A Methodology for Designing Auxetic Metamaterials for Adaptive Systems

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To develop sustainable material systems, modern industries must create new, lighter systems using less materials without compromising their performances. Over the past thirty years, researchers from various disciplines have turned metamaterials as alternatives to natural materials. Among these materials, auxetics stand out due to their mechanical properties. Despite the fact that these materials have been experimentally used in architectural projects over the past two decades, design outcomes have predominantly relied on existing auxetic structures, limiting the use of them in architectural design solutions. This research aims to create a novel auxetic material system by focusing on the geometry of auxetic materials and their smart transformations, embedded within the morphological structures of these materials. The methodology of the study consists of four stages, including identifying geometrical parameters of auxetic metamaterials, setting the computational model, digital fabrication, and physical experiments. This study has progressed based on feedback from computational and physical models to evaluate the behavior of the system, which is passively activated by the applied forces. To evaluate the results, physical prototypes were produced for obtaining empirical data. Experiments applied on physical prototypes were conducted on two different materials, including biopolymer polylactic acid and thermoplastic polyurethane. Thus, the auxetic behavior of different materials were observed and compared. In the future, the integration of the proposed system with responsive materials will enable the development of adaptable systems for large-scale architectural applications.

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Keywords: Auxetic materials, Computational design, Metamaterials, Prototyping, 3D Printing.

Uyarlanabilir Sistemler için Genişleyebilen Metamalzemelerin Tasarımına Yönelik bir Metodoloji

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Sürdürülebilir malzeme sistemleri geliştirmek için, modern endüstriler performanslarından ödün vermeden daha az malzeme kullanarak yeni, daha hafif sistemler yaratmalıdır. Son otuz yılda, çeşitli disiplinlerden araştırmacılar doğal malzemelere alternatif olarak metamalzemelere yönelmiştir. Bu malzemeler arasında, mekanik özellikleri nedeniyle esnetildiğinde genişleyebilen(auxetics) malzemeler öne çıkmaktadır. Son yirmi yıl içerisinde bu tür malzemeler, mimari projelerde deneysel olarak kullanılmış olsa da tasarım çıktıları genellikle mevcut yapı tiplerine dayanmaktadır. Bu durum, ilgili malzemelerin mimari tasarım çözümlerindeki kullanımını sınırlandırmaktadır. Bu araştırma, genişleyebilen malzemelerin geometrisi ile bu malzemelerin morfolojik yapıları içinde gömülü olan akıllı dönüşümlerine odaklanarak, yeni bir genişleyebilen malzeme sistemi oluşturmayı amaçlamaktadır. Çalışmanın metodolojisi genişleyebilen metamalzemelerin geometrik parametrelerinin belirlenmesi, hesaplamalı modelin oluşturulması, sayısal üretim ve fiziksel deneyler olmak üzere dört aşamadan oluşmaktadır. Bu çalışma, uygulanan kuvvetle pasif olarak etkinleşen sistemin davranışını değerlendirmek için hesaplamalı ve fiziksel modellerden alınan geri bildirimlere dayalı olarak geliştirilmiştir. Sonuçları değerlendirmek için, ampirik veriler elde etmek üzere fiziksel prototipler üretilmiştir. Fiziksel prototiplerle yapılan deneyler, biyopolimer polilaktik asit ve termoplastik poliüretan olmak üzere iki farklı malzeme üzerinde gerçekleştirilmiştir. Böylece farklı malzemelerin davranışları gözlemlenmiş ve karşılaştırılmıştır. Gelecekte, önerilen sistemin tepkimeli malzemelerle entegrasyonu sayesinde büyük ölçekli mimari uygulamalara yönelik uyarlanabilir sistemlerin geliştirilmesi mümkün olabilecektir.

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Anahtar Kelimeler: Genişleyebilen malzemeler, Hesaplamalı tasarım, Metamalzemeler, Prototipleme, 3B Baskı.

1. INTRODUCTION

Production strategies developed by modern industries have led to unsustainable systems due to the perception and utilization of natural materials as inexhaustible resources (Jalkh, 2020). Today, the growing awareness of these limited resources has triggered a paradigm shift, prompting designers to critically question what they design, produce, and how they go about doing so. In this context, modern industries must develop new and lighter material systems that reduce material consumption without compromising mechanical performance (Parente & Reis, 2024). Establishing a sustainable system and developing innovative solutions are only possible through an integrated and interdisciplinary approach (Delikanli & Cagdas, 2021). Over the past thirty years, researchers from various disciplines, through interdisciplinary collaboration, have turned to metamaterials as alternatives to natural materials (Naboni & Pezzi, 2016; Papadopoulou et al., 2017; Lu et al., 2022; Qu et al., 2024). Among these metamaterials, the most intriguing ones are "auxetics" due to their extraordinary mechanical properties.

The term auxetic originates from the Greek word "auxetikos" meaning tending to expand or increase. Auxetics were first defined by Evans in 1991 as materials with a negative poisson's ratio (NPR). The Poisson's ratio, introduced by the French scientist Simeon Denis Poisson, is a constant that characterizes a material's elasticity (Uzun, 2010). This ratio is defined quantitatively as the ratio of transverse contraction to longitudinal extension in a material. Most materials known today exhibit a behavior, where they become thinner when stretched and expand when compressed **(Figure 1).** However, auxetic materials display a counterintuitive behavior: they expand when stretched and contract when compressed (Liu & Hu, 2010; Park et al., 2015). This behavior enables different areas of application at architectural scale as a material system. These types of materials reduce the amount of energy required to create a three-dimensional (3D) form and distributes the internal mechanical forces of the system, ensuring a balanced form, similar to natural systems that achieve maximum performance with minimal energy input (Vivanco et al., 2023). However, this largely depends on the design of the material system and its usage scenario.

