves, our inhabited spaces, and how we interact with others in both physical and virtual spaces.

In this light, the paper investigates the outcomes of a social mixed reality project called Bodies Without Organs, which rigorously refers to its theoretical roots to experiment with methodologies exploring our present condition of embodied experiences in virtual space. Taking this into account, the project considers the expression 'becoming-with-avatar' as a generative mode for the social mixed reality experience, with the objective of expanding the deterritorialised human subjects' tactility, presence, and sociability caused by isolation and lockdown in a networked space through embodied telepresence with the applications of intelligent API agents.

2. THEORETICAL READING OF BWO

> *Consider a blind man with a stick. Where does the blind man's self begin? At the tip of the stick? At the handle of the stick? Or at some point halfway up the stick? These questions are nonsense because the stick is a pathway along which differences are transmitted under transformation, so to draw a delimiting line across this pathway is to cut off a part of the systemic circuit which determines the blind man's locomotion.*[1]

What is the relationship between the environment, the stick, and the blind man's perceptual apparatus? Gregory Bateson's famous thought experiment suggests that the blind man's cognitive and proprioceptive processes are not located in the brain. Instead, through the object of the stick, perceptual modes extend from the 'boundaries of self' to the environment, where the material properties of the stick, the surroundings, and the body combine in their affordances to build a new sense of corporeality.

The object of the stick, which is an extension of the human body, changes how the body and the environment are connected. In this regard, the blind man conceptualises the stick as an integral part of a larger network consisting of humans and objects. This instance of the interchangeability of human sensorium and technological objects blurs the boundaries of the human as an autonomous subject. Instead, it portrays it as a mix of human and non-human actors working together through a network.

Similarly, Deleuze believed that the traditional concept of the human body as a static and unified entity was no longer applicable in the contemporary era. He contends that our bodies are currently more akin to networks or machines, with interchangeable parts that can be rearranged or reconfigured according to our needs. Deleuze expresses the openness of the human subject assemblage by employing Antonin Artaud's philosophical concept of the body without organs, in which the subject moves from one assemblage to another via deterritorialization and reterritorialization[1]. According to Deleuze and Guattari, the philosophical concept of the body without organs is defined as a body that is not determined by specific organs or organ functions but rather as a fluid entity constantly changing due to its environment and the forces acting on it. In Chapter 6: How Do You Make Yourself a Body Without Organs? of A Thousand Plateaus, Deleuze and Guattari provide a definition of the BwO:

> *A BwO is made in such a way that it can be occupied and populated only by intensities. Only intensities pass and circulate. Still, the BwO is not a scene, a place, or even a support upon which something comes to pass. It has nothing to do with phantasy; there is nothing to interpret. The BwO causes intensities to pass; it produces and distributes them in a spatium that is itself intensive, lacking extension. It is not space, nor is it in space; it is a matter that occupies space to a given degree—to the degree corresponding to the intensities produced.*[II]

It is non-stratified, unformed, intense matter, the matrix of intensity, intensity = 0; but there is nothing negative about that zero; there are no negative or opposite intensities. Matter equals energy. Production of the real as an intensive magnitude starting at zero.

The definitions suggest similarities between the characteristics of BwO and human plasticity as matter that can be occupied, populated by intensities, and subsequently moved into new assemblages through the ability to exchange its parts.

According to Deleuze and Guattari, each actual body, besides its routines, has also a virtual dimension that contains a vast repository of potentials of connections, effects, and movements. Deleuze refers to this set of potentials as the BwO. To intentionally experiment with oneself in order to discover and activate these virtual potentials is to 'make a body without organs'. These potentials are mainly actualised through encounters with other bodies, or BwO, or what he calls 'becoming'.

Furthermore, for Deleuze and Guattari, a process of transformation, flight, or movement within an assemblage is called 'becoming.' The process of 'becoming' serves to accommodate for relationships between the individual parts of the assemblage rather than considering it a whole, where the specific elements are kept in place by the organization of unity. In the process of 'becoming, one element of the assemblage is drawn into the territory of another element, altering its value as an element and creating a new unity where characteristics of the individual parts are replaced by the emerging properties of the whole.[III]

Discovering what a body can accomplish and what a body may become sensitive to is part of becoming a BwO. This process involves the development and organization of new senses, forces, and problems through activating one's virtual potential. According to Rosi Braidotti, the contemporary philosopher and feminist theorist, the BwO is '*a leap forward [...] toward a creative* *reinvention of life conditions, affectivity, and figurations for the new kinds of subjects that we have already become*'.[IV] The concept of BwO serves as an account for the posthuman theory, which favors the perspective of drawing attention to nonhuman entities and decentralizing the human subject in a process of uncertain and open-ended becoming.

In a similar vein, Katherine N. Hayles refers to the widespread nature of the distributed subject of the human condition as cognitive assemblages, '*in which cognitions are distributed between human and technical actors, with information, interpretations, and meanings circulating throughout the assemblage in all directions, from humans into machines, then outward from machines back to humans.*'[V]

According to Hayles, technology significantly contributes to the formation of human identity and experience. 'When the individual is seen as part of a distributed system, rather than leaving the body behind, it is necessary to extend embodied consciousness in highly specific, local, and tangible ways that are unimaginable without electronic prosthetics.'[VI] Hayles' concept of the posthuman as an assemblage is the literal merger of material and information, in which boundaries get blurred between 'material' and 'information' consisting of assembled parts and sub-parts, which dynamically change.

This decentralised image of the human condition undermines conventional ideas of the body as a single, independent entity. Instead, it considers the body a complex system of interconnected pieces that combine human and nonhuman elements to benefit the whole. In other words, for Hayles, our subjects have transformed into '*an amalgam, a collection of heterogeneous components, a material-informational entity whose boundaries undergo continuous construction and reconstruction.*'[7]

Similarly, Colomina and Wigley emphasise the mode in which human-machine assemblage constantly shapes and brings new intelligence to this synthesis. In Are We Human? they assert that the human subject is increasingly constructed as an assemblage of telecommunication networks, digital interfaces, clouds, and databases as the plastic character of human subjectivity extends into and through our prosthetic digital technologies to shape its plastic nature:

> *An array of constantly evolving algorithms—artificial neural networks and deep learning systems—monitor every gesture we make and continuously rebuild intricate statistical images of each of us. Each Internet search, post, transaction, and physical movement modifies this quantified human. The fact that you are reading this sentence may leave*

a trace. Self-design turns out to be an uncanny encounter between what we offer and the image of ourselves that we are offered on our little screens. The algorithm shows us what it thinks we want to see, as if in a strange kind of mirror that has become the new space of design.[VIII]

By emphasizing that we are the only species capable of design, Colomina and Wigley challenge the logic of our self-perception. They put forth the notion of the 'plastic human', who is continually designing itself through technology, whether through a shoe that alters the structure of our feet, a cell phone that modifies the wiring in our brains, or the stick of the blind man extending its sight through tactility. They claim how people live in a world of datascapes, information, and viruses. Calculations and decisions are made by algorithms. The modern city is frightening, and possibly the real person is inside the databases rather than here.

Seeing oneself in a database and constructing oneself an online persona has become commonplace over the past decades with the increased use of digital media and social media platforms that have shown us that they can be closely integrated to mediate our subjects, allowing us to construct and distribute them. Attention, cognition, and haptic and proprioceptive interactions constantly feed into the realm of machines '*in exchange for global infrastructural services that provide each of us a fixed and formal online identity and a license to use their services.*'[IX] When we see social media and digital technologies as part of our synthetic embodiment, we see the body as a complex system of interconnected parts whose emerging qualities can't be reduced to its components any longer.

We can see how this human-machine assemblage has exposed a new spatial dimension of design territory premised on identity politics, sociability, and community in today's Internet and media technologies, which are converging on the idea of personalization and social networking.

With the vast amount of information and resources available online, individuals are able to create and curate their own persona or identity. Through social media platforms, blogs, and other online channels, people are able to share their thoughts, experiences, and perspectives with the world. This ability to share and connect with others has led to the development of strong online communities and networks. For many, the Internet and digital media culture have become an integral part of their lives as they provide a space for self-expression and connection with others. Therefore, it is necessary to investigate the implications of these technologies for human subjects and the architecture of our spaces of coexistence.

3. SPATIAL EMERGENCE

In this regard, the outbreak of the COVID-19 pandemic and the resulting physical restrictions, isolation, and lockdown measures have profoundly affected how we interact with each other and our physical and virtual surroundings. One of the most significant changes has been the way that social interactions have moved online, forcing us to seek alternative ways of being and living together in virtual spaces. This has had a profound effect on our understanding of spatiality, as we are now living in a time where physical distancing is the norm. In response to this, a new form of social interaction has emerged in human subjects' communication and social constructs: Social VR.

Social Virtual Reality, or SocialVR (e.g., SecondLife, RecRoom, AltSpaceVR. High Fidelity, Sansar, VRChat, etc.), is an Internet-based social interaction paradigm mediated by immersive technologies and taking place in predesigned three-dimensional virtual worlds where individuals or collectives represented by an avatar, may engage in real-time interpersonal conversation and shared activities.[X]

FIGURE 1: ./studio3 Master Your Disaster Student Exhibition at Sansar

This technology has been used for years in gaming and entertainment, but its potential for social interaction was largely untapped until recently. While SocialVR is simply another form of online communication, its implications for emerging architectural spaces are much broader. Social VR technologies are transforming our spatiality by creating new ways of experiencing the space in which we communicate through the production of digital environments that can be experienced in embodied ways.

More specifically, SocialVR allows users to interact with each other in virtual reality (VR), creating a sense of presence and telepresence[2], and co-presence even when they are physically apart.[XI]

In contrast to conventional means of telecommunication based on transmitting information over distances in the form of voice telephone calls, data, text, images or video, SocialVR is concerned with spatial and embodied telecommunication methods of the Internet that stream objects, bodies, and spaces across remote places. When compared to traditional screen-based telecommunication systems, VR-based telepresence systems applied for remote spatial socialization, allow users to more directly express their feelings and impressions through sharing their physical presence alongside voice information, spatially.

In the past years, transitioning from screen-based communication to wearable spatial computing technology such as VR and MR glasses, social VR has become an emerging way of gathering, socializing, and sharing from our homes. The ability to provide an embodied sense of telepresence—an experiential state of being fully present in a live virtual space remote from one's physical location—is what makes these technologies and their application interesting as a medium of spatial production moving towards what has become a social space of telecommunication.

SocialVR, therefore, represents a fundamental shift in how we perceive ourselves, our identities, and the architecture of our social lives. In other words, it profoundly affects the way we think about our social selves, our inhabited spaces, and how we interact with others in both physical and virtual spaces. This also brings about a new emerging condition of corporeality, which leads human subjects to question how and through which sensoriums we inhabit this world.

Legacy Russell, in her Glitch Feminism: A Manifesto, insists on dissolving the gap between the digital world and the real world, to which we are always connected. Her Manifesto offers a new ecological reading of questions such as *How do we find out who we are within this digital era? Where do we create the space to explore our identity?* She proposes our relationship with our digital personas in a provocative and meaningful slogan: '*Usurp the Body, Become Your Avatar!*'[XII] Becoming your avatar is then embracing your mediated online character. Becoming your avatar is not just a political act but also a mode in which the materiality of online culture crystallises itself AFK and affords new subjects and ideas for worlding[3] to emerge.
How then can we think of 'becoming' as a method for worlding?

What kinds of spatialities can this hybrid human subject open up? How does SocialVR transform places? What would it mean to live in different dimensions at the same time, and what implications does this have for our private and public spheres?

FIGURE 2: Bodies Without Organs Social Mixed Reality: Local Multi-User Experience

4. BODIES WITHOUT ORGANS - A SOCIAL MIXED REALITY PLATFORM[4]

In order to address these questions, the following section of this paper will explore the creation of a SocialVR project called *Bodies Without Organs*, which was designed to investigate the contemporary condition of our embodiment and our spatial practices after adopting new social behaviours during COVID-19-related critical times, such as isolation, lockdown, and social distancing, that have forced us to seek alternative modes of being together. The project refers to the socio-spatial impacts of media, investigating how new media and communication technologies could shape and transform the spatiality of our everyday lives.

Considering this, the BwO multi-user mixed reality project explores online modes of spatial production strategies that incorporate objects with both physical and digital materialities into a physical/virtual overlap: it creates a multi-user and multi-location spatial platform that transforms the inhabited space into a public space of social interactions by projecting remotely shared spatial content and embodied avatars onto the physical environment.

This embodied spatial platform focuses on an extended architectural practice called 'socio-spatial' that investigates the notions of **embodied telepresence** and **sociability**. Here, spatial computing turns the built environment into a medium of spatial telecommunication where embodied telepresence and social interactions taking place in a virtual dimension are hosted and shared across a network.

The project considers the aforementioned 'assemblage thinking' as a methodological approach towards understanding how complex social, technical, and cultural spaces are established and maintained by a multitude of heterogeneous entities to constitute presently human subjects. Thoroughly tied to notions of fluidity, complexity, and exchangeability, 'assemblage thinking' offers a practical and theoretical foundation which allows the project to investigate the mediated emerging spaces of human sociability.
This social mixed reality experience, which interweaves bodies, the Internet, and new media technologies with architectural space, requires a more detailed explanation.

5. METHODOLOGY: ASSEMBLING INTELLIGENT API AGENTS OR HOW TO MAKE YOURSELF A BODY WITHOUT ORGANS?[5]

How does coupling the virtual avatar with the human body extend the bodily and spatial affordances within the physical/virtual overlap?

As stated in the introduction, '*making oneself a body without organs*' entails experimenting with the virtual potentials of the human body and is always already a process of becoming where one piece of the assemblage is drawn into the territory of another piece, exchanging its value as an element and bringing about a new unity. The project uses the notion of becoming as a methodological concept for creating interactive virtual avatars in which many nonhuman things participate as subjects, in reference to Haraway's statement that '*to be one is always to become with many.*'[XIII]

Considering this, the project takes into account the expression 'becoming-with-avatar' as a generative mode for the social mixed reality experience aiming to expand the deterritorialised human subjects' tactility, presence, and sociability caused by isolation and lockdown in a networked space through embodied telepresence.
The term embodied presence refers to the sense of being physically present within a space or environment.[XIV] However, achieving such embodiment through mediated communication channels such as video conferencing

platforms presents challenges due to limited sensory feedback. In contrast, Mixed Reality provides opportunities for more profound immersion into digitally reconstructed worlds where interaction feels natural; thus creating higher levels of physical presence than previous media forms could offer.

Embodiment increases social connectedness because feeling "present" in one's surroundings enhances interpersonal interactions' perceived realism.[XV] Consequently, improving users' experience of presence by increasing their ability to communicate naturally via non-verbal cues like gestures, which are critical components when conveying emotional messages during conversations.

The importance of embodying avatars to evoke the sense of telepresence in virtual environments has been widely discussed by Taylor, for whom presence is a key feature of immersive virtual worlds. It gets down to the core of what it means for an experience to have the 'genuine' quality that tells us, 'I am here.'[XVI]

For Taylor, the primary aspect of presence in digital spaces is how it manifests as an embodied activity. One becomes rooted in the virtual environment through a performance of the body, in this case, through the avatar.[XVII] However, the key to evoking the sense of presence is the social interactions that situate it in a social scenario. Subsequently, its consideration of 'presence' is the sense of being with other people in a shared virtual environment or, equivalently, the sense of togetherness.

Therefore, the project is concerned with the creation of a virtual avatar for embodied telepresence that manifests its properties in human cognition, perception, tactility, and proprioception.[6] In order to achieve this human-avatar synthesis, the project will assemble API agents in the Unity Game Engine.

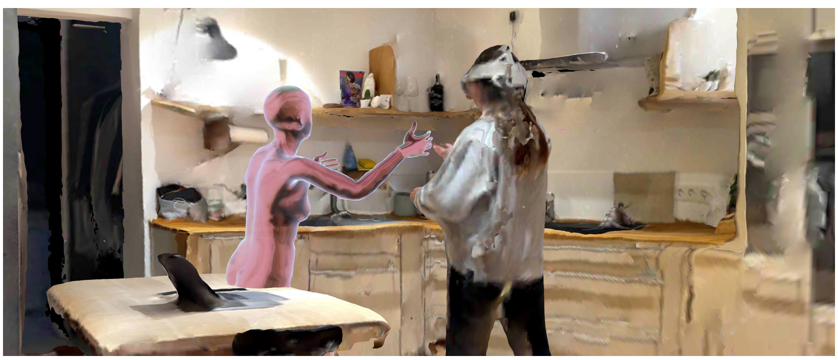

FIGURE 3: Bodies Without Organs Social Mixed Reality: Spatial Telecommunication through Embodied Telepresence

API is the acronym for Application Programming Interface, a software intermediary that allows two or more applications to talk to each other. [XVIII] Today, most social media companies offer APIs so third-party developers can build new applications on top of their platforms. Different APIs have the ability to connect different pieces of software to create new and innovative applications. An API is often used to refer to web APIs, which allow communication between computers that are joined by the internet.[XIX] As protocological[7] objects, APIs allow interested parties to access the data and functionality of online services in a very controlled manner.[XX] Also, developers and researchers can access the API to retrieve, store, and manipulate digital traces left by the users for further empirical studies.[XXI]

In the context of this project, the human body is perceived as BwO, an open and plastic territory—the place upon which discrete API agents' transmission of digital information can be inscribed and actualise their potential. When they implant themselves upon the BwO, the BwO assumes a form, and this form is conducive to the specifics of the API agents that have imposed themselves upon it. In other words, APIs as discrete agents need the BwO as a site of production that hosts and nourishes them. They '*attach themselves to the body without organs as so many points of disjunction between which an entire network of new syntheses is now woven, marking the surface off into coordinates, like a grid.*'[XXII] This is what Deleuze conceives of the human body as a machine: an assemblage of parts of different organs with many connections.

