ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL

COMPUTATIONAL DESIGN OF SPACE-ADAPTIVE STRUCTURES FOR POST-DISASTER SHELTERING

M.Sc. THESIS

Furkan Berke ÇİLESİZOĞLU

Department of Architecture

Environmental Control and Construction Technologies Programme

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

AFET SONRASI BARINMA İÇİN UZAM-UYARLANABİLİR YAPILARIN HESAPLAMALI TASARIMI

YÜKSEK LİSANS TEZİ

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Furkan Berke ÇİLESİZOĞLU, a M.Sc. student of ITU Graduate School student ID 502221505, successfully defended the thesis entitled "COMPUTATIONAL DESIGN OF SPACE-ADAPTIVE STRUCTURES FOR POST-DISASTER SHELTERING", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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to my family and professors who unconditionally believed in me and supported my academic journey.

FOREWORD

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Furkan Berke ÇİLESİZOĞLU
(Architect)

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ABBREVIATIONS

2D	: Two-Dimensional
3D	: Three-Dimensional Printing
3DP	: Three-Dimensional Printing
AD	: Algorithmic Design
BIM	: Building Information Modeling
CAD	: Computer Aided Design
CD	: Computational Design
CDT	: Computational Design Thinking
CNC	: Computer Numeric Control
DoF	: Degree of Freedom
DR	: Dynamic Relaxation
FEA	: Finite Element Analysis
FDM	: Fused Deposition Modeling
FEM	: Finite Element Method
FRLC	: Fiber Reinforced Lightweight Concrete
MDF	: Medium Density Fiber
NURBS	: Non-uniform rational B-spline
PD	: Parametric Design
PLA	: Polylactic Acid
TBEC	: Turkey Building Earthquake Code
TS	: Turkish Standard

SYMBOLS

α	: Angle
δ	: Displacement
σ	: Stress
E	: Modulus of Elasticity
E_d	: Earthquake Effect
G	: Dead Load
PGA	: Peak ground acceleration [g]
PGV	: Peak ground velocity [cm/s]
Q	: Live Load
R_x, R_y, R_z	: Rotation
S_{aeD}(g)	: Design Spectral Acceleration
S_1	: Map spectral acceleration coefficient for 1.0-second period
S_{D1}	: Design spectral acceleration coefficient for 1.0-second period
S_{DS}	: Short-period design spectral acceleration coefficient [dimensionless]
S_S	: Short-period map spectral acceleration coefficient [dimensionless]
T_x, T_y, T_z	: Translation
T(s)	: Period

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COMPUTATIONAL DESIGN OF SPACE-ADAPTIVE STRUCTURES FOR POST-DISASTER SHELTERING

SUMMARY

Earth is in a continuous state of revolution and evolution. These transformations are directed by self-organized mechanisms driven by the pursuit of a minimum energy state. With advancements in technology, it has become apparent that such systems can be observed at every scale of nature. Elements are interconnected through dynamic interscalar relationships, exhibiting emergent qualities. These systems exist in equilibrium and are inherently adaptive, constantly responding to changes by either resisting or accommodating them. Moreover, these principles are also evident in cultural systems. However, civilization has often been considered an antithesis to nature's inertia: whereas nature is balanced and in motion, humanity is progressive yet stagnant. Recent global catastrophes, intensified by broader patterns of climate disruption, have revealed the vulnerabilities of a static building culture, mostly its inability to adapt to environmental changes and forces. Combined with the environmental impact of construction and the depletion of material and energy resources, these shifts underscore the urgency of developing intelligent, resource-efficient design solutions. In parallel, cultural transformations are also prompting contemporary architecture to prioritize flexibility and reusability. Therefore, changing times require a changing architecture that can respond to changes.

In the field of adaptive architecture, despite increasing interest and necessity, structural systems adapting to changes have not been clearly defined or widely established. Space-adaptive structures, within the scope of this research, are defined as adaptive systems capable of generating spatial configurations with altered qualities through reassembly and reconfiguration of their components. These systems require interdisciplinary collaboration between research fields such as structural engineering and computational design, supported by knowledge from kinematics and robotics. This shift also necessitates a rethinking of design and tectonics, as performative, dynamic, and interactive aspects become increasingly important in these structures.

Computational design represents a significant milestone in understanding the complex behaviors of space-adaptive structures and allows us to design them, with a synchronous perspective that involves all the design possibilities. Design possibilities multiply due to the transformation capabilities of these systems. Through the component-system relations, distinct design characteristics of space-adaptive structures are analyzed and identified as reassembly, reconfiguration and response. Components of a space-adaptive structure are reassemblable parts that are designed for multiple assemblies and disassemblies. Connections between components are uniquely engineered to make multiple configurations possible at a variety of angles. Through reconfigurable mechanisms, structural arrangements can be modified without full disassembly, enhancing the response to changing demands. Thus, space-adaptive structures respond to internal and external stimuli as a system through reassembly and reconfiguration of their components.