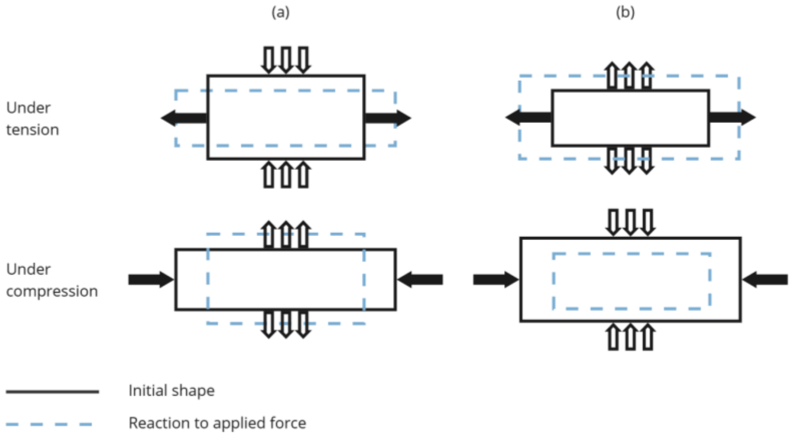


Figure 1: The deformations of materials with positive (a) and negative (b) poisson's ratios under force, adapted from the work of Nasiri (2024).

The deformation mechanisms of auxetic materials are primarily attributed to their cellular arrangements and geometric structures rather than their chemical composition (Carneiro et al., 2013; Naboni & Mirante, 2015). These structures consist of the periodic repetition of specific unit cells, characterized by significant transformations in pore size. Due to their nonlinear twisting and ability to adjust porosity and negative Poisson's ratio, these systems are widely studied in materials science (Naboni & Pezzi, 2016; Mesa et al., 2017). Classifying these geometric structures is essential for researchers to understand "*how auxetic effects can be achieved, how auxetic materials can be produced, and how their properties can be optimized and predicted*" (Oner et al., 2020). Auxetic structures are mainly divided into four subgroups as (1) chiral structures, (2) rotating structures, (3) re-entrant structures, and (4) foldable structures **(Figure 2).** These transformations bring out the auxetic properties by altering the material's inherent characteristics (Dong & Hu, 2023).

Interest in auxetic materials has increased over time in terms of exploration of their material behavior and transformational properties. In the following sections, the gap in the literature will be identified by focusing on the potential applications of auxetics, which continue to be experimentally developed across various disciplines, and the recent advancements in their use within the field of architectural design.

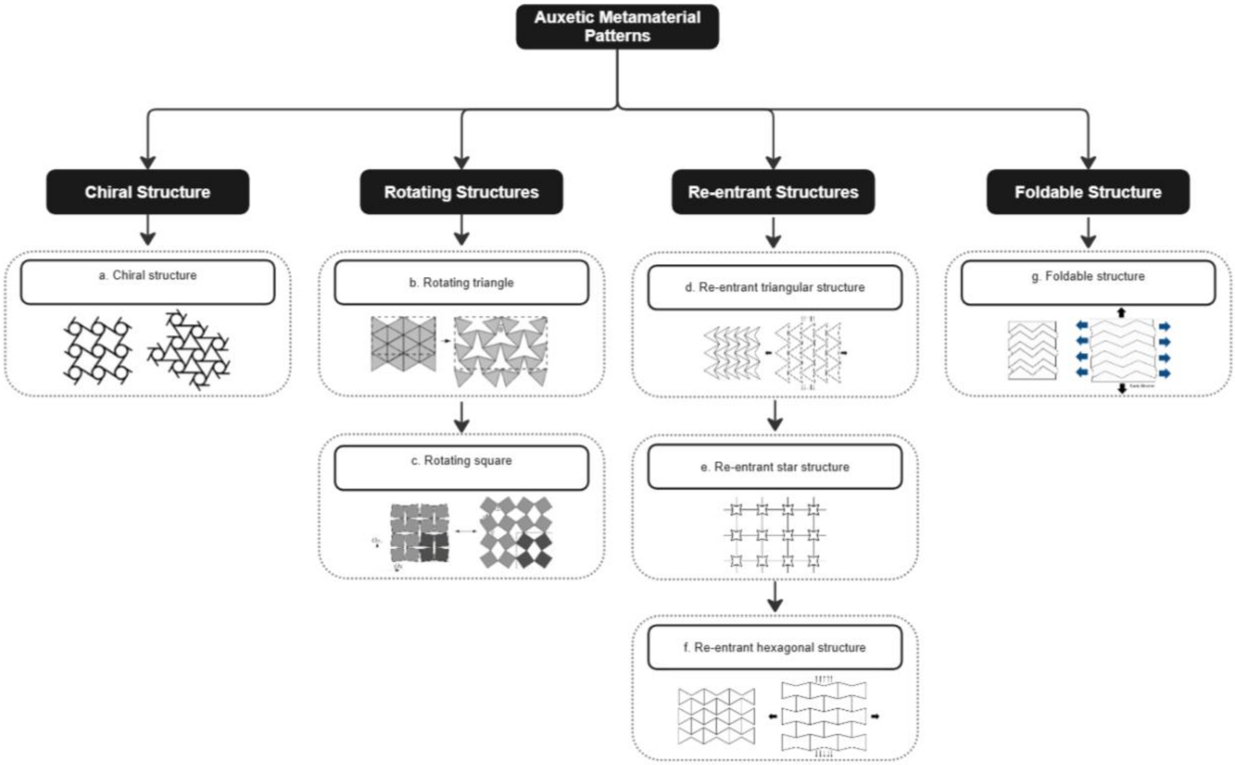


Figure 2: Classification of auxetic metamaterial patterns, adapted from the work of Dong and Hu (2023).

1.1 Applications of Auxetics as a Novel Material System

Interest in such materials historically began in 1987 with Lakes' production of auxetic foam through triaxial compression, heating, and cooling processes applied to polyurethane foams. In subsequent years, various auxetic materials have been engineered and produced, including cubic metals, zeolites, silicates, hydrogels, aerogels, auxetic fibers, and molecular-level auxetic polymers (Tripathi, 2024). "Auxetics" at the molecular level, such as liquid crystalline polymers (LCPs), are specifically engineered through nanoscale chemical synthesis. In contrast, "auxetic fibers" can be produced at the nano-, micro-, and macro-scales, depending on the intended application (Liu & Hu, 2010). Glynn et al. (2018) describe these materials as the man-made of the future, exhibiting superior properties that are not yet found in nature. Compared to traditional materials, they demonstrate resistance to indentation, higher fracture toughness, synclastic curvature formation capacity, energy absorption, variable permeability, and shear resistance. These advanced characteristics make them prime candidates for numerous potential applications.