When API agents are considered in terms of their sociomateriality, they are seen as constituent actors who play a big part in establishing the social and physical relationships between bodies. [XXIII]

The notion of sociomateriality proposed by Orlikowski[XXIV] and Orlikowski and Scott[XXV] is founded on the agential realist philosophy developed by Barad. [XXVI, XXVII,XXVIII] It aims to comprehend the constitutive entanglement of the social and the material in everyday organizational life and is based on the intersection of technology, work, and organization.[XXIX] It is the outcome of thinking about how language, interaction, and organizing practices are intertwined with human bodies, spatial configurations, physical objects, and technologies. Instead of assuming that entities, people, and technologies have inherently determinate boundaries and properties, they are seen as relational effects, continuously performed in a web of relations. Barad[XXX] defines agency as the '*enactment of iterative modifications to particular practices through the dynamics of intra-activity*' as opposed to placing agency in humans or in technologies.

In that regard, the project promotes APIs (application programming interfaces) as discrete digital communication agents with their own agential meanings and conceives their interactions as constituting the whole socio-spatial experience of BwO. In this regard, the main application of APIs focuses on two features to produce a distinctive avatar that evokes the sense of embodied telepresence—its presence in the real world and its social interactions in the virtual world.

5.1 Creation of the emobdied telepresence

This chapter explains how the project was developed into a mixed reality prototype application built on sociability and embodied telepresence by connecting multiple API agents such as the Pose Estimation API and the Hand Tracking API to track the user's movements, proprioceptive mechanisms, and gestures. Also, the Passthrough API was used to create a seamless integration between the virtual and real environments. Finally, the Networking API is used to enable sharing of experiences between multiple users. All of this together results in a social mixed reality environment that delivers the experience of embodied telepresence. It transforms the body into a collection of ubiquitous media objects distributed and situated in clouds for remote communication, dissolving the hardware and software on the body: "*The body as a frame becomes a 'coprocessor' of digital information.*"[XXXI]

Pose Estimation API and Hand Tracking API are two technologies that can be used to achieve this goal. Pose Estimation API uses computer vision algorithms to estimate the position and orientation of a user's body in real time, while the Hand Tracking API tracks the movement of the user's hands.

5.1.1 ***Pose Estimation API:*** The Pose Estimation API uses computer vision algorithms to estimate the position and orientation of a user's body in real-time. In the context of virtual reality (VR), pose estimation is used to track the movements of the user's body and translate them into corresponding movements in the virtual environment. It typically involves algorithms to detect and track key points on the user's body, such as hands, head, and feet. These key points are then used to calculate the user's pose in real-time.

A popular third-party add-on for pose estimation in Unity is RootMotion's VR IK tool. VR IK is an inverse kinematics (IK) system that can be used to accurately track the user's movements. VR IK is particularly useful for VR applications involving physical interaction with the virtual environment, such as allowing visitors to take advantage of the physical body's capabilities, which is inextricably linked to personal expression, kinesthetic and proprioceptive embodiment, and spatial knowledge.

5.1.2 ***Hand Tracking API:*** Hand Tracking API is a feature provided by the Oculus Integration SDK. It is a software interface that allows developers to track and recognize hand movements and gestures in real-time. The Hand Tracking API uses machine learning algorithms to detect and track the position and movement of the user's hands. It detects the orientation of the hand and the position of each finger, as well as the user's hand gestures, such as pinching, grasping, and releasing. This API provides detailed information about the user's hand movements that can be used to control virtual objects in the application.

The hand-tracking API is a critical component of a mixed reality environment created with a passthrough API that overlays physical and virtual spatial experiences in real time.

5.1.3 ***Passthrough API:*** The Passthrough API is a feature provided by the Oculus SDK that allows developers to create mixed-reality applications in Unity. It allows developers to access the world around the user in real-time and display it as an overlay on top of the virtual environment created by the application. This creates a unique experience where the user can see and interact with both the physical and virtual worlds simultaneously.

The Passthrough API uses the cameras on the Oculus Quest2 headset to capture the real world and transmit it to the application in Unity. The captured images are then processed by the Passthrough API to align with the virtual environment and displayed as an overlay in real-time.
When the Hand Tracking API is used in conjunction with the Passthrough API, the user can use their hands to interact with the physical and virtual worlds simultaneously. The Hand Tracking API detects the user's hand movements, and the Passthrough API overlays the virtual objects on the physical environment, giving the impression that the virtual objects are physically present in the real world, making it easier for the user to interact with the virtual objects in a more natural way by using their hands instead of a controller or other input device.

5.1.4 ***Networking API:*** Networking APIs are essential for creating an embodied telepresence experience shared by multiple users in a mixed-reality environment. By using Networking API, the system can synchronize data between devices and enable communication between users.

In an embodied social mixed reality experience, where multiple users are present in the same virtual space at the same time, it is vital to establish a social environment where they can interact with each other. This interactivity requires real-time synchronization of their movements and actions, as well as the ability to communicate via voice or text chat.

A network API such as the Normcore add-on for Unity enabled the synchronous exchange of information across different devices connected to the network. It ensured that all participants had access to current scene details, such as the positions of people or objects, in real time. It also enabled interactions by synchronizing user input (e.g., hand gestures), creating a synchronized experience for those sharing this platform from remote locations.

By incorporating the Networking API into our proposed approach, along with the Pose Estimation and Hand Tracking API, in conjunction with the Passthrough API, the BwO platform provides seamless spatial multi-user communication that offers opportunities for peer-to-peer collaboration beyond the capabilities of traditional video calls or conventional digital media platforms.

6. FINDINGS: ARRIVING AT EMBODIED TELEPRESENCE

When people enter the multi-user room-scale experience of the BwO platform, they are both 'here' in the physical space and 'there' in the virtual with the real-time representation of their proprioceptive selves 'acting-in-distance'. However, inside this experience, there is no distance between the 'here' body and the 'there' body.

The 'here' body, the physically grounded body, and the 'there' body, the virtual body, continuously entangle with one another through the proprioceptive mechanisms of the human body and the proprioceptive abilities of the virtual body. The user inhabits an avatar's body without ever losing connection with their own, sees the surrounding world through the gaze of the digital body, and recognises its basic arrangement from the well-known physical space - avatar and user become one, actualizing the sense of embodied telepresence.

In addition to the possibility of communicating in the physical (physical-virtual) presence of another person, the ability to use hands to express oneself with gestures and interact with the surroundings significantly enhances the sense of presence within mixed reality.[XXXII] The sense of touch plays a uniquely important role in human interaction. It is related to notions of closeness and intimacy and, as our language shows, is often used as a metaphor for emotional impact.

Moreover, the virtual avatar enables users to use their hands to grab, pick, and manipulate virtual objects' positions in the world, creating a social and tangible environment in which the human subject is fully present in its bodily

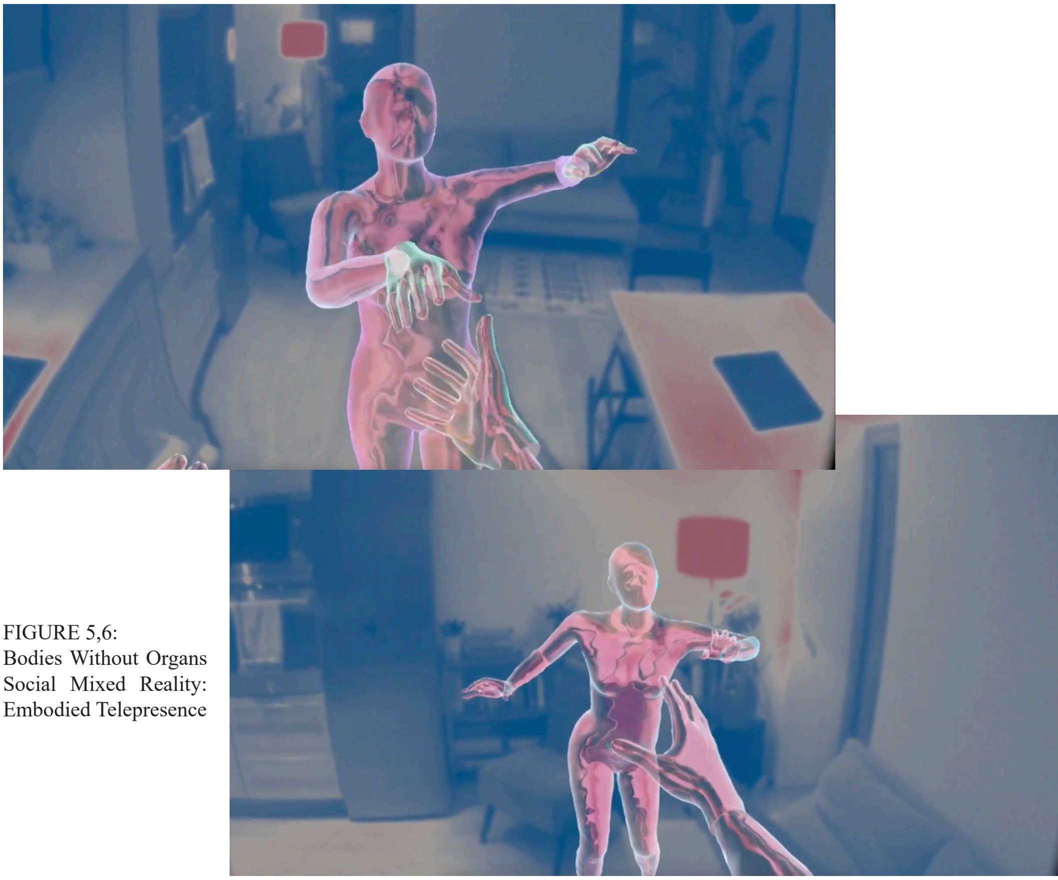

FIGURE 5,6:
Bodies Without Organs Social Mixed Reality: Embodied Telepresence

actions and interacts with both physical and digital worlds simultaneously in a ‘natural’ way.

In the age of the Internet and digital media, human subjectivity is widely distributed, embodied beyond the human frame and situated in networks and remote places. There is a certain tentacularity, an extended sensorium, in the act of touching and sensing distances through one’s digital avatar, immersed in synthetic, embodied, and organic relationships simultaneously. This vast network gives rise to a complex form of distributed embodiment and to new senses of self, cognition, and proprioception through the body’s digital mediation.

7. A USER TRAJECTORY INSIDE THE MIXED REALITY EXPERIENCE

In this small chapter, the paper further elaborates on the mixed reality experience of the BwO, from users' trajectory. Firstly, it is important to notice that this multi-location and multi-user social mixed reality project was used by a small group of people located in different countries for a period of time during the lockdown and was used for long-distance communication, particularly to meet for work sessions, talk, and socialise.

Within the experience, we see full-body virtual avatars of remote participants, housed in the virtual dimension and seamlessly embedded in the physical room setup. This physical/virtual overlap space enables users to maintain their relationship with their physical room activities while expanding their social interactions inside the virtual space.

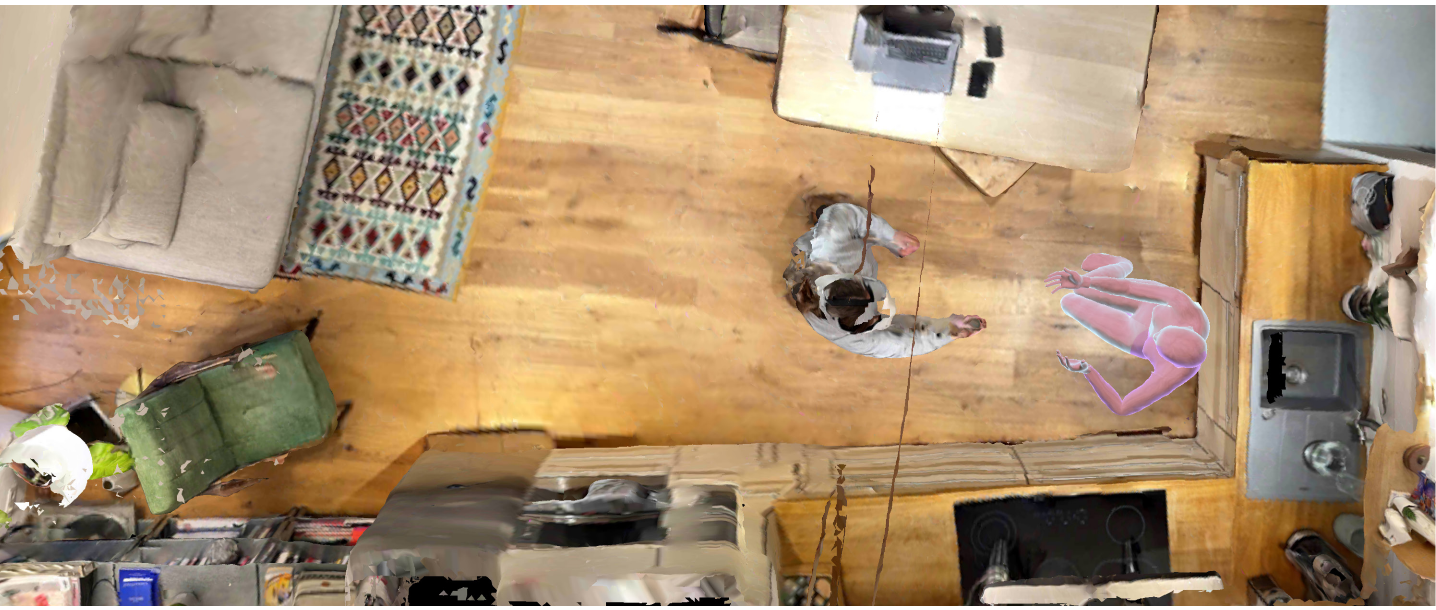

FIGURE 7: Bodies Without Organs Social Mixed Reality: Entering Remote Spaces with Embodied Telepresence

The physical room envelops the contents of the virtual space, thus allowing users to use the physical space as their main reference for navigation. Consequently, the ability of visitors to navigate within the virtual space is limited by the size of the physical room.

This does not mean that a remote visitor cannot suddenly emerge from your kitchen or that a pair of hands cannot mysteriously emerge from your closet. Because of the overlap of physical rooms in a shared virtual space, virtual avatars can be near or far, depending on the size and the obstacles present in their physical space.

8. DISCUSSION: PRIVACY CONCERNS RELATED TO PERSONAL AND SPATIAL DATA

The human body and its plastic matter have become an extreme territory of inexhaustible data extraction of behavioural patterns through social media platforms, haptic graphic user interfaces, wearable devices, and algorithmic intelligence feeding their intangible information back to humans to construct a personalised reality in tangible ways. Especially with the advent of spatialization of the web, the media objects that populate the Internet are no longer 2D and tangible only through screen-based communication technologies, but rather 3D media objects that include the real-time movements of our bodies, objects, and architectural spaces. This means there is an emerging online spatial dimension to our everyday practices through social media technologies.

However, this is not to congratulate the discourse of enterprise tech giants on establishing their market growth around the mediated identity of human subjects using their social media services; it is rather to emphasise and rigorously study the emerging spatiality around this assembled subject.

Therefore, in the context of this research, besides considering API agents' capacities to offer online modes of embodied spatial telecommunication, APIs are seen critically as protocological objects, allowing in these vast social networks communication and connectivity between peers, and between databases and users to take place. More and more, APIs become tools for accessing personal data related to biometric variables, spatial organization, spanning from physical characteristics and movements of a person to voice interactions, from room dimensions of a user to the visited contents, which creates a doubtful environment around this platform regarding sharing personal data that is no longer peer-to-peer, but mediated through corporate companies' servers, collected, processed, stored, and governed. Additionally, it is important to mention that the social mixed reality project of *Bodies without Organs* has not collected or stored any personal data related to the participants to constitute the embodied telepresence and the spatial telecommunication.

9. CONCLUSION: SOCIO-SPATIALITY: A PHYSICAL-VIRTUAL OVERLAP

Today, the internet, telecommunication technologies, and the architecture of how we live together are undergoing radical changes with the introduction of spatial computing and increased use of social media platforms.

The fact that networked virtual spaces (SocialVR) can be accessed from anywhere with embodied avatars has opened up new spatial design territories where social activities, online culture, and embodied practices merge on the cultural horizon of media technologies and become a locus for the growing culture of global connectivity & sociability. However, in contrast to conventional means of telecommunication based on transmitting information over distances in the form of voice telephone calls, data, text, images, or video, Bodies without Organs Social Mixed Reality Experience is concerned with spatial and embodied modes of online telecommunication that stream objects, bodies, and spaces across remote places.

BwO Installation investigates the emerging spatiality around the subject as machinic assembly, using a theoretical and practical approach exemplified in a social mixed reality project to demonstrate how the human body and its identity are pushed into the plastic territory of exchangeability, self-representation and spatial organization, tied to the Internet's materiality. As a result, in the context of this research, virtual avatars are considered in their sociomateriality and regarded as critical mediators between organic and inorganic, physical and virtual, for an online mode of embodiment and spatial production. Thus, their social, material, and spatial implications are discussed in a broader context.

Through the embodied telepresence – that is made possible via interactive full body and networked avatars, the social mixed reality experience of BwO makes the subject a ubiquitous being, blurring the boundaries between subject and object, local and global, human and nonhuman. This augmented condition of the human subject inevitably brings about new spatial affordances. As one is grounded in the proprioceptive mechanisms of the physical body navigating the physical space while simultaneously inhabiting the virtual dimension. Consequently, the augmentation of the spatial capacities of physical space through spatial computing technologies produces temporal assemblages of spatial instances with new affordances that entangle online and offline materialities.