Among these applications are impact/ballistic protection, acoustics, automotive, shape-memory polymers, wearable strain sensors, electromagnetic shielding, smart filters, rehabilitation, biomedical, and sports applications. Another significant application of auxetic materials is their potential use in building systems as more sustainable materials (Nasiri, 2024). Due to their morphological structure, these materials are force-sensitive, flexible, and adjustable. They can be activated with less energy, offering a sustainable alternative to complex and costly kinetic systems (Tibbits, 2017; Papadopoulou et al., 2017). In recent studies, a dual-layer sample was produced by bonding auxetic foam with a polyurethane film; when immersed in hot water, this sample bent into a ring shape and quickly reverted to its original form upon removal (Tripathi, 2024; section 6.4). Given the advantages offered by this material system, researchers and professionals from various disciplines such as materials science, engineering, and architecture will continue to develop diverse strategies for its design and production. This, in turn, will give rise to a new material practice where designers are actively involved in the manufacturing process (Oxman, 2015).

1.2 Recent Advances in Auxetic Material Applications in Architecture

The application of these material systems in the field of architecture began in the 2010s. In 2013, Themistocleous from UCL developed a methodology for the design of pneumatically activated auxetic systems and focused on their simulation (Themistocleous, 2013). In 2015, Naboni and Mirante from ACTLAB examined existing auxetic patterns and explored their use in bending-active shell structures, although no new auxetic structures were proposed (Mirante, 2015). Also in the same year, Park et al. (2015) attempted to create morphological variations of the most commonly used re-entrant honeycomb structure in the literature. They combined 2D sheet structures to produce simple 3D compositions and theoretically proposed multi-material additive manufacturing for transitions between hard and soft materials in 3D cubes. Zaha Hadid Architects also utilized auxetic cutting patterns on 2mm steel plates in the Volu dining pavilions to achieve double curvature without molds (Louth et al., 2017; Albag, 2021). Unlike smart transformations in auxetic structures, their study primarily focused on generating curvature. Later in 2018, topologically optimized and functionally graded cable networks were produced and applied to a chair (Tish et al., 2018).

In the same year, Belanger et al. (2018) used auxetic patterns to produce a slumped glass structure and examined the acoustic effects within the glass. However, in this study, the movable auxetic geometric structure was locked and fixed in the glass. The following year, Pertigkiozoglou (2019) utilized auxetic slits in aluminum sheets to create free-form deformable surfaces. However, instead of auxetic-driven transformations, slits have been utilized to generate curvature on the surface.

As the present day is approached, explorations of these material systems have persisted. Martínez (2021) produced porous sheet structures using parametric growth processes through coding. After optimizing these structures, Negative Poisson's Ratio (NPR) was indirectly observed. However, since tensile and compression tests were not performed in a physical environment, clear information about the auxetic behavior of the produced structure could not be obtained. Later on, Ozdemir et al. (2022) at ICD Stuttgart produced a self-shaping metamaterial shell using a re-entrant honeycomb auxetic structure. Hygrosensitive wood actuators were placed between the shell layers and left to dry, completing a self-shaping process after 152 hours. Although this approach was innovative, the wood actuators did not integrate well with the existing structure, and as the shell did not shape as desired, it was supported from its center of mass to facilitate the shaping process after 72 hours. In this study, auxetic behavior guided by patterns did not occur; instead, the transformation was achieved through the wood bilayers. Lastly, Nasiri (2024) focused on generating existing auxetic geometries using the Shape Machine tool, a generative shape grammar tool, through simple initial shapes and rules. Since no physical production was undertaken in this study, an integrated system of form and material behavior was not observed.

Upon reviewing the conducted studies, it is evident that most of the designs and productions in the literature predominantly utilize existing auxetic structures. Additionally, many studies address auxetic patterns solely as fixed surface coatings, without observing the intelligent transformations embedded morphologically within the material. Accordingly, this paper aims to make an original contribution to the literature by presenting the proposed methodology for developing novel auxetic systems and their practical applications in architectural design contexts.

In the following section, the methodological process will be introduced to address key questions: What are the critical parameters of an auxetic system? Which materials and manufacturing methods can be used to produce auxetic structures? How can the behavior of these structures be tested?

2. METHODOLOGY

The auxetic behavior is achieved through an integrated approach involving specific unit cell arrangements, appropriate material selection, and the direction of the applied forces. Considering all these factors, the methodology is built upon a workflow based on feedback from both computational and physical models, and consists of four stages: (1) identifying geometrical parameters of auxetic metamaterials, (2) setting the computational model, (3) digital fabrication, and (4) physical experiments **(Figure 3).**

1. Identifying geometrical parameters of auxetic metamaterials: The selected auxetic design is examined and the parameters that constitute the behavior of the system are extracted.
2. Setting the computational model: Using these parameters, a custom-designed auxetic pattern is created in algorithmic design environment. Subsequently, a three-dimensional (3D) shell structure is created through coding to observe its transition from a planar to an out-of-plane state and to explore the potential architectural applications of a customized auxetic structure.
3. Digital fabrication: For the production of the designed auxetic structure, additive manufacturing, 3D printing more specifically, is chosen, and Biopolymer Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU) are selected as materials for prototyping.
4. Physical experiments: Prototypes are produced to test the auxetic behavior in physical environment. The smart transformations of the material under tensile and compressive forces are observed and measured.

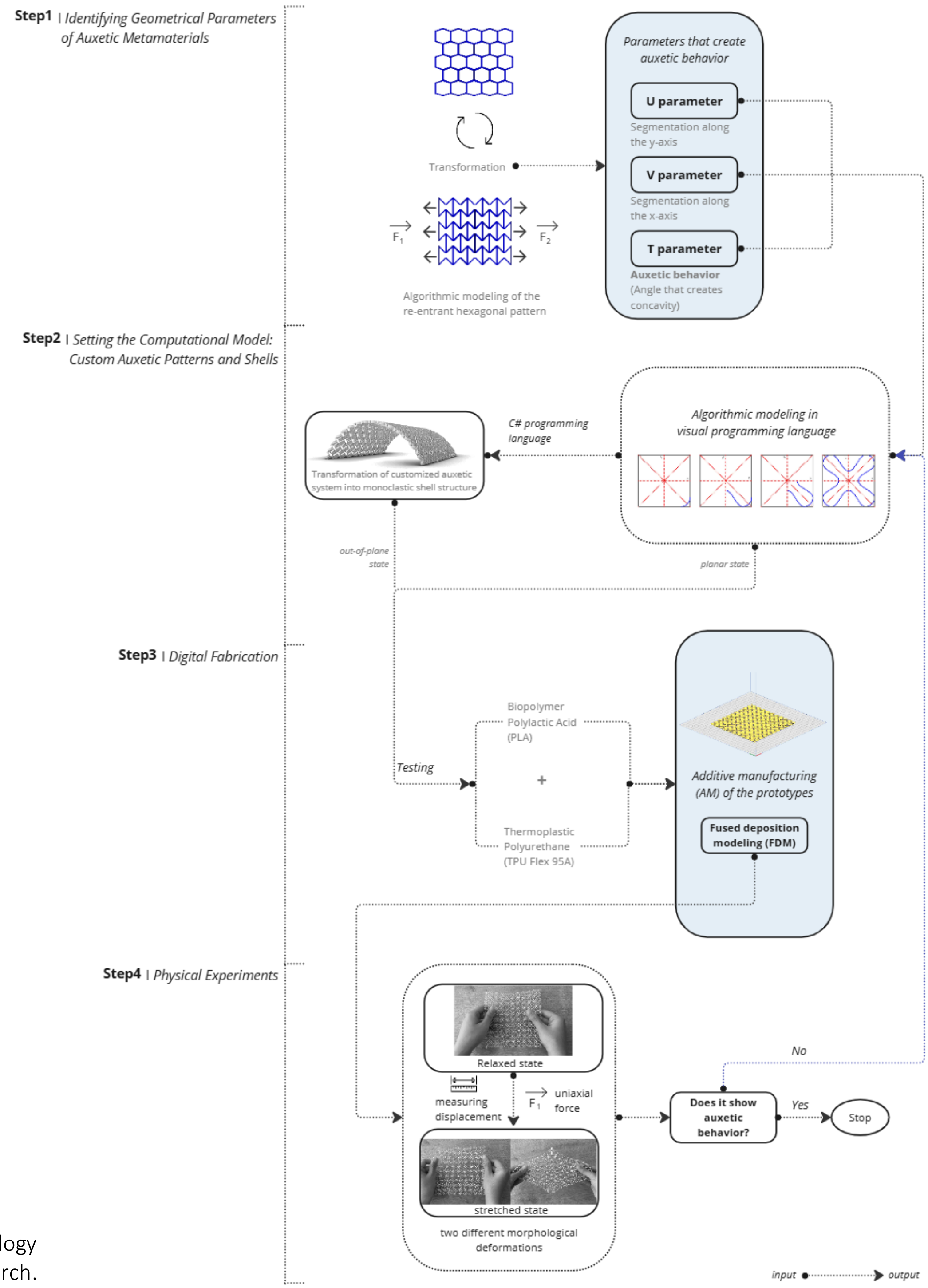


Figure 3: Methodology of the research.

2.1 Identifying Geometrical Parameters of Auxetic Metamaterials

One of the most studied auxetic geometries in the literature is the re-entrant honeycomb structure (Jalkh, 2020; Parente & Reis, 2024; Bol et al., 2024). The reasons for selecting this geometry by various researchers include its high deformation capacity, geometric simplicity, and the absence of the need for additional processing such as cutting. Furthermore, it exhibits spontaneous hinge behavior without the use of traditional hinges. However, the extensive use of only this geometry has limited diversity. Considering the advantages of this geometry, the re-entrant honeycomb structure is chosen as the first step to create a new auxetic structure from the existing one. The selected auxetic pattern is modeled in a computational design environment, and its deformation is simulated **(Table 1).**

The auxetic behavior in these structures arises from the displacement of two opposite corner points of a hexagonal unit, which move inward and outward under applied forces. Subsequently, three parameters—u, v, and t—are defined to generate any re-entrant cell arrangement. Among these, one of the most critical parameters is the t-angle parameter, which leads to concavity within the cell. This parameter governs the movement of the ribs, enabling the units to function as hinges and achieve auxetic behavior. The u and v parameters segment the structure along the y- and x-axes, respectively. The auxetic behavior is primarily controlled by the t-angle parameter, which ranges between 0 and 1 and determines the concavity in the cell geometry. **Figure 4** depicts the unit cell structure and its tessellation, where t denotes the angle between the concave ribs, and l and h correspond to the unit's horizontal and vertical dimensions, respectively.

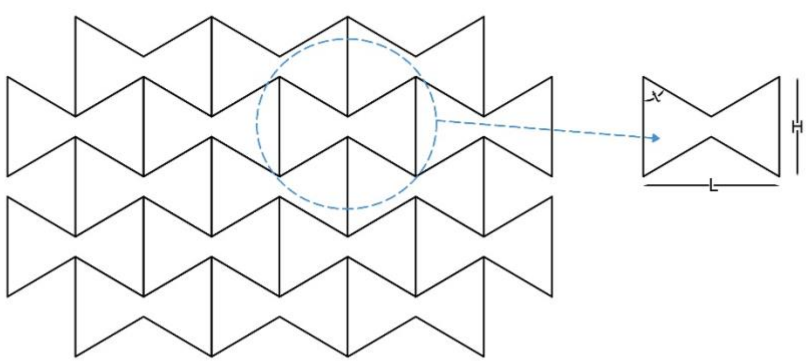


Figure 4: Schematic representation of a re-entrant hexagonal pattern, adapted from the work of Ghiasvand et al. (2023).