When the physical space hosts the virtual spatial content at its 1:1 scale and becomes the envelope for the online virtual content, they combine in their affordances to unite for a new intelligence of space where physically limited spaces expand with virtual materiality and construct a mixed-reality experience. This kind of spatiality in which physical and digital materialities constantly inform each other defines the 'mixed reality' experience and opens up a shared virtual spatiotemporal dimension allowing the users to 'act at a distance' through the medium of spatial and embodied data transmission occurring within the inhabited hybrid dimension.

This 1:1 overlapping physical and virtual space profoundly impacts our spatial perception. First and foremost, it provides a brand-new understanding of how expanding physical spaces with the capabilities of virtual overlay content can offer a variety of architectural programs, ranging from social gatherings to globally relevant data flowing into the virtual space that can be navigated with the practice of the body. Second, it allows us to consider how physical spaces are no longer static and isolated in their materiality but are instead hybridised, linked, and affected by online materials. All of this enables remote and temporal access to portions of users' private and non-private spatial content from anywhere enabling the remote integration of events and social activities into the places we inhabit every day.

NOTES

1 In critical theory, deterritorialization is the process by which a social relation, called a territory, has its current organization and context altered, mutated or destroyed. The components then constitute a new territory, which is the process of reterritorialization. (Deterritorialization, 2022.)

Wikipedia contributors, "Deterritorialization," Wikipedia, August 5, 2022, https://en.wikipedia.org/wiki/Deterritorialization.

2 One definition of telepresence is 'one's sense of being present in the mediated environment rather than the local physical surroundings' (Steuer, 1992). The user's perception of the environment and space in the mediated world is closely related to this aspect of presence. A person's 'virtual self is experienced as the actual self' to a greater or lesser degree when engaging in self-presence, as opposed to telepresence. This aspect of presence is distinct from telepresence because it has nothing to do with sensory realism but rather with the extent to which one may empathise with and feel like an extension of one's virtual body, emotions, or identity (Ratan & Hasler, 2009). Last but not least, 'social presence', also known as 'co-presence', is the 'feeling of being with another' (Biocca et al., 2003) and is based on how easily one perceives to have 'access to the intelligence, intentions, and sensory impressions of another' (Biocca, 1997).

3 Worlding is a particular blending of the material and the semiotic that removes the boundaries between subject and environment, or perhaps between persona and topos. Worlding affords the opportunity for the cessation of habitual temporalities and modes of being.

4 The project BwO installation was developed at ./studio3 Institute for Experimental Architecture as a part of a Generative PhD supervised by Univ. Prof. DI Kathrin Aste. The ./studio3, a unit of the Faculty of Architecture at the University of Innsbruck, researches and teaches at the interface of experimental architecture, contemporary art and culture, investigating both the correlation between architectural design and the artistic process of creation and their significance for real and virtual space. In interaction with art, culture, media, and technology, a transdisciplinary approach is pursued that understands design as an experimental epistemic practice, as a process that both scientifically explores and artistically discovers architecture in order to creatively meet the complex challenges of our time. By combining assemblage as a compositional, articulated, and tectonic design principle with bricolage as a material, resource-saving, and even compromising implementation strategy, studio3 situates its practice and teaching of architecture that is both artistic and socially and environmentally aware.

5 In their book A Thousand Plateaus (1980), Gilles Deleuze and Félix Guattari pose a very specific query: 'How Do You Make Yourself a Body Without Organs?' It may be essential to notice that Deleuze himself does not provide a substantial answer to this issue. This puzzle is addressed in detail in the Plateaus article of the same name, in which the Body without Organs (BwO) is defined along with its role within Deleuze's apparatus of desire and several examples of bodies that appear to satisfy the BwO's stated criteria are provided.

6 The term 'proprioception' describes a person's awareness of their body as a unified whole through their own efforts at movement. The inability to sense one's own body might lead to disorientation. One of the most convincing ways to externalise and (re)present proprioception's data is to reproduce its structure and artificially enhance it with technology. Spatial computing allows for the seamless translation of bodily motions into augmented virtual bodies that can heighten the sense of presence they provide. (Fedorova, 2013)

7 Fedorova, Ksenia. "Mechanisms of Augmentation in Proprioceptive Media Art." M/C Journal 16, no. 6 2013. https://doi.org/10.5204/mcj.744

8 For Galloway (2004), 'Protocol is that machine, that massive control apparatus that guides distributed networks, creates cultural objects, and engenders life forms', 'Protocol is a system of distributed management that facilitates peer-to-peer relationships between autonomous entities.'

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AN APPROACH FOR DESIGNING ARCHITECTONIC STRUCTURES WITH BIO-INSPIRED PATTERNS

ABSTRACT

The paper focuses on applying bio-inspired generative design (GD) strategies in architecture. The aim is to produce innovative designs by developing architectural methods and tools that adapt patterns underlying biological behaviours. The emphasis in explorations was on biological phenomena that can play the role of underlying design patterns. The complex behaviour of natural systems represented by bio-inspired computational algorithms was then used to produce designs, i.e., information-related biological functions are transformed into technical functions to solve design problems. In this scenario, computer-generated design artefacts were produced by an algorithmically determinate system of rules. The suggested approach was tested through design experiments. Integrating biological and technical information was realized using a visual programming environment in a computer-aided design (CAD) system, facilitating design exploration and visualization. The logical set of rules was implemented to automate the design process. The obtained designs demonstrate the sustainability of the suggested approach.

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BIO-INSPIRED COMPUTING
BIOLOGICAL SYSTEM MODELLING

1. INTRODUCTION

It has been repeatedly shown that sourcing biology as knowledge and inspiration in architecture, frequently in conjunction with other sources, is effective.[1,2,3,4,5] Applying bio-inspired generative techniques in architectural design is the central subject of this study. The usage of systems for autonomous formation in the design process is implied by the generative design (GD) methodology. In these processes, designs emerge from modifying various applied generative system parameters.

Diverse natural or artificial systems could be used in a GD as mediums for creation. However, the application of automated computational systems is the most frequent. Furthermore, current computational systems increasingly feature a great deal of openness, dynamism, and unpredictable behaviour, forcing them to shift design from traditional, centralized approaches to nature-inspired, self-organizing techniques. Respectively, utilizing the complex behaviour of biological entities for generative systems heavily relies on computer technologies. Although different strategies have been explored, [6-21] there are still many opportunities to study, analyse, classify, and develop them in terms of design patterns and how they could be potentially systematically applied to solve design problems.

Correspondingly, this paper is directed at modelling bio-inspired mechanisms and exploring whether some biological behaviours can play the role of basic design patterns and generate designs. The aim was the creation of design procedures and tools from the adaptation of natural phenomena underlying each pattern. In the described approach, the development and application of a generative strategy based on biologically inspired patterns are part of the creative process. In addition, the application of these generative strategies in the conceptual stage of the design process is reviewed along with its potential and limitations.

Starting from the brief analysis of concepts, available methods, and tools, we propose and test an approach that combines biological and technical information in a compatible way through design experiments. The task was to select and outline design situations in which this approach is relevant and define design methods and tools.

Respectively, information-related biological functions are translated in terms of technical functions to solve problems of designing architectonic structures. In this set, computer-generated design artefacts are produced by an algorithmically determinate system of rules.
GD activity requires precisely defining the problems to solve and accurately comprehending the relationships, flows, and performances to provide design solutions with the desired qualities of biological systems. On the other hand, the GD methodology avoids preconceived solutions and psychological inertia due to the finite experience. The bottom-up approach drives designers through problem abstraction and after through the abstraction of solution.

In this research, the relationship between different fields is explored and visualized in a CAD system with the aid of visual programming. This approach was selected because architectural designers are familiar with CAD environments. Modern CAD systems enable constraint-based modelling in which every element may be connected using parameters, relationships, and references. The logical set of rules can be implemented to automate the entire or part of the design process, providing the possibility to create an integrated functional structure.

Using nature as a model and mentor and appropriating biological patterns can lead not only to rational design solutions but also to the design process's optimization. Finally, this paper may be interesting to those involved in architectural design and those generally interested in design methodologies, particularly computational GD strategies, because the approach can be generalized and applied to various design domains.

2. UNDERLYING CONCEPTS

Patterns in both animate and inanimate natural worlds are visible regularities, outcomes of complex self-organization governed by physical laws and biological processes. Sciences, including mathematics, physics, chemistry, and biology (especially evo-devo), can describe pattern formation at different levels and scales. Visible natural patterns find explanations in chaos theory, fractals, logarithmic spirals, topology, and other mathematical constructs. Exact mathematical perfection can only approximate natural entities; however, many patterns from nature can be modelled mathematically and simulated with computer graphics.

Attempts to explain the order in nature date back to ancient Greek philosophers, including Plato, Pythagoras, and Empedocles, who anticipated modern concepts.[22,23] Studies of symmetries and spirals remain relevant in modern times. Since Leonardo Fibonacci formulated the Fibonacci sequence in 1202.[24] spiral arrangements were the subject of studies by diverse authors, including Leonardo da Vinci, Johannes Kepler, Charles Bonnet, Karl Friedrich Schimper and Alexander Braun, Auguste and Louis Bravais, Adolf Zeising, and A.H. Church, D'Arcy Thompson.[25] Studies of soap films started in the 19th century with the pioneering work of Joseph Plateau, who formulated minimal surfaces.[26] The problem of foams, i.e., packing equal volume cells, was solved by Lord Kelvin. His 1887 solution was only improved after the 1993 Weaire-Phelan structure, which was applied to the envelope of the Beijing National Aquatics Centre constructed for the 2008 Summer Olympics. [27,28] Alan Turing studied mechanisms of morphogenesis.[29] He proposed a reaction-diffusion model and formulated the Turing pattern describing spots and stripes in nature. Aristid Lindenmayer developed the L-system, a formal grammar for modelling plant growth based on the mathematics of fractals.[30] Benoit Mandelbrot's Fractal Constructs[31] is the final contribution to the discipline of mathematics of patterns, which was gradually developed through the works of Gottfried Leibniz, Georg Cantor, Helge von Koch, Waclaw Sierpinski, and others.

Visible patterns in nature include symmetries, trees, fractals, spirals, chaos, flow, meanders, weaves, dunes, bubbles, foam, tessellations, cracks, spots, stripes, and patches. While symmetries are pervasive in nature, fractals only approximate the phenomenon of self-similarity (such as branching) since infinite iteration is not possible in the natural world. Spirals are common in plants and some animals, notably molluscs. Patterns, including chaos, flow, meanders, weaves, and dunes in nature, are the results of dynamic nonlinear processes. At the same time, bubbles and foams are optimal structures that, like all natural systems, tend to stabilize in a state of minimal energy. Respectively, these systems are applied in architecture for the design of lightweight structures like tensile membranes, researched and designed by Frei Otto[32] or or Buckminster Fuller's geodesic domes.[33] Tessellations are a common motive in art and design; however, it is less easy to find exactly repeating tiling in living things. Crack patterns are linear openings formed in materials to relieve stress, while spots, stripes, and patches in the biological world have evolutionary reasons related to natural selection and survival (*Figure 1*).

Current research on the application of some natural patterns for producing artificial intelligent systems for GD in architecture has been the subject of several publications.[34,35,36,37,38]

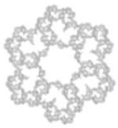
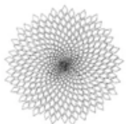
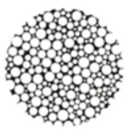
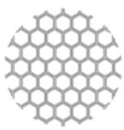
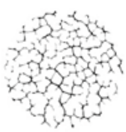
Type		Materialisation	Formation
Symmetry		_bilateral symmetry in animals _bilateral/radial/fivefold floral symmetry _sixfold symmetry in snowflakes _crystal symmetry	_developmental process _ecological causes _crystallisation process
Trees Fractals		_branching _self-similarity [e.g. clouds, river networks, geological fault lines, mountains, coastlines, animal coloration, snowflakes, crystals, blood vessel branching, Purkinje cells, actin cytoskeleton, ocean weaves]	_growth pattern modelled by L-system fractals _self-similarity approximated by fractals
Spirals		_plant spirals - arrangement of leaves on a stem, parts of composite flower head and seed head [e.g. sunflowers, pineapple, pinne cone] _animal spirals [e.g. molluscs]	_phyllotaxis spiral generated from Fibonacci ratio _special case of self-similarity _lowest-energy configurations that emerge through self-organisation _reaction-diffusion processes _natural selection causes
Chaos Flows Meanders		_vortex streets in form of zigzagging _patterns of whirling vortices _meanders in form of curved bands in rivers or other channels	_dynamic system modelling based on chaos theory, fractals, some cellular automata [e.g. Wolfram's Rule 30] _fluid flow processes
Weaves Dunes		_chaotic ripple pattern of any larger body of water or send [e.g. crescents, very long straight lines, stars, domes, parabolas, and longitudinal or seif shapes] _ patterns in vegetated landscape [e.g. forests on mountain slopes after wind disturbance]	_dynamic system modelling [e.g. modelling behaviour of mechanical weaves that propagate through a medium making it oscillate] _morphogenesis [e.g. weaves occurring in forests on mountain slopes after wind disturbance during regeneration]
Bubbles Foam		_soap films and spherical bubbles _foam of different materials in nature [e.g. living cells, radiolarians, sponge spicules, silicoflagellate exoskeletons and the calcite skeleton of sea urchin]	_minimal surfaces modelling [form-finding and optimisation - minimisation of energy] _dens packing structure modelling [note. foams composed of soap films obey Plateau's law]
Tessellations		_tessellated structures built by animals [e.g. nests of social wasps, honeycomb] _tessellations in animals' osteoderms [e.g. bony fish, reptiles, pangolin] _tessellations in plants [e.g. salk fruit, snake's head fritillary] _tessellated structures of minerals	_patterns formed by repeating lines all over flat surface, arrays
Cracks		_patterned ground in permafrost soils with an active upper layer _fissured pattern that develops on vertebrate brains [note. the pattern of cracks differ for elastic and inelastic materials]	_process of forming linear openings in materials to relieve stress [e.g. shrinking cracks caused by thermal concentrations, physical process of constrained expansion]
Spots Stripes Patches		_pigmentation patches in animals: spots [e.g. leopard, ladybug], stripes [e.g. angelfish, zebras], blotches [e.g giraffe] _vegetation patterns: stripes [e.g. tiger bush], patches [e.g. in flat terrains hexagonal gap pattern and spot patters] _patterns created by animals [e.g. Mima mounds of the of the Northwester US, fairly circle of Namibia] _growth colonies [e.g. bacteria colonies, slime mould]	_modelling reaction-diffusion systems / activator-inhibition mechanisms [e.g. shapes dependant on the growth condition, (in particular stresses), dynamics of chemical signalling (slime moulds), cellular embodiment (elongation and adhesion)] _evolutionary reasons [e.g. camouflage, signalling, mimicry, simbiosis] [note. pattern formation is genetically controlled, and often involves each cell in a filed sensing and responding to its position along morphogen gradient]

FIGURE 1: Visual patterns in nature

Bio-inspired mechanisms in design

Terms bionics/biomimicry/bio-mimetic/bio-inspiration/bio-appropriation are synonyms used to denote a multidisciplinary scientific field in the expansion that studies modes of transposition and implementation of patterns found in nature into science, engineering, art, and design. The aim is the production of optimal solutions that have specific desirable attributes of biological systems. *Figure 2* summarizes the comparison between biological and architectural systems.

Biological systems	Architectural systems
Efficiency because of the long and constant process of natural evolution	The improvement of efficiency solved through the process of optimization
Environmentally responsive and fit into their environment	Very little environmentally responsive
Environmentally influenced self-assembly	Externally imposed from
Hierarchical structure	Mostly monolithic, little or no hierarchy
Adaptive in function and morphology – growth and repair	Construction and fabrication

FIGURE 2: The comparison between biological and architectural systems

Just like nature, architecture is centred on organization and materialization, deals with morphology and structure, and is made up of individual functional elements that work together as a whole. However, the comparison (*Figure 1*) shows the superiority of natural systems and the high standards that nature has set before artificial systems. An example is the diversity of natural forms and organisms in metabolic balance with their surroundings, resulting from continuous evolution and development through natural selection. Therefore, deriving solutions for design problems from natural processes implies the position of nature as a mentor/model/system.

In line with the previous several interesting research projects and initiatives have been launched, such as *AskNature*, a project of the Biomimicry Institute, an organization dedicated to promoting the practice of looking to nature for inspiration to solve design problems in a regenerative way.[39] Another interesting initiative is *BioFabForum*, a community for knowledge exchange and experimentation around the manufacturing of/with biological materials.[40]

Building on the tradition of interdisciplinary research on natural structures established by Frei Otto at the University of Stuttgart,[41] the Institute for Computational Design (ICD) collaborates on various projects that use bio-inspired patterns and computational processes in architectural design.[42] For decades, the *MediaLab* at the Massachusetts Institute of Technology (MIT) has been conducting research on transformative systems, experiences, and technologies that help people reimagine and redesign their lives by fusing art, science, design, and engineering. Some of their projects combine design, biology, and the use of cutting-edge technologies.[43]

Also, the *Urban Morphogenesis Lab* at the Bartlett School of Architecture experiments with the application of the latest scientific findings within unconventional computing and biological and artificial intelligence to various complexity and scale of design from objects to architecture and the urban.[44] On the other hand, an example of an architectural firm specializing in biotechnology for the built environment is *ecoLogicalStudio*. The studio has built a distinctive portfolio of biophilic artworks, living architectures, and blue-green masterplans.[45]

According to Vincent,[46] there are three different levels of transposition of biological mechanisms into the architectural design process: copying, pattern recognition, and the TRIZ theory of inventive problem-solving-based approach. Copying biological entities is the lowest, most obvious, but insufficiently general approach. The properties of the most often copied biological objects include form, structure, and texture. Although this approach has a disadvantage that biological systems and their mechanisms can be taken out of context without sufficient understanding of the reasons for their effectiveness, there are numerous examples of copying formal patterns of natural structures such as leaves, shells, trees, and bones.

Pattern recognition is the second level of translation (applied for design experiments in this study). At this level, a more general approach is used, which includes recognizing patterns and identifying principles and ways of solving biological problems. Many successful engineering solutions use simple and apparent principles from nature, such as structural hierarchy or the case of tensioned structures, where stress concentrations are eliminated thanks to their shape. The essence of this approach is in recognizing, solving, and eliminating problems. The scale of the problem can vary. At the nanometre-to-millimetre scale, observations equate to material synthesis; observations on the millimetre-to-meter scale are applied to objects, structures, and mechanisms; and at the level of a kilometre and more, populations and ecosystems are considered.

The third translation level is based on the TRIZ, a system developed for innovative engineering problem-solving. At this level, patterns are more abstract, and problems are defined within a narrow framework. The process consists of three steps: first, it is important to picture the ideal outcome without regard to the technological requirements needed to achieve it; second, express that outcome through the functional requirements necessary to produce it; and third, create a list of all the resources that are currently available.

Biological patterns are a frequent inspiration for the conception of generative systems in architectural design. Generative systems can be ordered (sets, symmetries, trees, tessellations, number sequences, the golden ratio, spirals), disordered (systems based on chaos, randomization, stochastics), and complex. Complex systems that represent a mixture of order and disorder function similarly to biological systems that are the inspiration and basis for their creation.

A complex system is any system that includes a large number of interacting components, agents, or processes. The overall activity of the complex system is non-linear. They are emergent and adaptable. Components, or building blocks of complex systems, can also be complex systems. Usually, complex systems are in the field of thermodynamic gradients and are characterized by energy dissipation. These systems are not in energy equilibrium but can be stable despite that.

The process of development in nature inevitably leads to complexities. Simple building units achieve hierarchical complexity in nature by economic means. For example, DNA coding of all natural forms is achieved using only four nucleotides, which use only twenty triplets to specify amino acids, producing proteins that construct hierarchically structured organisms. Also, the entire spectrum of specific properties of biomaterials is achieved using two polymers (proteins and polysaccharides) and several additives.

The previous supports the thesis that simple rules can generate the properties of emergence and seemingly non-deterministic behaviour. A set of small actions starts the process, and combined with other small actions, it works until a recognizable global pattern of behaviour appears. When a certain critical limit of complexity is reached, organisms gain the ability to self-organize and self-reproduce in countless ways, producing not only equally complex but also more complex entities from themselves.

Bio-inspired computing in design

Computer models are used in pattern formation studies to replicate various patterns. Some computer systems used to model complex systems are L-systems, Fermat Spiral (Vogels Sunflower), Phyllotaxis, Reaction-Diffusion Systems, Diffusion-Limited Aggregation (Drunken Man Algorithm), Evolutionary Computing, Neural Networks, Cellular Automata (CA), Artificial Life, and Swarm Behaviour. Applications of these simulations as generative systems in architectural design result in objects whose forms are not perceived as fixed entities but as reactive structures. These semi-organic objects behave, in a certain way, like living organisms.

The use of computer algorithms in design goes beyond the traditional CAD paradigms. By developing automated systems that anticipate conditions and respond to their requirements, computational algorithms more effectively utilize the potential of computers when generating design solutions on an interactive basis. Automated computational systems are most often used in GD processes. A computer-generated design is based on an algorithmically determined system of rules (program instructions). In this process, the human designer allows a generative computer system to participate in decision-making and the designation of the final designs, maintaining the position of the one who decides the rules.

GD discourse is inspired by instability and complexity, while methods applied in the design process are rooted in modelling the systems' dynamics. Darwin's theory of evolution also suggested a shift away from Newton's paradigm of stability and toward more recent research (e.g., by Ilya Prigogine) on instability, the phenomenon of small changes in initial states that result in significant amplification of the effects of change. On the other hand, the development process inevitably leads to complexities. According to Sodu, GD is a morphogenetic process that employs non-linear algorithms to build an endless number of unique, non-repeatable outcomes that, like in nature, are produced by idea code.[47] An example is generative schemes that use evolutionary algorithms (EA) to create variations.

Unlike the conventional approach in which the relationship between the subject (designer) and the object is most direct, the GD process involves creating a generative system (production means or exploratory construct) that mediates the creation of the object. In such a setting, the essence is mastering the relationship between the design object, rules (specifications), and conditions (constraints).

Usually, the GD process includes the development of a project diagram, a vehicle for creating variations development, and a means for selecting the desired results. Without the intention of linearizing, the process generally has two stages. The first stage includes a definition of the problem, the formulation of a set of rules, conditions, and restrictions relevant to searching for solutions and their transformation into an exploratory system/construct that, in the second stage, is used for design explorations and the production of solutions.

Some computational design tools that simulate the growth and development of architectonic structures and find optimal solutions include *Gener8* – an interactive tool for a surface generation that integrates growth and evolutionary search using EA and L-systems[48] ; *MoSS* (Morphogenetic Surface Structure) – a modelling tool based on the L-system[49] ; *AgencyGP* – a tool for designing non-hierarchical organizations[50] ; programme by Broughton et al. that uses L-systems[51].

Creation of tools for design exploration has been realized using scripting (e.g., *AutoLisp, Rhinoscript, Scriptographer*), classical program editors (e.g., *Processing, Fluxus, openFrameworks, Visual Basic, Phyton, C#*), or graphical program editors (e.g., *Max/Msp, Pure Data, Isidora, Grasshopper, Dynamo*). However, the widely used visual editor for the *Rhinoceros* 3D CAD system, *Grasshopper*, currently stands out due to the widespread usage of parametric tools, graphical programming, and the community formed around it.

Grasshopper offers components for generating tessellations, including 2D and 3D Voronoi diagrams, meshes, and meta-balls. Besides David Rutten's *Galapagos* evolutionary solver[52], a standard component in *Grasshopper*, various plugins that implement bio algorithms are developed, some of which are listed in *Table 1*. Also, the *Anemon* plugin by Mateusz Zwierzyski[53] enables the creation of loops in *Grasshopper* and could be used differently. For example, it could be applied to create irregular growth patterns based on L-systems using recursive functions. Finally, Daniel Piker's *Kangaroo physics*[54] plugin could simulate diverse physical processes.

Integrating parametric and simulation tools into the design process has encouraged new rhetoric, allowing objective external information to determine the values that generate design solutions. Leach[84] believes that using performance as input in an architectural design opens the door to a new paradigm and that this approach to design *challenges the top-down hegemony of the form-making process by replacing it with a bottom-up logic of form-finding*.

Plugin	Author	Description
Rabbit[55]	Morphocode	Simulates diverse biological and physical processes, including L-systems and CA
Phyllomachine[56]	Daniel González	Simulates development processes based on the principle of phyllotaxis
Leaf[57]	Sadiwali	L-system engine
Fractal[58]	ARPM Design and Research	Allows creation of 3 different types of mathematically generated fractals derived from Fermat Spiral and Diffusion Limited Aggregation
Parkeet[59]	Parakeet3d	Generates geometrical and natural patterns/tessellations
Armadillo[60]	Dig.Tools	Generates arrays and tessellations
Starfish[61]	Michael Weizmann	Generates various patterns, mostly 2D tessellations
Bullant[62]	GeometryGym	Generates minimal surfaces, symmetry automation, tessellation (polygon packing), geodesic domes
Voronax_GH[63]	Programming Architecture	Generates Voronax, a structure obtained by relaxation of the Voronoi diagram over a free-form surface
Millipede[64]	Panagiotis Michalatos	Contains components that generate iso-surfaces and minimal surfaces
Minimal Surface Creator[65]	Cerver	Generates minimal surfaces from boundary curves or performs minimal relaxation on a mesh
Dragon-Turtle[66]	Cryptid	Has a turtle drawer, that allows for L-systems to be drawn with a series of predefined character relationships
Kthulhucat[67]	Willtao	CA engine
Goat[68]	Simon	Evolutionary solver
Octopus[69]	Robert Vierlinger	Performs Multi-Objective Evolutionary Optimization introducing Pareto-Principle for Multiple Goals, Backpropagation Neural Nets, and CPPN-HyeprNEAT
Biomorpher[70]	John Harding	Implements interactive EAs, enabling designers to engage with the process of evolutionary development
Oppsum[71]	Opossum Support	Optimization solver with surrogate models
Quelea[72]	Ixfschr	Simulates physical processes – the behaviour of complex systems composed of agents
Boid Library[73]	Jan Pernecky	Swarm behaviour library
Nursery[74]	Gwyllo	Simulates CA and Boid systems and can be used for agent-based modelling
Nuclei[75]	Madalin Gheorghe	Simulates particle behaviour ant their environment
Silvereye[76]	Silvereye	Particle Swarm Optimization (PSO) algorithm, a member of the Swarm Intelligence family of methods
Physarealm[77]	Maajor	Enables agent-based modelling based on Physarum Polycephalum algorithms (similar to ant colony algorithm)
Antoni[78]	Sepehr Beyhaghi	Simulation and optimization of ant colony system
Crispercas9[79]	Sepehr Beyhaghi	Combination of Genetic Algorithm-Ant colony-Particle swarm
Crow[80]	Pennjamin	Artificial Neural Networks
Dodo[81]	Lorenzo Greco	Collection of components for machine learning, optimization, and geometry manipulation, inter alia it includes neural networks and swarm optimization
LinchBox and *LunchBox ML*[82]	Nathan Miller	Generates diverse tessellations and includes machine learning components for regression, clustering, and neural networks
Wasp++[83]	Blake Hageman	Generates aggregations enabling deterministic control of aggregation patterns and hierarchical systems (based on L-Systems) and recursions

TABLE 1: Plugins that simulate biological patterns *Grasshopper*

Emphasizing the benefits of introducing top-down objectivity into the design process, Menges[85] writes that *finding form externalizes the relationship between the process of formation, the driving information, and the resulting form*.

On the other hand, Kilian[86] notices that the expression of design intent is moved from literally giving form to the specification of contextual parameters, initial conditions, and the optimization system itself. It is this definition of the relationships between the input data, the exploratory system, and the evaluation of the final product that quite precisely describes the design process in which the form-finding approach is applied. However, the claims related to the effects of introducing bottom-up objectivity into the design process are exaggerated at the moment and, in some way, camouflage the numerous and complex decisions and the choices that must be made in the design process.

The algorithmic implementation of generative systems has opened a debate about whether the application of this approach can be considered a design process. Krish[87] finds that GD is the conversion of computational energy into creative, exploratory energy that helps human designers explore various design possibilities under the influence of modifiable constraints. GD is an unconventional design approach, given that the digital media used for production have a critical generative capacity and that the forms produced in this way result from dynamic processes that are unique in their response to the set conditions.

The function of generative systems, in a certain way, exceeds the role of tools, especially in the sense that they actively participate in the creation of designs and, in some way, shape the designer's thinking process. In certain aspects, the system assumes the role of a designer, but the initial step of forming a construct (generative system) relies on the designer's abilities – intuition, perception, analogy, and imagination, which traditionally represent the driving force of architectural ideas. Finally, GD should not be understood as an autonomous direction within architecture since it does not address the content but primarily refers to the techniques used in the creative process.

3. DESIGN EXPERIMENTS

The application of bio-inspired GD strategies can be summarized with three key concepts: diagramming, collectivity, and evolution. Furthermore, it is possible to establish a relation between these concepts and concepts of representation, composition, and variation (*Figure 3*), which could be further translated into design aspects.[88] Nevertheless, it should be noted that information is the basis for creating objects and that GD always involves the evolution of the underlying data.

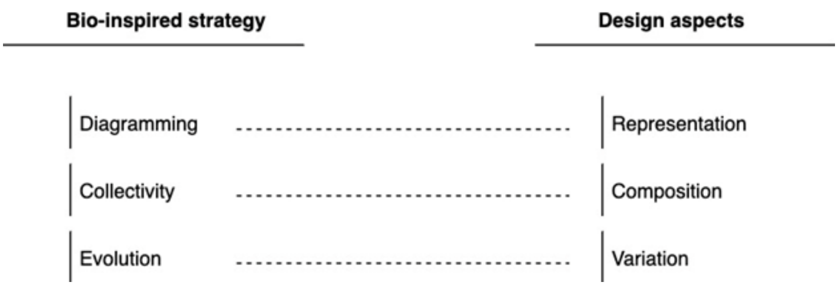


FIGURE 3: Mapping bio-inspired strategies into design aspects

The previous hypothesis was tested through six design experiments using the following bio-inspired patterns: L-Systems, Zoomorphism, Voronoi diagram, Swarming Behaviour, Phyllotaxis, and Cellular Automata (CA).

Method

In this study, research by design methodology was applied. The phases in the process, which are typical for GD discourse, include specification of design intentions, requirements, and constraints, generative system development, design exploration, and design selection. In addition, the pre-GD stage in this research also includes biological phenomenon analysis. The applied design process is based on GD for architecture workflow by Villaggi and Nagy[89] and illustrated in *Figure 4*. However, it must be emphasized that the design process is not linear, and these phases are not implemented sequentially.

The goal of analysing a particular biological phenomenon is to identify design potentials that might be turned into design aspects. The result of this phase is an abstracted pattern that describes the functionality of the analysed biological system and will be further exploited in developing a generative system.

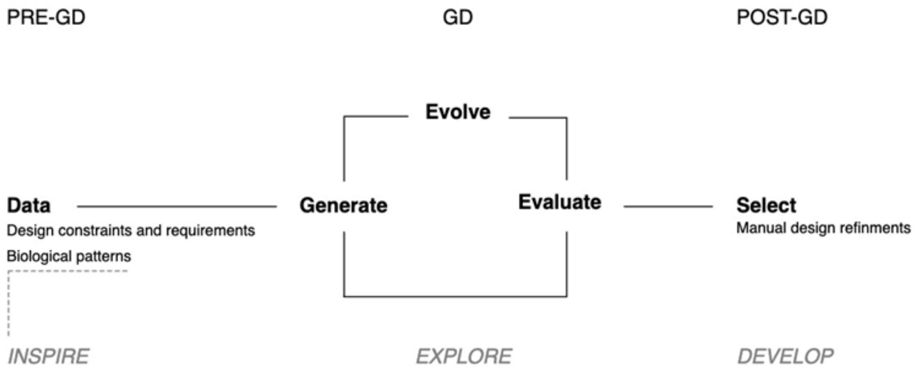


FIGURE 4:
Representation of the GD process based on the workflow proposed by Vilaggi and Nagy[90]

Within the phase of generative system creation, the task was to define the design procedure – an algorithm based on the bio-inspired pattern. The algorithm was then implemented using *Grasshopper*, a visual programming editor. Custom *Grasshopper* definitions, developed for every design situation, drove parametric design explorations within the *Rhinoceros* CAD environment. Parametric modelling facilitated the fast production of design alternatives.

Given that the applied GD approach is based on the interaction of the designer and the computer, a dynamic context for form exploration, interpretation, and decision-making was built using various objective and subjective information. In this setting, the bottom-up design gradually emerged during the iterative process by manipulating parameters, modifying and improving parametric settings, and human-designer interventions. Although computational tools drove the process of design alternatives production, the designer's creativity, intuition, knowledge, and experience controlled the entire process, from problem abstraction, through explorations, to the selection of the design alternative suitable and interesting for further development. On the other hand, using autonomous computational methods in the design process enabled the avoidance of preconceived solutions and psychological inertia due to the designers' finite experience and the emergence of unanticipated design outcomes. Furthermore, applied design methodology offered varying nature-like designs confirming that the forms derived from the process informed by bio-inspired patterns could be functional, structurally rational, and aesthetically pleasing.

4. RESULTS AND DISCUSSIONS

Figure 5 summarizes design experiments performed in order to test the design hypothesis.

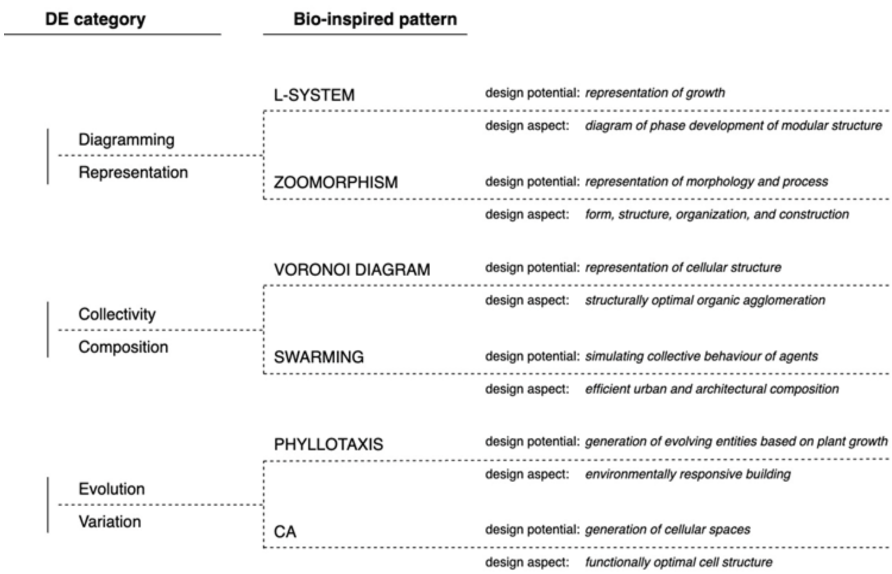


FIGURE 5: Design research overview

Design experiments: Diagramming/Representation

The first example tests the application of diagramming strategy in the design of modular architectonic structures with the prospect of growth and extension through the phase construction. The growth pattern of biological entities was seen as design potential for representing the phase development of an architectonic structure. Therefore, the growth pattern represented by L-systems was used in creating of the design exploration system.