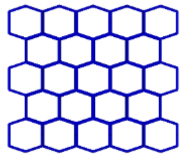
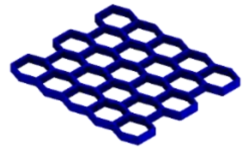
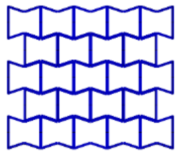
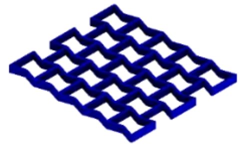
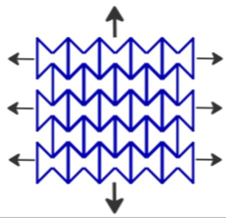
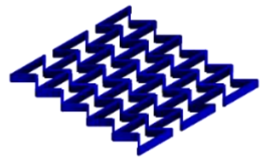
Parameters	Top view	Perspective view
t=0.40 ° u=5 unit v=5 unit w=0.03m h=0.3m		
t=0.60 ° u=5 unit v=5 unit w=0.03m h=0.3m		
t=0.80 ° u=5 unit v=5 unit w=0.03m h=0.3m		

Table 1: Auxetic behavior of the re-entrant hexagonal structure, proposed by Evans (Jalkh, 2020), simulated by the authors.

Where t is defined as the angle between the concave ribs, u as the total number of divisions along the Y-axis, and v as the total number of divisions along the X-axis, w as the width of the ribs, h as the height of the ribs.

2.2 Setting the Computational Model: Custom Auxetic Patterns and Shells

The parameters u, v, and t are derived from the previous section after understanding the behavior of the system. At this stage, a new auxetic pattern is proposed as an alternative to existing auxetic models using these parameters. The newly created pattern is intended to exhibit concave to convex behavior without requiring additional processing, such as cutting or traditional hinging, as seen in re-entrant structures. In this context, a pattern with concave features is initially considered, and its geometric representation is abstracted before the algorithm is developed. To create the pattern, the first step involves dividing a square unit into eight parts and drawing an arc from the diagonal of the square. In the second step, a curve is drawn connecting this arc with the y-axis. In the third step, a mirror operation is applied to the shape obtained in the second step, and the three created curves are combined to form a corner of the pattern. Finally, a polar array process is applied to this created unit, completing the final pattern **(Figure 5).**

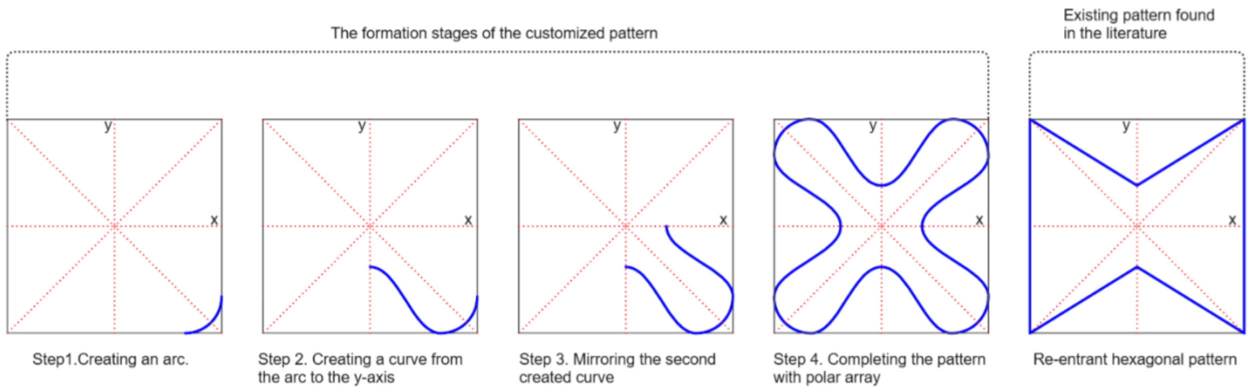


Figure 5: Steps to create a new auxetic pattern.

To explore potential architectural applications of the customized auxetic structure, a three-dimensional (3D) shell structure is created from the proposed auxetic pattern. Due to limitations in the visual programming language (such as a high number of vertices and extended computation time) when generating a shell-like form from this model, a custom code is written in the C# programming language **(Figure 6).** The input values in this code are as follows: interval UT = the total value of the shell structure on the y-axis, interval VT = the total value of the shell structure on the x-axis, int NU = the total number of customized pattern units created along the y-axis (taken as 10 in the created example), and int NV = the total number of customized pattern units created along the x-axis (taken as 15 in the created example). The generated code creates U and V lists by dividing the lengths of two vectors named UT and VT into NU and NV ranges, respectively. The U and V lists are thereby created to contain a specific number of intervals, with each interval dividing the vector lengths into equal parts.

```
Script component: C#

/**/
private void RunScript(Interval UT, Interval VT, int NU, int NV, ref object U, ref object V)
{

  double dU = UT.Length / NU;
  double dV = VT.Length / NV;

  List<Interval> u = new List<Interval>();
  List<Interval> v = new List<Interval>();

  Interval uInterv = new Interval(0, dU);

  for(int j = 0; j < NV; j++)
  {

    for(int i = 0; i < NU; i++)
    {
      u.Add(uInterv);
      uInterv = new Interval(uInterv.Max, uInterv.Max + dU);
    }
    uInterv = new Interval(0, dU);
  }

  U = u;

  Interval vInterv = new Interval(0, dV);

  for(int j = 0; j < NV; j++)
  {

    for(int i = 0; i < NU; i++)
    {
      v.Add(vInterv);
    }

    vInterv = new Interval(vInterv.Max, vInterv.Max + dV);
  }

  V = v;
```

Figure 6: Script created in C# programming language to create a 3D shell structure.

2.3 Digital Fabrication

Additive manufacturing processes such as FDM (Fused Deposition Modeling) and SLS (Selective Laser Sintering) are good alternatives for producing auxetic designs with geometric complexity (Bol et al., 2024). In this study, the FDM technique will be used to save time and quickly produce parts, as 3D parts are directly heated and extruded through a nozzle from a CAD file. At this stage of the study, two materials with different mechanical properties are selected to examine auxetic behavior: one flexible and one rigid. First of all, thermoplastic polyurethane (TPU) is chosen as the flexible material due to its superior elasticity compared to other available thermoplastic polymers (Elmrabet & Siegkas, 2020). Secondly, polylactic acid (PLA) is chosen as a rigid material due to its ability to be processed at lower temperatures while maintaining high dimensional accuracy (Ramírez-Revilla et al., 2022), compared to alternatives such as acrylonitrile butadiene styrene (ABS), acrylonitrile styrene acrylate (ASA), and polyethylene terephthalate glycol (PETG). **Figure 7** illustrates the digital fabrication stages of models created.

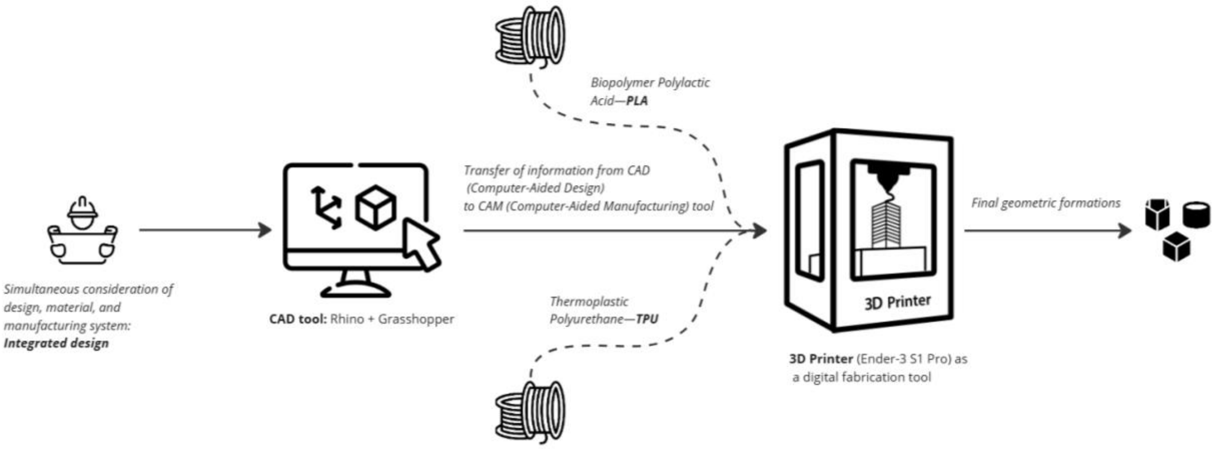


Figure 7: Illustrating the digital fabrication stages of the designed auxetic structures.

2.4 Physical Experiments

Simulations conducted solely in computational environments are insufficient for accurately capturing auxetic effects. Therefore, the relationship between material behavior and the proposed cellular arrangement should rather be empirically tested. Auxetic behavior is influenced by factors such as geometric design (special cellular arrangements), material type, and the direction of the applied force. In this regard, the impact of applied forces is examined following the digital fabrication process. Given that auxetic structures are highly sensitive to external forces, as illustrated in the methodological framework, an exploratory investigation is conducted by manually applying force along different axes. This experimental approach provides a deeper understanding of material responses and smart transformations. Subsequently, displacement is measured with a ruler by marking reference points at the sample's edges before and after force application. Thus, the study systematically analyzes the impact of two materials with distinct properties on auxetic behavior.

3. RESULTS & DISCUSSION

In this study, design parameters were defined to a system exhibiting auxetic behavior, and the system's behavior was tested in both computational and physical environments. The findings will be discussed based on prototypes made from different materials and geometric variations.

3.1 Prototype Comparisons

To test whether the initially developed design parameters meet geometric and behavioral relationships in a physical environment, small-scale prototypes were produced and physical experiments were conducted. Small-scale prototypes were developed by printing grid-structured samples with dimensions of 150x150x3 mm. Subsequently, in-plane and out-of-plane forces were applied to observe the morphological effects as well as limitations and potentials of different material types.

The results of physical experiments conducted using two different materials—rigid (PLA) and flexible (TPU)—are presented below **(Table 2).** First, the sample created with Biopolymer Polylactic Acid showed no deformation when an in-plane tensile force was applied, and no auxetic behavior was observed. Additionally, when the magnitude of the force was further increased, fractures occurred between the unit cells. This material was deemed unsuitable for further studies due to issues such as brittleness, stiffness, and lack of flexibility.

The sample made from Thermoplastic Polyurethane, although slower and requiring more time to print, was found to be successful in exhibiting auxetic behavior **(Table 3).** When in-plane tensile force was applied to this material, two separate shape deformations were observed, and these displacements were measured and recorded as 2.5 cm and 6 cm, respectively. When out-of-plane force was applied to the samples, the Biopolymer Polylactic Acid showed less capacity for curvature formation compared to the Thermoplastic Polyurethane.