L-systems is a parallel rewriting system developed by biologist Aristid Lindenmayer in 1968 as a result of his studies of the development of simple multicellular organisms, including yeast, filamentous fungi, and the growth pattern of various types of bacteria.[91] The system was later extended to describe higher plants and complex branching structures. L-system represents an example of formal grammar that consists of a set of production rules, an alphabet of symbols that may be used to create strings, a starting "axiom" string from which to build, and a method for turning the generated strings into geometric shapes.[92]

It was created to describe how simple organisms develop formally and to illustrate the neighbourhood relations between plant cells. The L-system applications include modelling plant development's growth processes, describing the plant cells' behaviour, modelling the morphology of various organisms, and generating self-similar fractals.[93] Some non-biological application of L-systems was examined by Goel and Rozenhal[94], while Hansmeyer[95] focuses on architectural application.

In the example, the L-system pattern was used to explore the design of modular architectonic structures' layouts. The capacity of the L-system to describe growth patterns was exploited to represent the principle underlying phase construction of the structure. The algorithm was implemented using Morphocode's plugin *Rabbit* for *Grasshopper*.[96] The developed *Grasshopper* definition included components that facilitate the generation of recursive 2D patterns, which are then interpreted three-dimensionally in terms of the space frame. This definition generates patterns from the input string, a rule definition, and the number of generations. Also, parametric input could be assigned to the angle in composition. Several input strings and rules were used to generate patterns before the decision of the most suitable based on aesthetical and functional qualities (*Figure 6*).

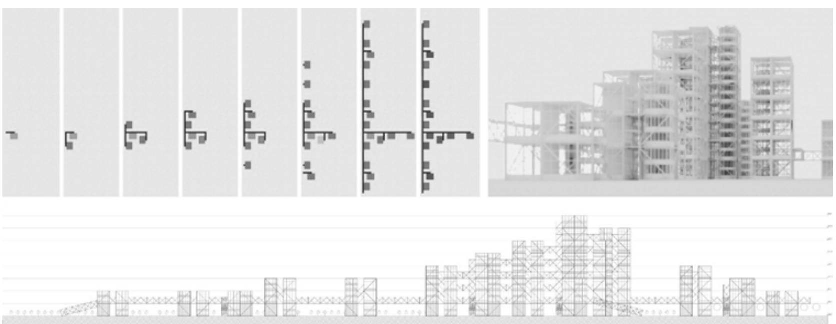


FIGURE 6: Design exploration using L-Systems
(Studio M01–Spatial Structures: Synergetic patterns, class student Karlo Mihalus Dianovski, University of Belgrade – Faculty of Architecture, 2019)

In the following example of the diagramming/representation strategy, zoomorphism was used for formal, structural, functional/organizational design aspects and the construction process. The application of zoomorphism in architecture was discussed in several publications.[97,98,99]

Inspiration for the design was driven by *Arthropoda*, a class of invertebrate animals that have an exoskeleton and a morphologically clear, heteronomous body segmentation. The exoskeleton of these animals serves not only as protection but also as a surface for the attachment of muscles. In addition, this waterproof membrane protects against desiccation and provides a sense of interaction with the environment. The architectural intention was to transform qualities of the exoskeleton, segmentation, and environmental responsiveness to design aspects of a research center building. These qualities were architecturally interpreted by forming a building envelope made of rigid spatial structure (exoskeleton) and environmentally responsive soft fiber-reinforced membrane. The organic aesthetic of the structure was additionally achieved by segmentation (*Figure 7*).

The design was generated by a definition that uses components of several *Grasshopper* plugins. Applied plugins include *Exoskeleton*,[100] a plugin that transforms a network of connected lines into wireframe mesh by creating rounded nodes using the principle of the convex hull of a set of X points in Euclidian space. For finding convex hull Gift wrapping/the Jarvis March algorithm was applied. Also, a component that implements the Catmull-Clark algorithm, *WbCatmullClark* of the mashing plugin *Weaverbird*,[101] was used to refine the edges and curves of the generated mesh. Finally, due to the functional/organizational requirements, the building was divided into three segments using the custom Grasshopper C# component.

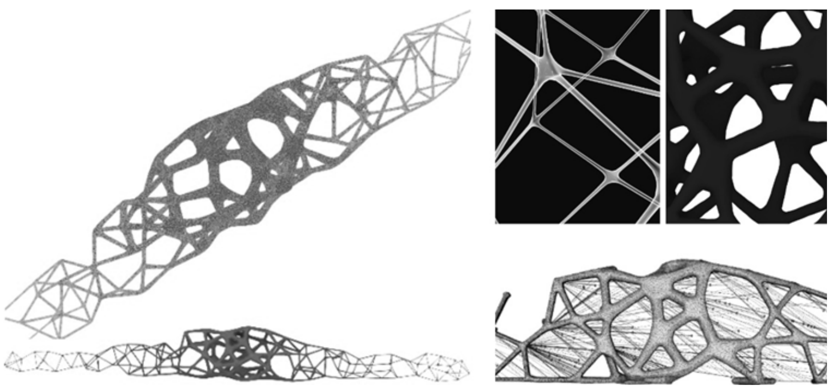


FIGURE 7: Design exploration using zoomorphism
(Studio M01–Spatial Structures: Synergetic patterns, class student Isidora Zimović, University of Belgrade – Faculty of Architecture, 2020)

For generating fiber patterns in the reinforced membrane Agent component of the *Quelea*[102] plugin for agent-based modelling was applied. This part of the code simulates a specific construction process – the waving of threads by a swarm of small robots that can move on both horizontal and vertical surfaces. Similarly to the spider's web weaving process, these robots would densely weave and intertwine the layers of fibers and harden them with special glues. Previous was realized by giving small robots, represented by "agents" in a simulation, a certain intensity of force and behavior patterns, which then form threads, i.e., carbon fibers on the membrane (*Figure 7*).

Design experiments: Collectivity/Composition

The application of collectivity/composition was tested by designing an organic architectonic agglomeration composed of cells representing vertical urban gardens. The design ambition was to create a spatial structure that would retain the optimality and organicity of biological structures such as cells and bone microstructure. The Voronoi diagram was applied to model the nature-like structure. This geometric tool facilitates understanding the physical constraints that drive the organization of biological tissues.

Voronoi tessellation is a partition of a geometric entity into regions close to each given set of objects. In the simplest case, these objects are just a finite number of points in the plane/body and are called seeds/sites/generators. Each seed has a corresponding region, called the Voronoi cell, consisting of all points of the plane/body closer to that seed than any other.[103] The Voronoi diagram has application in crystallography, a science of determining the arrangement of atoms in crystalline solids. The pattern is also differently applied in architectural design.[104,105,106]

The algorithm that enables the partition of the design domain (the cubic volume) into cells (polyhedrons) around a randomly generated set of points (Voronoi seeds) was implemented using a standard *Grasshopper* component for generating Voronoi tessellation in 3D. However, in order to satisfy the building's functional requirements, an additional part of the code for generating ortho Voronoi cells was written. Numerous aggregations produced by the code were first narrowed by using subjective aesthetic criteria, and then on selected designs, structural analysis was performed using Finite Element Analysis (FEA) plugin *Millipede*.[107] This enabled informing the decision-making process with the structural performance of aggregations. The outcome is a composition that resulted from gradual adjustments based on functional, aesthetical, and structural requirements (*Figure 8*).

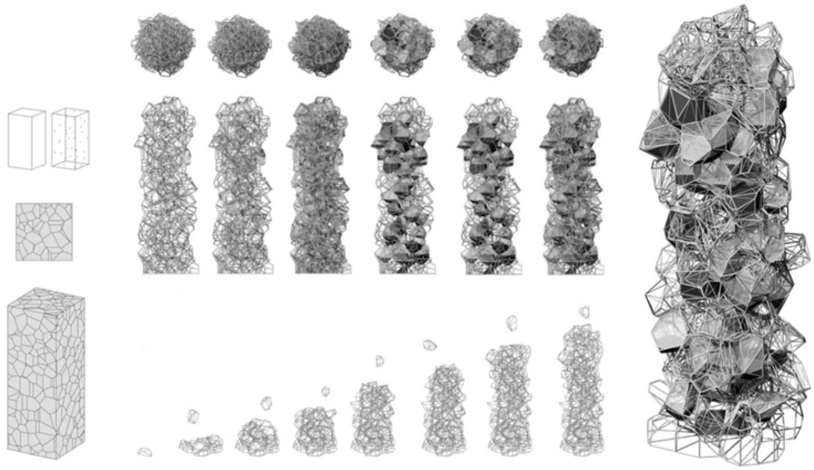
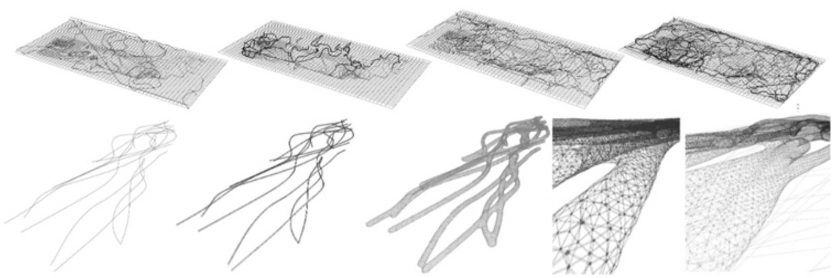


FIGURE 8: Design exploration using a 3D orthogonal Voronoi diagram
(Studio M01–Spatial Structures: Synergetic patterns, class student Irina Žerađanin, University of Belgrade – Faculty of Architecture, 2019)

FIGURE 9: Design exploration using a swarming pattern
(Studio M01–Spatial Structures: Synergetic patterns, class student Isidora Kojović, University of Belgrade – Faculty of Architecture, 2019)



In another example, the application of collectivity–composition was tested using the swarming, collective behaviour of diverse entities, particularly animals, of similar sizes, which aggregate together to generate the urbanistic and architectural design. From a more abstract point of view, swarm behaviour is the collective motion of many self-propelled entities. From the perspective of the mathematical modeller, it is an emergent behaviour arising from simple rules that individuals follow and do not involve any central coordination. Active matter physicists also study swarm behaviour as a phenomenon that is not in thermodynamic equilibrium and, as such, requires the development of tools beyond those available from the statistical physics of systems in thermodynamic equilibrium.

Agent-based modelling is a rule-based computational modelling methodology that focuses on rules and interactions among the individual components or the agents of the system. This modelling method aims to generate a population of the system components and simulate their interactions in a virtual world. Agent-based models start with rules for behaviour and seek to reconstruct the observed patterns of behaviour through the computational instantiation of those behavioural rules. The application of agent-based modelling in architectural design was the subject of various studies.[108,109,110,111]

To conduct design research computational algorithm using *Quelea*,[112] a plugin that simulates the behaviour of complex systems was developed. The program simulates simple agents (geometrically represented by points) that are allowed to move according to a set of basic rules. Trajectories describing particle motions in the post-GD phase were translated into architectonic structures (*Figure 9*). Agent-based design approach facilitated to embed in the architecture of several characteristics of biological agent models, such as modularity, emergence, abstraction, and stochasticity. The rules of its agents define the modular behaviour of an agent-based model. Existing agent rules can be modified, or new agents can be added without modifying the entire model. Emergent properties are exhibited through individual agents that interact locally with rules of behaviour. Agent-based models result in a synergy that leads to a higher-level whole with much more complex behaviour than each agent. Abstraction is exhibited by excluding non-essential details and simplification, while stochasticity is manifested through the system's behaviour that appears to be random.

Design experiments: Evolution/Variation

The evolution/variation was explored by designing a vertical garden for food growth in greenfield urban areas. The design intention was to create a tower that would embody plant growth and enable optimal sunlight. The phyllotaxis phenomenon was appropriated in this example to create a GD explorer.

From the physical perspective, spirals are the lowest-energy configuration that emerges through the self-organization process in dynamic systems. From a chemical perspective, a reaction-diffusion process that includes both activation and inhibition can produce a spiral. From a biological perspective, arranging leaves as far apart as possible in any given space is favoured by natural selection as it maximises access to resources, especially sunlight, for photosynthesis. The application of phyllotaxis pattern in architecture was the subject of several studies.[113,114,115,116]

Phyllotaxis, appropriated from botany, is related to the spiral arrangement of leaves on a plant stem. Botanists define the phyllotactic range as part of the circle through which a new leaf rotates from an older one. In a repeating spiral, the rotational angle from the leaf to the leaf can be represented by a fraction of a full rotation around the steam. The divergence angle is set based on two assumptions. First, the plants have an infinite number of leaves; second, maximum sun exposure is the only factor determining the leaf's position. Although this is not entirely true, the standard angle in nature is 137.5 degrees, or 1/phi, approximately 0.618. The numerator and denominator usually consist of a Fibonacci number and its second successor.[117] Also, a growth spiral can be viewed as a special instance of self-similarity from the perspective of the contemporary fractal construct.

For simulating phyllotaxis, the plugin *PhylloMachine*[118] was used. *Grasshopper* definition produced mesh with phyllotaxis proportions that have a topology described by two Fibonacci numbers. A simple number sequence describes mesh topology (indices of vertices of faces, parastichies spirals, cycles, and topological neighbours) without geometric calculation. This parametric definition aided design exploration and production of a range of formal solutions by varying parameters of the mesh geometry, including height, radius, division, smoothness, angle, and depth. The result of design exploration is a variety of cellular meshes in architectural terms interpreted as the building's exoskeleton (*Figure 10*).

Besides aesthetics, building performance related to the insolation necessary for plant growth was used in the process of design selection. Insolation as objective criteria, informed decision-making process ensuring the functionality of the design. This approach facilitated the design to evolve towards a solution that has better environmental responsiveness. The environmental analysis was performed using the plugin *Ladybug*.[119] The outcome of this design experiment is a structure that was a result of variation and gradual adjustments based on performance and aesthetical demands proposal.

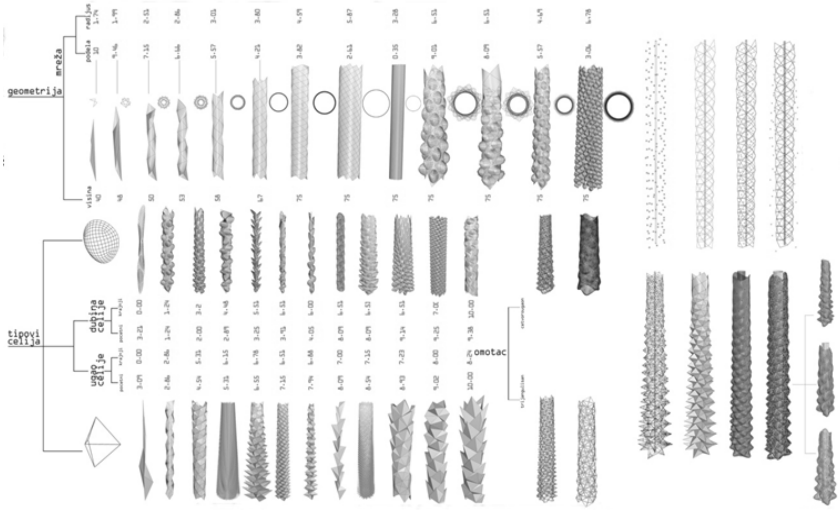


FIGURE 10: Design exploration using phyllotaxis pattern
(Studio M01–Spatial Structures: Synergetic patterns, class student Teodora Marić, University of Belgrade – Faculty of Architecture, 2019)

In the last example, evolution/variation was also explored by designing vertical modular cell structures for food production. The phenomenon that inspired design was nature's morphogenetic process of pattern formation. Pattern formation in developmental biology is a process through which essentially similar cells in a developing tissue in an embryo take on complex forms and functions. In nature, pattern formation is genetically determined, and each cell in a field senses and reacts to its position along a morphogen gradient during pattern development. Short-distance cell-to-cell communication via cell signalling is then used to refine the initial pattern. To simulate this process, CA as a conceptual form generator was applied. This system was used to facilitate the exploration of volumetric spatial configuration features and to indicate levels of natural lightning using cell states.

Originally developed in the 1940s by Stanislaw Ulam and John von Neumann, CA is a tessellation automata. A CA consists of a regular finite-dimensional grid of cells, each of a finite number of states, such as on and off. A set of cells called neighbourhood is defined relative to the specified cell for each cell. An initial state (time t=0) is selected by assigning a state for each cell. Then, a new generation is created (advancing t by 1) according to some fixed rule (generally, a mathematical function) that determines the new state of each cell in terms of the current state of the cell and the state in its neighbourhood.

Typically, the rule for updating the state of cells is the same for each cell and does not change over time, and is applied to the whole grid simultaneously. However, exceptions are known, such as the stochastic cellular and asynchronous cellular automata. It was not until the 1970s and Conway's Game of Life, a two-dimensional CA, that interest in the subject expanded beyond academia. Then, in the 1980s, Stephen Wolfram engaged in a systematic study on one-dimensional elementary, CA. His research assisted Matthew Cook in showing that one of these rules is Turing-complete. The application of CA in architectural design was presented in several studies.[120,121,122,123]

In order to use CA for open-ended design exploration, a tool that generates 3D compositions was developed using Morphocode's plugin *Rabbit*.[124] An elemental unit/cell architecturally is interpreted as a functional unit – a room/garden. The generative tool enabled to exploration of variations of possible solutions resulting from the tempo-spatial development of initial cell configuration over time (*Figure 11*).