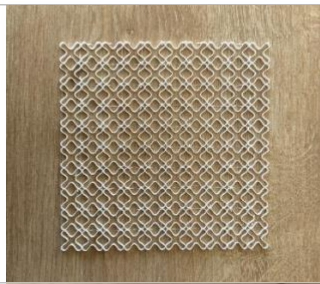
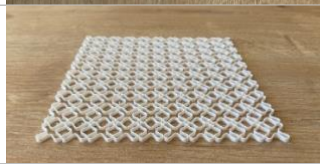
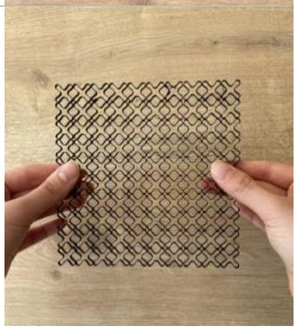
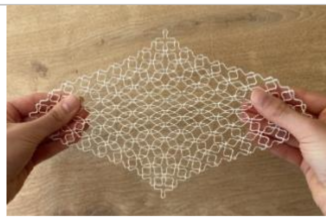
Material	Biopolymer Polylactic Acid	Thermoplastic Polyurethane
Top View		
Front View		
In-plane Force	 relaxed and stretched state	 **1. Shape Deformation** relaxed ⟶ stretched state *a displacement of 2,5 cm*  **2. Shape Deformation** relaxed ⟶ stretched state *a displacement of 6 cm*
Out of Plane Force	 minor monoclastic behavior	 monoclastic behavior

Table 2: Physical testing of prototypes made from Biopolymer Polylactic Acid (PLA) and Thermoplastic Polyurethane (TPU).

Material	*Biopolymer Polylactic Acid (PLA)*	*Thermoplastic Polyurethane (TPU Flex 95A)*
Auxetic pattern	Custom pattern	Custom pattern
Pattern size	150x150 mm	150x150 mm
Material thickness	3 mm	3 mm
Print speed	100 mm/s	20 mm/s
Print time	1 and a half hours	12 and a half hours
Machine type	Ender-3 S1 Pro	Ender-3 S1 Pro
Technology used	Fused deposition modeling (FDM)	Fused deposition modeling (FDM)
Flexibility feature	Limited	High
Displaying curvature?	Yes	Yes
Extruder temperature	210 °C	230 °C
Table temperature	75 °C	50 °C
Does it exhibit auxetic behavior?	No	Yes

Table 3: Comparison of prototypes made of Biopolymer Polylactic Acid and Thermoplastic Polyurethane.

3.2 Pattern Variations

The custom-designed pattern was placed on a 10x10 grid in the algorithmic design environment, and the deformation mechanism of the system was examined to observe auxetic behavior. When the angle parameter t, which triggers shape distortions in the pattern, was varied, the system's behavior changed accordingly. For instance, as t increased from 0.00 to 0.60, the system transitioned from convex to concave behavior. As the t parameter approached 1, the system contracted, resulting in smaller pores. Conversely, as t approached 0, the pores expanded **(Table 4a).** To address various architectural needs and further refine the auxetic structure, a point attractor that reacts to the existing curves has been incorporated into the system. By breaking the uniformity observed in **Table 4a**, this approach produced alternative configurations. Various states based on different parameters are documented below **(Table 4b).**

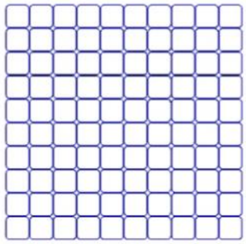
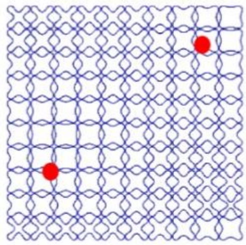
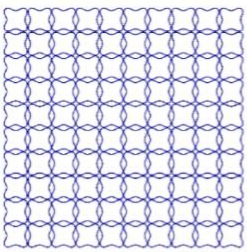
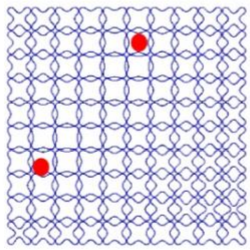
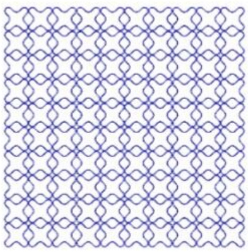
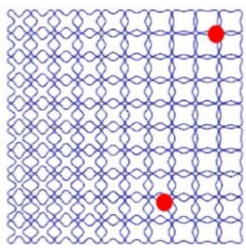
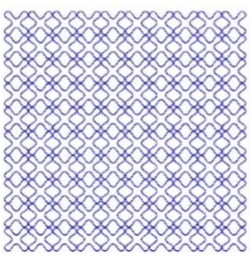
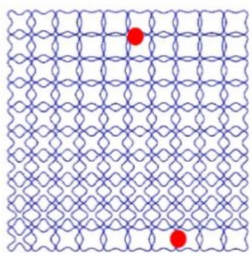
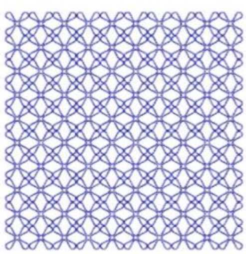
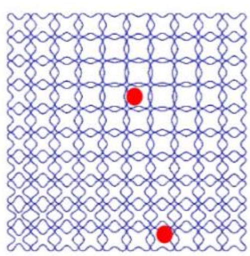
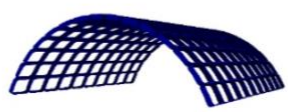
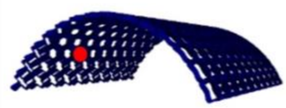
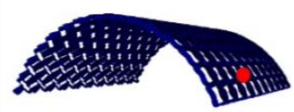
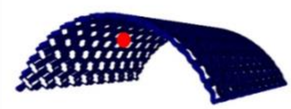
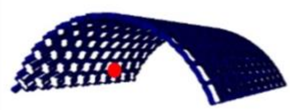
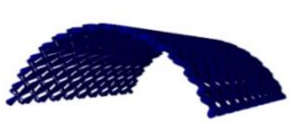
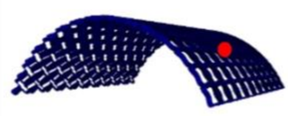
(a) Parameters	Top view	(b) Parameters	Top view
t=0.00 ° u=10 unit v=10 unit		State1 u=10 unit v=10 unit	
t=0.20 ° u=10 unit v=10 unit		State2 u=10 unit v=10 unit	
t=0.40 ° u=10 unit v=10 unit		State3 u=10 unit v=10 unit	
t=0.60 ° u=10 unit v=10 unit		State4 u=10 unit v=10 unit	
t=0.80 ° u=10 unit v=10 unit		State5 u=10 unit v=10 unit	

Table 4: Exploration of pattern variations:
(a) States created by changing t parameter
(b) States created with point attractor (red dot).