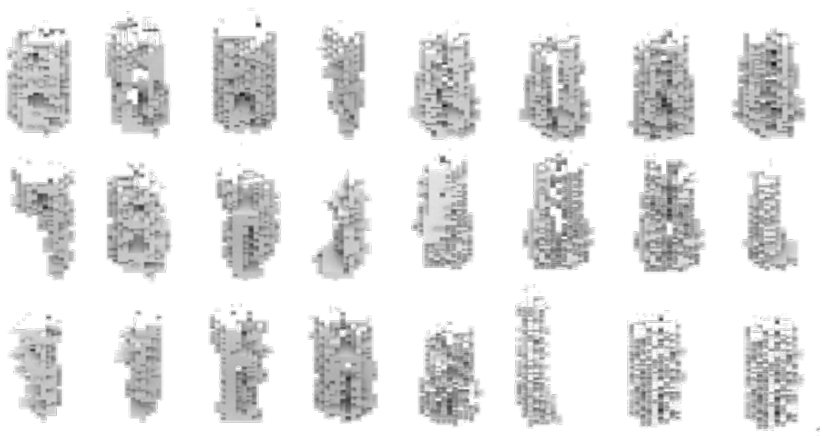


FIGURE 11: Design exploration using CA
(Studio M01–Spatial Structures: Synergetic patterns, class student Katarina Petrović, University of Belgrade – Faculty of Architecture, 2019)

During the generative system creation, in all presented examples, much work was dedicated to analysing and describing the underlying biological phenomenon. Applied CAD system enabled constraint-based modelling in which every element may be connected using parameters, relationships, and references. Parametrization facilitated fast and easy manipulation and changes.

Also, the choice of adequate design methods and tools that will not disturb the nature of the creative process was important—selecting program modules, creating costume codes, and extending tools to fit architectural requirements and provide a design exploration environment that is flexible and enables fast production of alternative solutions characteristic for the initial phase of the design process. Additionally, design generation and performance analysis within a parametric CAD environment have proven to be effective in facilitating fast and easy changes, control of the from-finding of complex geometry, the emergence of various designs, and evolution towards effective solutions in the iterative design process.

On the other hand, GD activities needed a precise definition of the problem to solve to accurately understand the relation, flow, and performances of obtained designs. The lack of predetermined shapes prevents designers from striving for predefined solutions and limitations they could introduce in the exploration process. Instead, interactive manipulation of parameters produced diverse shapes, enabling relatively fast exploration. Complex designs created by bio-inspired patterns are valued for their spatial features in architectural design and for the outcomes' frequent unpredictability or unexpectedness, allowing designers to expand their imagination boundaries. In this set, the design results from the adequate combination of parameters, and the task of the designer, positioned between soft control and management, is to define sets of parametric relations. Results are figurations that closely build different relations within its environment.

5. CONCLUSION

The study shows how bio-inspired patterns might be used as a design driver for the conceptual design of architectural structures. Computational technologies enable the implementation of diverse, complex systems based on biological phenomena that can direct the GD process toward producing exciting proposals. Furthermore, bio-inspired patterns should not only be seen as a method to intensify the form of architectural structures but also as a method to improve performance.

Design situations presented in this paper test distinctive principles of applying bio-inspired strategies – mapping/representation, collectiveness/composition, and evolution/variation. The design process in all cases involved exploration of the biological phenomenon, formulation of design inputs, employment of a design exploration system, and evaluation of the end products.

In all cases, design is created through designer–machine interaction, which drives digital parametric modelling. Design explorations and improvements are based on simulation feedback and the designer's explicit decisions and modifications grounded in experience, perception, or intuition.

Like in all generative processes, the final form was not predetermined, but the design evolved during the exploration phase under the control of an algorithm with a certain degree of autonomy. Diverse shapes could be created by interactive parameter manipulation, allowing for relatively fast exploration. In the applied generative framework, computational tools are restricted to specific tasks. At the same time, designers consider different design requirements and choose a design (out of the range of solutions) that best fits various aspects and is interesting for further development.

Further research could include explorations by applying other bio-inspired patterns and possibilities of further design automation. For example, optimization algorithms could be introduced to automate the search process. Finally, bio-inspired design is an interdisciplinary field, and the development of co-design and co-fabrication strategies based on the collaboration of diverse disciplines and the inclusion of diverse knowledge and expertise in the design and construction processes is another research direction.

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ENSURING SUSTAINABLE URBAN PLANNING WITH THE HELP OF PARAMETRIC DESIGN TOOLS

ABSTRACT

This research aims to explore and answer the question of what sustainable urban patterns are and how a computer can help urbanists generate a range of urban patterns that can be evaluated for sustainability. It does that in the case study area in Belgrade by employing the concepts of transect urbanism and parametric design. First, the research defines the concept of sustainable density and links it to the concept of urban transects to identify sustainable urban patterns. These are later used to generate evaluation-ready results through an evolutionary algorithm. The goal is to sustainably connect the areas of Zemun with the area of New Belgrade, which have different densities and morphological patterns. The generated results were evaluated using both quantitative criteria (Floor area ratio) and qualitative criteria (Granularity, Building volumes and Urban structure) to identify the most suitable computer-generated results. The two assessments used in conjunction allowed for a more rounded evaluation of the possible outcomes and a better understanding of possible scenarios and strategies for development.

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KEY WORDS

SUSTAINABLE DENSITY
SUSTAINABLE URBAN PATTERNS
BUILDING BLOCKS
PARAMETRIC DESIGN
EVOLUTIONARY GENERATION
URBAN PLANNING
URBAN GROWTH

1. INTRODUCTION

Addressing the intricate nature of sustainable urban growth (SUG) poses a significant challenge in urban planning, even though when searching through 'sustainable' literature, Carmona (2015) states that it is very hard to find clearly stated objectives translated into clear images and examples of town form, existing or proposed. However, urban density, amongst other things, plays a crucial role in ensuring it, particularly through the densification of built-up areas while protecting agricultural lands and forests. Neither too sparse nor too dense urban patterns ensure SUG. The former takes up too many resources, and the distances become longer, making people reliant on personal transport. The latter creates unliveable spaces where the diversity and the characteristics of the urban area are lost. Silva and Clarke (2022) describe the damaging effects the urban sprawl has on the environment associated with the increase in the use of private motorised transport, furthermore, low-density development occupies proportionally larger areas of land. Angel et al. (2021) emphasise the goal of densifying urban areas to mitigate the environmental impact. Cuthbert (2006) says that the most suitable term for this is 'postmodernism' or 'sustainable development'. That is why it is crucial to determine a sustainable range of urban density for SUG. This not only preserves vital natural resources but also enhances the efficiency of spatial movement within urban environments. Recognising the varied nature of urban density, Angel et al. (2021) caution against relying solely on a single criterion. Instead, a comprehensive approach to SUG integrates qualitative and quantitative data. This nuanced perspective illuminates variations in structural or morphological density (measurable density) guiding the densification process by revealing where density is highest or lowest according to specific criteria. As per Maretto (2014), urban morphology can pose as a valuable tool that connects the technological aspects of sustainable strategies with different socio-economic aspects of urban design.

Determining an adequate range of urban density patterns for SUG can be achieved in many ways. This research adopts a concept of transect zones as a systemic structured approach to defining the connection between density and sustainable urban patterns (SUP). Similar to the varied nature of urban density, the transect method defines transect types based on the amount of open space regarding the built-up space creating a progression from less built-up transect zones (T-1) to medium built-up transect zones (T-4 and T-5) to very dense built-up transect zones (T-6 and T-7). A wide selection of transect types ensures their varied and applied use in different scenarios for different goals. The transect zones T-1 to T-3 are very sparse and represent rural to suburban areas and their morphological patterns. According to Silva and Clarke (2002), these fall within the urban patterns that are very demanding in terms of infrastructure and space for expansion. On the other hand, the T-6 and T-7 transect zones are very dense and represent too dense urban patterns that based on Donnely et al. [12] are on the dangerous edge of urbanism in terms of suitable living environments. This leaves the transect zones T-4 and T-5 where the variety of building types and morphological patterns is the highest and the buildings start clearly defining the open space as per Duany and Falk (2020). They are favourable zones for pedestrians because the movement of pedestrians is optimised for everyday needs. Based on the resource inefficiency of the transect zones T-1, T-2 and T-3 and the unliveable character of the transect zones T-6 and T-7, the T-4 and T-5 transect zones are the ones that represent the best urban patterns for this research as they enable walkability and high densities that make the public functions and infrastructure economically efficient. Ewing and Clemente (2013) also found that the quality of urban design was higher in the higher-density neighbourhoods and neighbourhoods that were primarily built in the 1960s and that the three density measures – FAR, population density and block FAR – are directly and significantly related to pedestrian counts.

Consequently, these criteria identify them as the most sustainable. A parametric approach was employed to find a set of possible permutations of how different transect zones can be combined into an urban pattern. In this research, an evolutionary approach (evolutionary algorithm) was used whereby different versions of urban patterns are generated by the computer. Each version is evaluated against a fit function (set goal) and recomputed again to advance the result. Each generation of results is, therefore, closer to the set target.

Parametric design as Çalışkan (2017) defines it is the study of compositional systems by defining the relationships between the dimensions of the form - components dependent upon various parameters.

Although the parametric variation affords a vast solution space with numerous deviations retaining the notion of surprise, the designer has control over the global behaviour of the system by alternating the morphological parameters (i.e. density, intensity, and closeness) and reflecting upon the visually represented spatial composition and pattern. According to Sakamoto and Ferre (2008), designing a complex pattern using traditional methods like drawing can be difficult. Algorithm-based design methods are better suited for creating patterns with numerous elements and harmonious variations in shape. Density can be determined both quantitatively and qualitatively, meaning that measurable data, such as Floor Area Ratio (FAR) and Floor Space Index (FSI) can serve as a quantitative dataset and morphological or urban patterns can serve as a qualitative dataset because of its descriptive, interpretation-based nature. As per Makower (2014) the research aimed to achieve SUG by achieving SUPs and scale diversity, as is seen in 'slow urbanism', where urban blocks or in this case building blocks evolve organically over time while being constrained by a fast-track programme.

Several studies have explored the potential of parametric design tools for sustainable urban planning. As highlighted by Taleb and Musleh (2015), later Zhang and Liu (2019), these tools enable the optimization of urban design parameters to maximize sustainability, with Taleb and Musleh focusing specifically on hot climates and Zhang and Liu on dense urban environments. Additionally, Pitts (2012) and Steinø (2019) emphasize the ability of parametric design to address both social and environmental criteria simultaneously. Yang (2023) even focuses on the optimisation of the urban block design through evolutionary computation. Much research has been done in the field of densifying existing built-up areas, however, they do not include generating a range of SUPs using evolutionary algorithms in an empty urban area.

In this context, the research paper on the case of New Belgrade (NBG) aims to explore and answer two questions. Firstly, what SUPs are and secondly, how can a computer help urbanists generate a range of urban patterns that can be evaluated in terms of sustainability?

2. MATERIALS AND METHODS

2.1. Case study area

As of the latest consensus, conducted in 2022 by the Statistical Office of the Republic of Serbia, 1.681.405 residents live in the Belgrade (main capital of Serbia) metropolitan area, with Zemun (ZMN) taking up 10,6% or 177.908 residents, while New Belgrade (NBG) takes up 12,5% or 209.763 residents. Since 2002, the population of the Belgrade metropolitan area has increased by 6.7%. As per the General Urban Plan, population increase in the forthcoming period is not predicted and the city should not be expanded, the emphasis on new development should be within the city itself. The plan also states that major changes may be expected within the single-family housing sector, which indicates densification of some sort. Belgrade's municipalities are very interesting and varied in terms of their structures. Many of them are known for their modernist layout and design, while others are known for their historical importance.

The case study area (*Figure 1*) is located between the two Belgrade municipalities of NBG to the east and southeast and ZMN to the north. The area itself is called Rasadnik Bežanijska kosa. The two municipalities are complete opposites regarding their urban structure (*Figure 2*). NBG is known for its modernist design and socialist modernist architecture. It was planned to follow the principles of the modernist functionalist movement based on Corbusier's Ville Radieuse. The area is divided into building blocks, which were built up with monumental residential and public buildings. Despite criticism of the modernist neighbourhoods, there are certain aspects that in contemporary neo-liberal conditions represent positive references such as putting a lot of thought and care into providing the residents with public infrastructure such as schools, kindergartens, shops, good public transport and access to quality open and green spaces. Dividing the neighbourhood into blocks and using massive apartment complexes defines the space and gives it unique properties such as a mix of varied urban patterns with different densities. Contrary to the modernist grid-based structure of the neighbourhood of NBG is an organically grown neighbourhood of ZMN, where the main building typology used is a single-family house with a maximum of two floors, a ground floor and an attic. The need of the owners for a big yard when building a house led to building blocks being formed, where the houses are positioned on the perimeter of the block forming a circumferential pattern of buildings with their yards and open spaces being positioned inside the block, resembling residential buildings with inner courtyards.

The case study area lies between NBG and ZMN, allowing consideration of mixing two very different typological structures to create a sustainable density (SD) of the area and a transition in the urban patterns between the two seemingly very different areas.

FIGURE 1: Case study area located between New Belgrade (east) and Zemun (North)

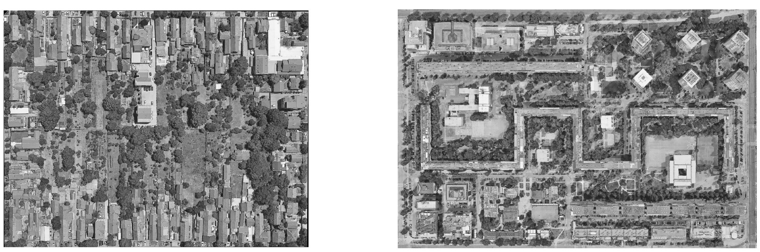


FIGURE 2: Example of a typical Zemun (left) and New Belgrade (right) building block

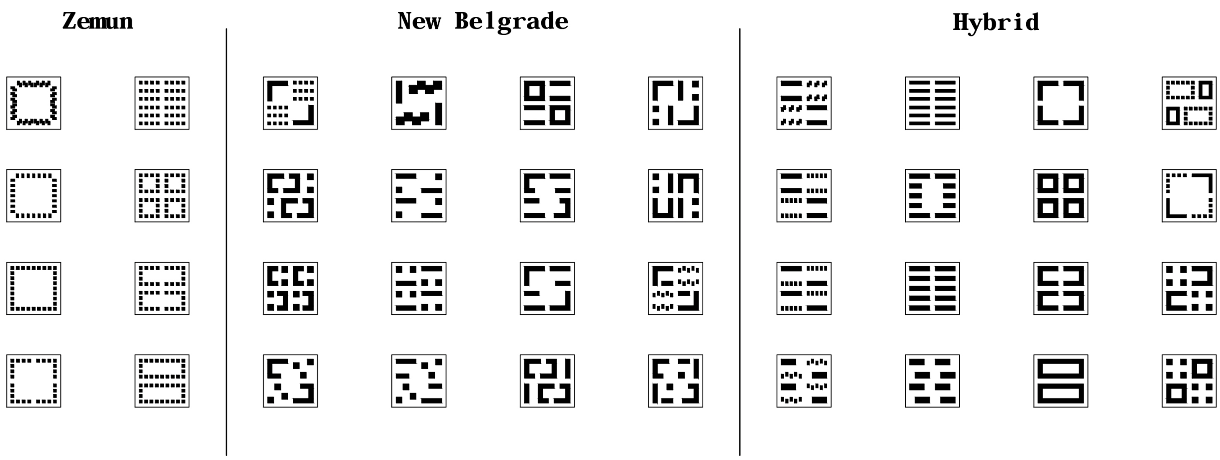
2.2. Method: synoptic survey

To link the conceptual framework of transects to the particular case of NBG, a 'synoptic survey' of the existing urban fabric and its classification was carried out. Sorlien et al. describe the analytical process as 'the synoptic survey'. They describe the synoptic survey as documenting the existing area via different mediums such as photography, drawing and measuring. For these things, the area has to be sectioned into urban dissects of the same size so that an accurate analysis can be done. In this research paper, the building blocks of NBG and ZMN served as urban dissects. A set of criteria had to be established for selecting and analysing them, as Angel et al. stated, for a holistic approach, multiple criteria need to be used since one criterion approach could lead to results that in this research do not include sustainable densification and diverse urban tissue. The research focused on residential building blocks with the same shape and size. Commercial and industrial building blocks were omitted.

A graph was created to map the building blocks for clarity and identification of spatial patterns (*Figure 3*). Their FAR values were mapped on the X-axis, while their morphological patterns were mapped on the Y-axis. The research focused on the three main groups of morphological patterns, point-, line- and grid-based morphology or a mix of these. The graph helped determine into which transect zone the existing building blocks fit or correspond to. During this mapping, it was determined that most of these building blocks fall into the range of FAR values between 0.11 and 0.37. Therefore, the existing building blocks can be classified as the T-4 and the T-5 transect zones, with some building blocks that could be classified as the T-6 or the T-7. The latter were then discarded when determining a guideline for designing the meta-building blocks for the insertion into the area. The morphological patterns that emerged on the graph were also crucial for the determination of the guideline. The ZMN building blocks could be divided into two distinct groups. Both groups had a point morphological pattern with differences in their structure. The first group that was suitable for the T-4 transect zone had a circumferential building structure while the second group did not, making it denser and consequently more suitable for the T-5 transect zone. However, the NBG building blocks formed no such groups and were mainly equally distributed along the FAR values. The graph did show that there were no strictly residential building blocks with just the point, line or grid morphological patterns, which means they had a mix of point and line, a mix of point and grid, a mix of line and grid and a mix of all three morphological patterns. All of this meant that the meta-building blocks were designed based on their morphological patterns and their structures.

UPPER FIGURE
FIGURE 3: Graph mapping the building blocks, NBG at the top and ZMN at the bottom.

LOWER FIGURE
FIGURE 4: Meta-building blocks



Three groups of meta-building blocks were created to ensure a quality transition between the density of NBG and ZMN and their morphological patterns (*Figure 4*). The first group was modelled based on the building blocks of ZMN, the second was modelled based on the building blocks of NBG and the third group was created as a set of hybrid building blocks mixing the ZMN and NBG characteristics. The hybrid building blocks took the morphology of either ZMN or NBG and started forming structural patterns that correspond to the opposite part. For example, one hybrid building block could take the morphology of a building block in NBG and the circumferential structure of a building block in ZMN. These three groups provided a qualitative sample pool for the evolutionary generation of new FAR values for the case study area.

2.3. Method: evolutionary generation

Given that the meta-building blocks were designed manually and represented qualitative data, the parametric design was chosen to help quickly create multiple evaluation-ready solutions via evolutionary generation of the FAR values in the case study area. Global system control and adaptability to criteria are also the two reasons why the parametric design approach was chosen. The software used in this research were Rhinoceros 3D, Grasshopper and Galapagos. Grasshopper is a visual programming interface for Rhinoceros 3D, which is a modelling software. It enables its users to create and manage complex parametric models via visually connected components.

Galapagos is a plugin for Grasshopper that helps with optimisation and evolutionary generation, allowing users to find the best possible solutions for set problems. Sakamoto and Ferre (2008) claim that the algorithmic control of pattern-oriented compositional systems, with harmonious morphological variations, surpasses the capabilities of traditional analogue methods such as drawing.

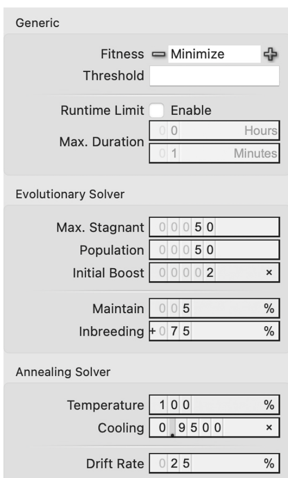


FIGURE 5:
Galapagos plug-in

Bentley and Corne (2002) investigated creative evolutionary systems and constructed a framework that served as a guideline for the evolutionary algorithm method. In the process of embryogeny, where the genotypes are mapped to phenotypes, the genotype serves as the instruction for the growth and development of the phenotype. Embryogenies offer a reduced search space, better enumeration, and the evolution of complex solutions and adaptability.

The embryogeny in this research was performed by the Galapagos plugin, which, through element iteration, determines the most optimal combination in regards to the predetermined target value. The optimisation was set by different parameters such as population size, max stagnancy, initial boost and inbreeding. The fitness parameter was set to minimise to get the result as close as possible to the fitness function (or the target value) (*Figure 5*). In short, the algorithm is used to generate new solutions by modifying genotypes (a set of initial patterns of area) comprised of the gene pool (a set of building block types - components). The genotype is decoded and, using components, the phenotype is constructed and evaluated against the fitness function (a final goal).

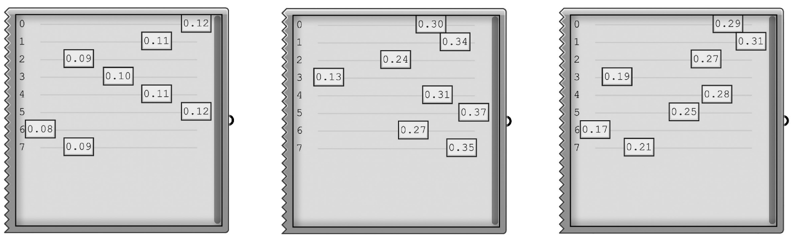


FIGURE 6: Gene pools for Zemun, hybrid and New Belgrade building blocks

The genotypes, represented by the FAR values, constructed three gene pools for each of the three groups of meta-building blocks (*Figure 6*). Each gene pool had a different range of FAR values depending on the group to which it belonged. Three different ranges ensured the separation of meta-building blocks of NBG and ZMN while simultaneously allowing the range of FAR values of the hybrid meta-building blocks to overlap with the other two gene pools, ensuring SD and a better transition between different densities of NBG and ZMN.

In an analogue manner, three fitness functions had to be determined since there were three different gene pools. The simplest fitness functions for these three different groups were the average FAR values that it needed to achieve. The fitness function for the gene pools of meta-building blocks of NBG and ZMN was determined by the average FAR of the existing building blocks, while the fitness function for the gene pool of hybrid meta-building blocks was set between the two to achieve SD and a quality transition between different densities of NBG and ZMN.

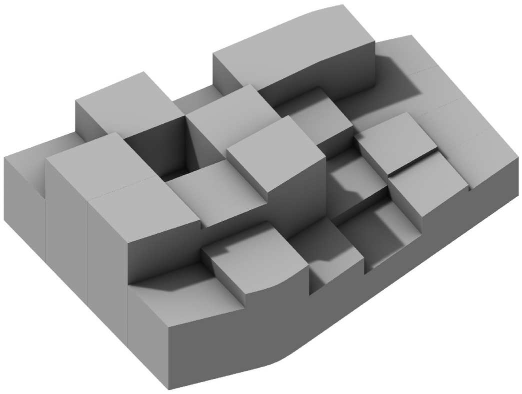


FIGURE 7: Generated FAR values extruded along the Z-axis

The ZMN value of the building block represents its FAR value and was generated by the evolutionary algorithm. That creates a visual representation of the different densities within the area before inserting meta-building blocks (*Figure 7*). Six variations were then generated that were ready for evaluation in terms of SD and the transition in different densities and morphological patterns.

3. RESULTS

3.1. Determining the criteria

Rule-based evolutionary generation of FAR values with a set target value ensured that SD was achieved in every generated solution and only the morphological pattern was left to evaluate. The morphological pattern was evaluated based on three criteria, namely (1) Granularity, (2) Building volumes and (3) Urban Structure. Each criterion had three values (Table 1); '+' (the pattern meets the criteria), 'o' (the pattern is partially meeting the criteria) and '-' (the pattern does not meet the criteria).

In the Granularity criterion, a meaningful progression of built-up tissue from the ZMN grain size to the NBG grain size was assessed. The criterion was met if a transition of morphological pattern progressed without any sudden or big changes or gaps between the neighbouring building blocks so that the density growth is linear. This is accomplished by ensuring median density values in intermediate blocks.

In the Building volumes criterion, a progression of volume (size and height of the individual buildings) from ZMN to NBG volumes was assessed. The criterion was similarly met when the transition of the morphological pattern progressed without any big changes in building volumes between the neighbouring building blocks.

Finally, the Structure criterion assessed the meaningful evolution of the urban structure of building blocks from ZMN to NBG. The criterion was met if a transition in morphological pattern without any nonsensical or sudden changes in urban structures was observed.

Description of evaluation	**+** **the result meets the criteria**	**○** **the result partially meets the criteria**	**-** **the result does not meet the criteria**
Granularity	The transition from ZMN to the NBG escalates from the finer to the coarser built-up tissue. There are no large jumps between adjacent building blocks with finer built-up tissue and adjacent building blocks with coarser built-up tissue.	The transition from ZMN to NBG partially escalates from the finer to the coarser built-up tissue. Part of the area shows appropriate, small jumps between the neighbouring building blocks, from finer to coarser built-up fabric. Part of the area shows big, inappropriate jumps between adjacent building blocks from finer to coarser built-up tissue.	The transition from ZMN to the NBG does not escalate from the finer to the coarser built-up tissue. Neighbouring building blocks show large jumps between adjacent building blocks with finer tissue and adjacent building blocks with coarser tissue.
Building volumes	The transition from ZMN to NBG escalates from low-volume building blocks to high-volume building blocks. There are no large jumps in volume between adjacent building blocks.	The transition from ZMN to NBG partially escalates from smaller to larger building volumes. Part of the area shows appropriate, small jumps between adjacent building blocks, from smaller to larger volumes of built-up tissue. Part of the area shows large, inappropriate jumps between adjacent building blocks from smaller to larger volumes of built-up tissue.	The transition from ZMN to NBG does not escalate from low-volume building blocks to high-volume building blocks. There are large jumps in volume sizes between adjacent building blocks.
Urban structure	The transition between adjacent building blocks is compositionally consistent - e.g. circumferential building blocks continue into circumferential building blocks or grids, linear into linear or grids but not circumferential into linear - buildings on the edge of adjacent building blocks do not form strong boundaries, perpendiculars, etc.	The transition between adjacent building blocks is compositionally partially consistent - part of the area is covered by building blocks where buildings on the edge of adjacent building blocks do not form strong boundaries, perpendiculars, etc. Part of the area is covered by building blocks where buildings on the edge of adjacent building blocks form strong boundaries, perpendiculars, etc.	The transition between adjacent building blocks is not compositionally consistent - e.g. perimeter to linear - buildings on the edge of adjacent building blocks form strong boundaries, perpendiculars, etc.

TABLE 1: A detailed description of the value definitions for the evaluation criteria.

3.2. Result evaluation (Table 2)

Evaluation criteria	Result A	Result B	Result C	Result D	Result E	Result F
Granularity	○	-	○	+	+	○
Building volumes	○	-	○	+	+	○
Urban structure	-	-	○	+	○	-

TABLE 2: Evaluation of generated results.

The first generated result, also result A (*Figure 8*), shows a transition in building blocks from ZMN to NBG that partially achieves two out of the three criteria and does not achieve the third criterion. A part of the area displays suitable and gradual transitions between the neighbouring building blocks from smaller built-up tissue to larger built-up tissue, while another part of the area displays big and nonsensical jumps between the two, making the granularity of the result partially achieved, and the criterion is not met fully. The gradual change of building volumes is also partially achieved. A part of the area displays meaningful transitions of the building volumes between building blocks, while another part of the area contains neighbouring building blocks with sudden jumps of building volumes between the neighbouring building blocks, making the meaningful transition of building volumes only partially achieved. While the previous two goals are partially achieved, the structure goal still needs to be achieved. The transitions in urban structures of neighbouring building blocks do not make sense and are inconsistent throughout the area. The most problematic is the transition from the second column to the fourth column of building blocks, where the structure changes from circumferential to non-circumferential and back to circumferential, continuing with the last two non-circumferential columns to the end.

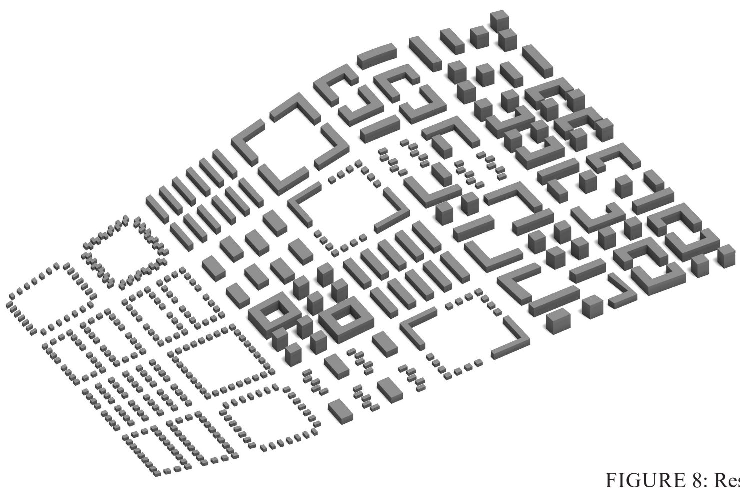


FIGURE 8: Result A

The second generated result, also result B (*Figure 9*), shows a transition from ZMN to NBG that does not achieve any of the specified criteria. The area does not show any gradual transitions between the neighbouring building blocks in terms of built-up tissue, building volumes and urban structure.

In the third and fourth columns, significant gaps in built-up tissue are visible as the building blocks progress from the second to the third column, only to revert to smaller building volumes with circumferential structures. This erratic development showcases a lack of meaningful transitions, making the overall transition lacking any resemblance of gradual change in the morphological pattern. The absence of coherence is particularly pronounced in this result, where the intended transition in morphological patterns between ZMN to NBG remains unspecific.

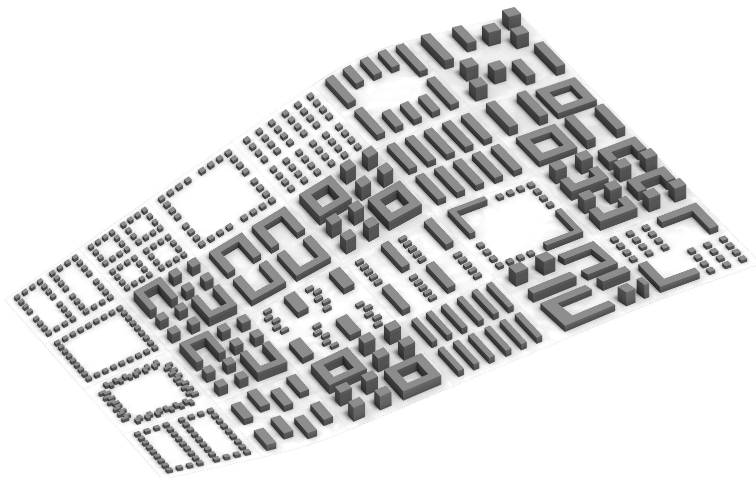


FIGURE 9: Result B

The third generated result, also result C (*Figure 10*), shows a transition from ZMN to NBG that is very close to being good in terms of all three criteria. The transition in morphological pattern from ZMN to NBG is visible in terms of granularity, building volumes, and urban structure; however, it lacks the ability to connect these three things gradually throughout the case study area. Even though a diagonal transition from the northwest corner to the southeast corner can be observed, the jumps in granularity, building volumes and urban structure are still too high. It is also visible that the low building volumes originating in ZMN reach very far into the case study area towards NBG in row one, while the higher building volumes originating in NBG reach very far into the area towards ZMN in row four. The change of granularity, building volumes and urban structure of rows two and three happens in the middle of the area, but the change in all of these three things is problematic in the second row, while the transition is good in the third row.

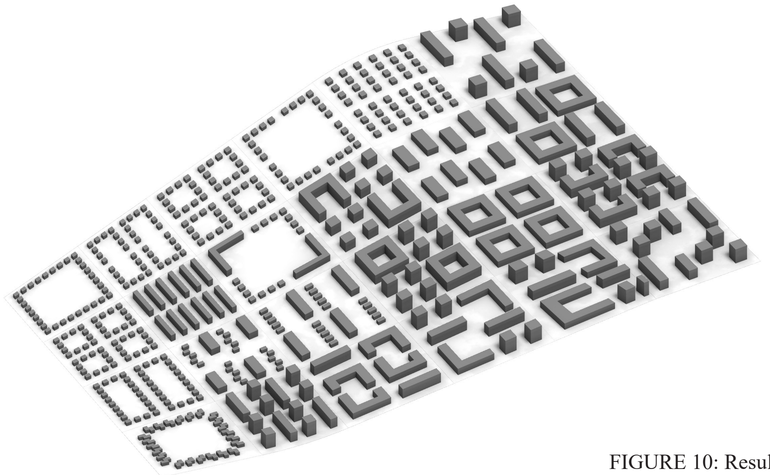


FIGURE 10: Result C

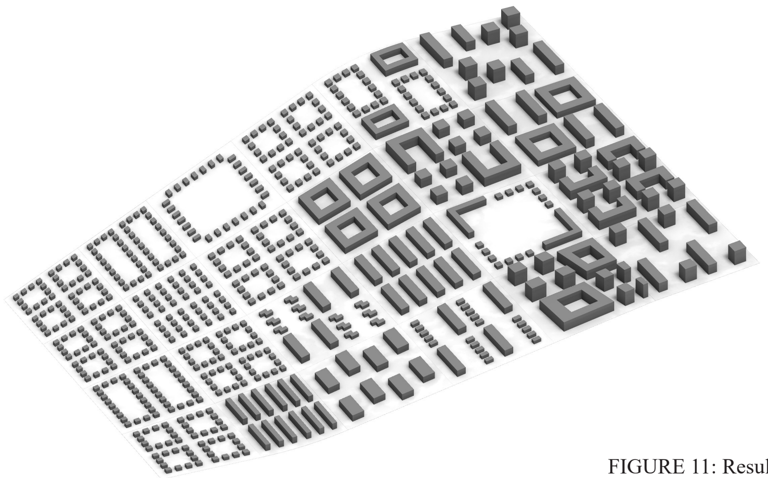


FIGURE 11: Result D

The fourth result, also result D (*Figure 11*), shows a transition from ZMN to NBG that satisfies all the criteria. Similar to the third result, the transition in morphological patterns can be observed from the northwest corner to the southeast corner. Contrary to result C, the observable transition in morphological patterns is gradual in all directions, within columns and rows themselves. The building block in the fifth column and the third row does stand out with its circumferential structure, however, it does not disturb the transition in morphological patterns as much. The transitions between granularity, building volumes and urban structure are very logical and meaningful, no sudden jumps are visible. The building blocks from the ZMN side very logically evolve into the building blocks on the NBG side.