To explore the potential architectural applications of a customized auxetic structure and to observe its transition from a planar state to a out-of-plane state, a three-dimensional (3D) shell structure was generated through coding. The dimensions of the ribs in the unit cell of this structure were kept constant, with a width of 0.05 m and a height of 0.3 m. The functionality of the code was tested in two distinct stages. In the first stage, when the angle parameter t of the customized auxetic pattern was varied, the resulting patterns were successfully generated on a monoclastic shell, and different phases of auxetic behavior were observed. As the parameter t approached 1, the porosity of the shell decreased and became more compacted **(Table 5a).** In the second stage, the effect of a point attractor integrated into the algorithm was examined. During this phase, the porosity within the monoclastic shell structure varied regionally, leading to the emergence of diverse conditions **(Table 5b).**

Table 5: Transformation of customized auxetic system into monoclastic shell structure:
(a) States created by changing t parameter
(b) States containing point attractor (red dot).

(a) Parameters	Two point perspective view	(b) Parameters	Two point perspective view
t=0.00° u=10 unit v=15 unit w=0.05 m h=0.3 m		State1 u=10 unit v=15 unit w=0.05 m h=0.3 m	
t=0.20° u=10 unit v=15 unit w=0.05 m h=0.3 m		State2 u=10 unit v=15 unit w=0.05 m h=0.3 m	
t=0.40° u=10 unit v=15 unit w=0.05 m h=0.3 m		State3 u=10 unit v=15 unit w=0.05 m h=0.3 m	
t=0.60° u=10 unit v=15 unit w=0.05 m h=0.3 m		State4 u=10 unit v=15 unit w=0.05 m h=0.3 m	
t=0.80° u=10 unit v=15 unit w=0.05 m h=0.3 m		State5 u=10 unit v=15 unit w=0.05 m h=0.3 m	

3.3 Evaluation of the Outputs

In this study, a new auxetic system was developed through physical prototypes using PLA and TPU. The TPU-based prototype exhibited two distinct deformation modes, confirming auxetic behavior. In the literature, Ozdemir et al. (2022) explored the architectural potential of these materials by creating a self-shaping auxetic shell. For the 1:10 small-scale prototype, they used PLA. In their study, no shape transformation was observed between the auxetic geometry units. Instead, they utilized the tunability of auxetic geometries, demonstrating that variations in geometric parameters influenced the shell’s curvature. However, unlike their study, this work preserved the movable mechanism of the auxetic system, enabling shape deformations.

Belanger et al. (2018) employed auxetic cutting patterns to fabricate slumped glass structures, leveraging the curvature-forming and acoustic properties. However, in their study, the movable auxetic mechanism was locked after fabrication, rendering it static. In contrast, the present study proposes the development of interactive, adaptive structures that respond to user needs and engage with their environment, envisioning future architectural scenarios. The auxetic system developed in this study exhibits adaptive properties due to its force-sensitive nature. These structures have various potential applications in architecture. One application is flexible and dynamic partitioning systems that allow a single space to adapt to different functions. Another application involves interactive installations created through auxetic surfaces that respond to touch or pressure.

For large-scale architectural applications, the designed system can achieve self-activation through two methods: integration with electrical control systems or passive mechanisms. The first approach involves costly kinetic mechanisms, requiring maintenance and energy consumption, making it unsustainable. Therefore, this study proposes the second approach: passive systems. Within this scope, the integration of auxetic systems with double-layered polymers could enable the development of dynamic shading systems.

4. CONCLUSION

Auxetic systems are rarely encountered in the field of architecture and continue to be experimentally developed by various researchers. In this study, a novel auxetic material system has been designed by introducing various design parameters for the use of auxetic systems in architecture. The proposed system was tested using physical prototypes made from different materials, and two distinct types of shape deformation were observed, confirming its auxetic behavior. In this study, the first type of shape deformation was utilized due to its more controlled nature and minimal displacement. However, in future research, the second type of shape deformation could also be used to develop environmentally responsive adaptive solutions.

The system developed in this research holds potential for various applications in future studies. Firstly, the designed system offers a promising approach for situations in architecture where variable environmental conditions are desired, such as acoustic manipulation, lighting, and airflow control, due to its ability to create variable porosity. Furthermore, due to the sound absorption properties of auxetic materials, they can be utilized as surface panels in interior spaces where excessive noise is undesirable and their performance could then be evaluated. Lastly, cases where regionally variable porosity is created allow for the creation of visually interactive systems for exhibition and gallery spaces by incorporating different colors and textures.

The high cost and limited availability of shape-memory polymers have hindered the testing of the system under activation by external stimuli such as temperature and humidity. By programming the expansion and contraction behavior of auxetic structures using materials such as bilayer polymers, future developments could contribute to the creation of climate-responsive facade systems that adapt to environmental changes. For instance, a dynamic facade or shading system could expand in hot weather to enhance airflow and/or provide shading, while contracting in cold conditions to improve thermal comfort.

Due to limited access to robotic fabrication, the physical prototypes in this study were constrained by the build volume of a 3D printer. Future research could explore collaborations in robotic fabrication, enabling the production of large-scale auxetic structures through robotic arms, the development of modular auxetic panels, and their robotic assembly. Such collaborations could facilitate the scalability and feasibility of auxetic systems in architectural applications. This research is expected to expand the conceptual framework of auxetic materials and inspire future studies to develop innovative solutions.

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Conflict of Interest Statement

The authors declare that there are no financial or other significant conflicts of interest that could have influenced the outcomes or interpretations presented in this study.

Author Contributions

Zehra Güloğlu: Conceptualization, Methodology, Validation, Investigation, Writing - original draft, Visualization. **Sevil Yazıcı:** Conceptualization, Investigation, Writing - review & editing. All authors have read and agreed to the published version of the manuscript.

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