The fifth result, also result E (*Figure 12*), shows a transition from ZMN to NBG that satisfies the criteria of granularity and building volumes while the criterion of urban structure is not entirely met. The fifth result did satisfy two out of the three criteria but with some setbacks. The transition in morphological patterns now appears to be from east to west and not so much from the northwest corner to the southeast corner. The transitions in granularity are logical and meaningful; nothing stands out in the transition of morphological patterns, and the evolution of building blocks with high granularity to building blocks with low granularity makes sense. There are no sudden jumps between two neighbouring building blocks with different granularities except for the fourth and fifth building blocks in the first row, but that change does not disturb the overall transition of morphological patterns. The volumes of the buildings also show logical evolution from the building blocks of ZMN to the building blocks of NBG. The urban structure criterion was partially met because of the building blocks three and four in the second row. Although the overall urban structure develops logically throughout the case study area, the mentioned building blocks are a setback to the overall structure of the morphological pattern in the area. If the building blocks three and four in the second row were inverted, the solution would meet all of the criteria.

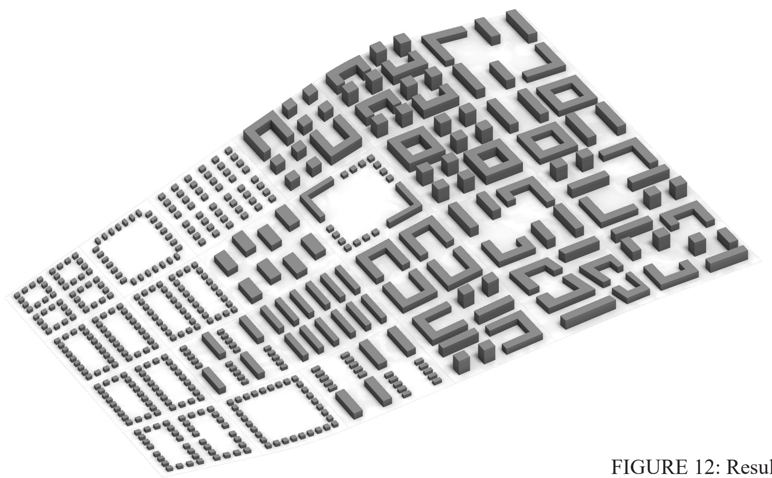


FIGURE 12: Result E

The sixth result, also result F (*Figure 13*), similar to result A, shows a transition in building blocks from ZMN to NBG that partially achieves two out of the three criteria and does not achieve the third criterion. While the evolution of the building blocks in terms of granularity can be visible, the transitions in granularity from the building blocks of ZMN to the building blocks of NBG are not always logical.

In the first row, there is a sudden jump from a building block with finer granularity to a building block with cruder granularity in building blocks three and four. A nonsensical evolution from building blocks with higher granularity to lower granularity also happens in the third row, where there is a jump to lower granularity from the second to the third building block, only for the building blocks with higher granularity to return the closer they are to NBG, where they suddenly change again from the fifth column to the sixth in the third row. On the contrary, the second and the fourth rows are not problematic in terms of granularity, and that is why the criterion was partially achieved. The same pattern could be recognised with building volumes, where rows two and four are not problematic at all, while the first and the third row show the jump in building volumes in the same places as the problems with jumps in granularity are visible. While the problematic jumps are only in two places in the case study area, they are significant enough to disturb the whole morphological transition, and the criterion of building volumes is, as a result, met partially. The criteria for urban structure were not met at all since there were noticeable changes in the structure of neighbouring building blocks in the case study area. The change of structure is not only visible in the first row in the neighbouring blocks three and four but also throughout the whole area. While the seemingly semi-logical transitions in the urban structures can be seen within the rows themselves, when looking at columns, the neighbouring building blocks seem to clash with one another throughout the whole area, disturbing the overall transition in morphological patterns, which meant that the criteria of urban structure was not met at all.

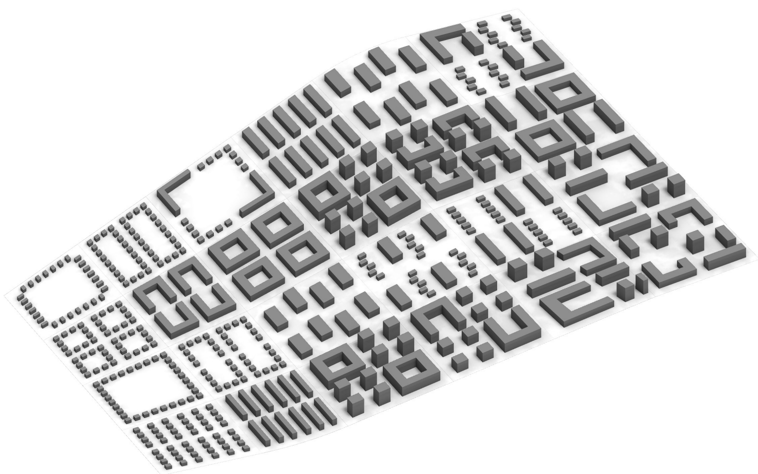


FIGURE 13: Result F

4. DISCUSSION

The evolutionary algorithm generated 6 different variations or results that were then evaluated against the set of criteria. The structure of the algorithm together with the fitness function ensured that the generated FAR values fell into the sustainable range, which was determined using the synoptic survey. The FAR values only represented the quantitative data output, while the qualitative results (the quality of transition of morphological patterns from ZMN to NBG) were evaluated by an expert. The transition of morphological patterns was evaluated against three different criteria, which were granularity, building volumes and urban patterns.

When all six variations were evaluated against set criteria, the similarities and differences between these started to emerge. Results A, C and F all partially meet the criteria of granularity and building volumes, meaning that even though a part of the area in these results shows good transition markers, a part of their areas displays sudden jumps and nonsensical transitions which makes them partially suitable. What differentiated them is that results A and F did not meet the criterion of urban structure while result C partially met it, meaning that results A and F displayed neighbouring building blocks which meant they did not show good transition markers from ZMN to NBG. Similarly to result C, result E partially met the criterion of urban structure, meaning that the overall transition was not broken, but some building blocks could be changed. Contrary to result C, result E met the criteria of granularity and building volumes, which meant that the transition of building blocks with different granularities and building volumes was logical and meaningful, creating a smooth and gradual transition from ZMN to NBG. Both results D and E met these criteria, with the difference of result D meeting the criterion of urban structure as well. Result B did not meet any of the criteria.

In conclusion, three out of six results partially met the criterion of granularity, two of the results met the criterion in its entirety, and one result did not meet the set criterion at all. Likewise, three out of six results partially met the criterion of building volumes, two results met the criterion, and one result did not. Unlike the first two criteria, three out of six results did not meet the criteria of urban structure; two results met it partially, and only one result met it fully. Considering that all of the results met the criteria for sustainable density, and only one result met all of the three qualitative criteria for a transition of morphological patterns, the best result is D, which met all of the criteria, followed by result E, which met two out of three criteria and partially met one criterion. Result C follows, which partially met all three criteria.

Results A and F, which partially met two out of three criteria and did not meet the third criterion at all, were followed by result B which is the worst result as it did not meet any of the three criteria.

After evaluating the six generated results in terms of their sustainability through quantitative and qualitative evaluation, we can now turn to the initial research question.

What are the sustainable urban patterns? Sustainable Urban Patterns (SUPs) in the research refer to gradual and logical transitions in morphological patterns from ZMN to NBG, meeting criteria such as granularity, building volumes, and urban structure. Identified through a transect-based approach, SUPs optimise density in areas with diverse building types, promoting walkability and economic efficiency. Utilising an evolutionary algorithm, these patterns balance quantitative factors like FAR with qualitative considerations, aiming to avoid unliveable spaces and achieve sustainable urban growth. Among the generated results, those fully meeting criteria (result D) are deemed most favourable, followed by those partially meeting two out of three criteria (result E). The study underscores the importance of a holistic approach to evaluating urban patterns, considering both quantitative and qualitative aspects.

Can a computer help urbanists generate a range of urban patterns that can be evaluated regarding sustainability? By using a computer and creating a generative algorithm for solution generation, it is possible to quickly generate a set of solutions that can be evaluated with given criteria. This shortens the design process significantly and offers designers a much better overview of the possible outcomes, enabling them to plan for future contingencies and understand possible scenarios and strategies for development, which would help ensure sustainable urban planning.

Parametric design allows the urban design process to be parametrically defined in several aspects, enabling a wide range of potential results (Silva, 2015). As the defining parameters can be changed, each alteration impacts the outcome, resulting in non-identical solutions as the parameters are locally defined. Further, as the visual programming languages commonly used to build generative algorithms in this context may vary in use and application, the algorithms themselves can also differ. For those reasons, the results cannot be comparable to similar research results in terms of generated parameters.

5. CONCLUSIONS

In conclusion, the research underscores the complexity of sustainable urban growth as a concept of sustainable density. It advocates for a balanced densification approach, avoiding excessively sparse or dense urban patterns. Using transect urbanism as a method, the definition of locally specific transect zones systematically connects density to the concept of sustainable urban patterns. The case study area in Belgrade examines locally defined transect zones, finding T-4 and T-5 the most optimal due to their high variety of building types and morphological patterns.

An evolutionary algorithm was used for the generation of six different urban patterns from an array of meta-building blocks. Results were then evaluated using a set of criteria (Granularity, Building volumes, and Urban structure) to understand how they mediate between and connect the areas of Zemun and New Belgrade. Two results met all of the criteria satisfactorily; three partially met them, and one did not. During the evaluation, the researchers noticed that to ensure better results, a bigger pool of meta-building blocks need to be designed with varied morphological patterns that occupy every possible FAR value, to create more varied and better results for an evaluation process. The authors conclude that the genetic algorithm is a great tool for urbanists to be able to quickly generate a set of evaluation-ready solutions, which are then used for easier predictions and a better understanding of different scenarios in the process of urban planning.

It is important to note that this research demonstrates how even a simple algorithm can be applied in the process of urban planning, making it easier and more accurate as it is based on locally defined parameters. More complex algorithms could yield better results by including additional parameters. However, it should also be noted that not every aspect of urban planning can be defined as a parameter, and this may not be the optimal approach for every scenario.

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A B S T R A C T S : S E R B I A N

IZGRADNJA NESTANDARDNIH ARHITEKTONSKIH ELEMENATA VELIKE RAZMERE PRIMENOM TEHNOLOGIJE 3D ŠTAMPE

Maša Žujović, Miodrag Nestorović

Napredak tehnologija digitalne izgradnje i aditivne proizvodnje poslednjih godina uticao je na arhitektonsku praksu i građevinsku industriju dovodeći do potrebe za preispitivanjem uobičajenih praksi i procesa arhitektonskog projektovanja. Brz razvoj i upotreba digitalnih alata, posebno 3D štampe, omogućio je projektovanje i izgradnju složenijih formi. Ovaj rad nudi pregled primena različitih tehnologija 3D štampe za izgradnju konstruktivnih elemenata, kao i pregled potencijala i ograničenja ove tehnologije. Polazeći od hipoteze da 3D štampa olakšava proizvodnju nestandardnih, složenih elemenata, istraživačko pitanje ovog rada glasi: Kako se potencijali ovih tehnologija mogu u potpunosti iskoristiti? Cilj ovog rada je da identifikuje relevantne publikacije, prikupi i sistematizuje metode 3D štampe, a zatim i da analizira trenutno stanje prakse kroz pregled literature. Identifikovani su relevantni projekti koji su potom kategorizovani na osnovu tipologije konstruktivnih elemenata. Potom su identifikovane i sistematizovane prednosti i nedostaci predstavljenih pristupa u odnosu na nivo slobode dizajna, složenosti i mogućnosti formiranja nestandardnih rešenja. Konačno, na osnovu rezultata pregleda literature, u radu se predlaže set strategija za efikasniju izradu nestandardnih arhitektonskih elemenata korišćenjem tehnologije 3D štampe.

KLJUČNE REČI: ARHITEKTONSKI DIZAJN, KONSTRUKTIVNI ELEMENTI, 3D ŠTAMPA, GRAĐEVINSKA INDUSTRIJA, DIGITALNA IZGRADNJA, NESTANDARDNE FORME.

HIBRIDNI STAMBENI PROSTORI U KONTEKSTU MODULARNE ARHITEKTURE I POTENCIJALA ZA AUTOMATIZACIJU MODELOVANJA

Jasmina Kosić Okanović

Složnost savremenog trenutka zahteva intenzivnu adaptaciju na različite modele stanovanja, rada, proizvodnje, potrošnje, transporta i socijalnih interakcija. Adaptabilnost, transformabilnost, otpornost, ekonomičnost, pristupačnost, kao i održivo zbrinjavanje resursa, ključni su pojmovi za suočavanje sa izazovima budućnosti i od esencijalnog su značaja u okviru arhitektonske profesije. Ovaj rad se bavi mogućnostima modularne arhitekture da odgovori na promene u sferi funkcija stanovanja, naročito na zahteve sve češće prisutne tipologije hibridnog stanovanja, kao i ispitivanjem mogućnosti automatizacije procesa modeliranja. Pod pojmom hibridnog stanovanja u ovom radu podrazumevamo arhitektonsku tipologiju stanovanja koja uključuje paralelno funkcionisanje stambenih i poslovnih sadržaja (tj. rada) unutar istog domaćinstva, pri čemu korisnici istovremeno poseduju i upravljaju obe funkcije..

KLJUČNE REČI: HIBRIDNO STANOVANJE, TRANSFORMABILNOST, MODULARNOST, AUTOMATIZACIJA

TELA BEZ ORGANA: TAKTILNOST UVEZANIH TELA

MA., Cenk Güzelis

Prostori i tela više nisu izolovana i statična, već su proširena, virtuelna, augmentovana i umrežena. Kada su fizički prostori postali nedostupni, prostorne računarske tehnologije i SocialVR platforme su transformisale našu izgrađenu okolinu u mesta udaljenog socijalizovanja i nove načine doživljavanja prostora zasnovane na udaljenom prisustvu i socijalnosti. Ovaj rad istražuje mešovitu realnost tela bez organa, koja uključuje fizičke i digitalne objekte u preklapanju fizičkog i virtuelnog. Kroz korišćenje API-ja kao što su Pose Estimation, Hand-Tracking i Passthrough, stvara se prostorno-vremensko iskustvo koje pretvara prostor u medijum telekomunikacije, gde se proprioceptivna tela i prostori prenose preko mreže.

KLJUČNE REČI: VR/AR PROMENA FIZIČKOG PROSTORA, SOCIJALNO DISTANCIRANJE VS FIZIČKO DISTANCIRANJE, GEJMING KAO ALAT ZA PROJEKTOVANJE, AVATARI KAO POSTHUMNA TELA, POSTAJANJA

PROJEKTOVANJE ARHITEKTONSKIH STRUKTURA BIO-INSPIRISANIM OBRASCIMA

Aleksandru Vuja, Jelena Milošević

Rad se fokusira na primenu bio-inspirisanog generativnog dizajna (GD) u arhitekturi. Cilj je stvaranje inovativnih dizajna razvojem arhitektonskih metoda i alata koji adaptiraju obrasce temeljene na biološkim ponašanjima. Kompleksno ponašanje prirodnih sistema predstavljeno bio-inspirisanim računalnim algoritmima korišćeno je za proizvodnju dizajna, tj. biološke funkcije povezane sa informacijama transformisane su u tehničke funkcije za rešavanje dizajnerskih problema. U ovoj situaciji, računarski generisani dizajnerski artefakti proizvedeni su algoritamski određenim sistemom pravila. Predloženi pristup testiran je kroz dizajnerske eksperimente. Integracija bioloških i tehničkih informacija realizovana je korišćenjem vizuelnog programiranja u CAD sistemu, što je omogućilo istraživanje dizajna i vizualizaciju. Logički skup pravila implementiran je za automatizaciju dizajnerskog procesa. Dobijeni dizajni pokazuju održivost predloženog pristupa.

KLJUČNE REČI: BIOMIMIKRIJA, BIO-INSPIRISANI DIZAJN, GENERATIVNI DIZAJN, DIZAJNERSKI OBRASCI, DIGITALNO PODRŽANO ARHITEKTONSKO PROJEKTOVANJE, MODELOVANJE BIOLOŠKIH SISTEMA

OSIGURAVANJE ODRŽIVOG URBANOG PLANIRANJA UZ POMOĆ PARAMETARSKIH PROJEKTANTSKIH ALATA

Filip Živković, Janez Peter Grom, Alenka Fikfak, Tomaž Pipan

Rad istražuje kako parametarski dizajn može pomoći u stvaranju održivih urbanih obrazaca. Kroz studiju slučaja u Beogradu, istraživanje koristi koncepte transektnog urbanizma i parametarskog dizajna kako bi generisalo urbane obrasce koji se mogu evaluirati u pogledu održivosti. Rad definiše pojam održive gustine i povezuje ga sa konceptom urbanih transekata kako bi identifikovao održive urbane obrasce. Ovi obrasci se zatim koriste za generisanje rezultata spremnih za evaluaciju putem evolucijskog algoritma. Cilj je održivo povezivanje područja Zemuna i Novog Beograda, koja imaju različite gustine i morfološke obrasce. Generisani rezultati su evaluirani pomoću kvantitativnih kriterijuma (odnos površine i spratnosti) i kvalitativnih kriterijuma (granularnost, obim zgrada i urbana struktura) kako bi se identifikovali najpogodniji računarski generisani rezultati. Kombinovana upotreba oba kriterijuma omogućila je sveobuhvatniju evaluaciju mogućih ishoda i bolje razumevanje mogućih scenarija i strategija razvoja.

KLJUČNE REČI: ODRŽIVA GUSTINA, ODRŽIVI URBANI OBRASCI, GRAĐEVINSKE JEDINICE, PARAMETARSKI DIZAJN, EVOLUTIVNO GENERISANJE, URBANI PLANIRANJE, URBANI RASTTALNO PODRŽANO ARHITEKTONSKO PROJEKTOVANJE, MODELOVANJE BIOLOŠKIH SISTEMA

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