Methodology follows a research-through-design approach to investigate rule-based and case-specific architectonics of these three design characteristic. Three case-studies corresponding to three design characteristics are designed and analyzed in the scope of this thesis.

The rule-based analysis focuses on the underlying geometry of the case-studies through shape computing and rules presented on graphs in 2D paper space. As such, positioning and pairings of the components are identified to create an understanding not based on objects or geometries, but instances of geometries repeated in different loops in different positioning with different pairings. Positioning and pairing of components create complex assemblies where components move together and are constrained against each other. Assemblies can be reassembled through these rules, whereas configuration and reconfiguration occur in the range of motion defined by the rules for each assembly and reassembly.

The case-specific analysis investigates the instances of space-adaptive structures, defined by choices (materials, dimensions, detailing) and factors (environmental, structural, functional) and generated through these parameters. Cases are computationally designed and display a complete design-to-fabrication-to-adaptation workflow.

The first design focuses on the reassembly aspect. It explores the possibilities of producing and generating a structural system composed of disassemblable and reassemblable components. These components are based on the most basic geometric form, the triangle, which also holds the potential to approximate free-form topologies through geometric discretization. Assembled through uniquely designed joints in three-dimensional space, these units form form-active structural systems. The design of these systems derives from the stress distributions, force flows, and material optimization embedded within these geometric elements.

The second design focuses on the reconfiguration aspect. Reconfiguration in this project emerges from the simple mechanisms between components. Case-specific decisions were made based on the spatial relationship of the structure, its positioning within space and between different spatial conditions. In this case, planar elements are employed to define a space, while also transferring loads to the ground and maintaining both vertical and horizontal stability. The connection points between these structural components allow for rotations, relative to each other, enabling the global form to dynamically adapt to spatial transformations.

The third design focuses on the response aspect and post-disaster sheltering. Post-disaster sheltering is an area where adaptability is especially important and required. In the aftermath of a disaster, massive transportation and deployment of shelters are required in the immediate timeframe. The structure employs a foldable mechanism that allows for easy transportation through folding into a package, rapid deployment through folding into a gridshell. Gridshell is a form-active structural arrangement where the structural behavior is based on axial transmission of loads made possible by the rotational freedom of its nodal connections and the rigidity of its geometric configuration. The is structure designed to able to respond to the environment by reconfiguring its components to an optimal stage. Structure gradually transforms into an interim stage through the reassembly of lightweight material cladding. This potential for incremental reassembly is achieved through vertical-axis connections at the nodes, allowing the structure to be incrementally upgraded into an intermediate stage for long-term sheltering.

In conclusion, reassembly, reconfiguration and response are interconnected design aspects that offer effective solutions in the contexts where a structure is expected to be flexibly adapted to evolving environmental conditions, user needs, and temporal dynamics i.e., post-disaster sheltering. Designing structures that can be reassembled, reconfigured, and respond according to both environmental conditions and functional demands introduces a new set of architectural values. Within this value system, structural elements, material behavior, movement, and performance become important design elements. Therefore, space-adaptive structures are not only systems that respond to material, structural, and constructional requirements but also represent a new conceptual design framework and a tectonic culture. The relationship between the space and structure is redefined with these new core elements in a more adaptable and responsive manner. This research contributes to the understanding and development of adaptive, computational, and performative design methods capable of shaping the future of architectural thinking, design and practice.

AFET SONRASI BARINMA İÇİN
UZAM-UYARLANABİLİR YAPILARIN HESAPLAMALI TASARIMI

ÖZET

Yerküre, sürekli bir devinim içerisindedir. Yeryüzü ve yeraltı, devrim ve evrim döngüleriyle dönüşümler geçirmektedir. Evrenin kendisi en az enerji durumuna ulaşma istenciyle, içsel bir eğilimle yönlenen kendi kendini örgütleyen mekanizmalar tarafından şekillenir. Teknolojideki gelişmeler sayesinde bu sistemlerin doğanın en alt ölçeğinden, atom altı parçacıklar, en üst ölçeğine, gezegenler, kadar her ölçeğinde olduğu gözlemlenmiştir. Bu sistemlerdeki öğeler, ölçekler arası devingen bağlarla bağlıdır ve kendiliğinden beliren nitelikler sergiler. Doğal sistemler, sürekli bir denge durumunda olup değişimlere direnç göstererek ya da onlara uyum sağlayarak tepki veren doğuştan uyarlanabilir yapılardır. Bu ilkeler yalnızca doğada değil, kültürel yapılarda da görülebilir. Ancak, uygarlık doğanın eylemsizliği karşısında çoğu zaman karşıt bir konumda değerlendirilmiştir. Doğa dengeli ve sürekliyken, uygarlık ilerlemeci ama durağandır. Günümüzde, iklim değişikliğinin daha geniş ölçekli eğilimleriyle şiddetlenen global ölçekteki afetler, durağan yapı kültürünün zayıflıklarını, özellikle de çevresel değişimlere ve dirençlere uyum sağlayamama durumunu ortaya çıkarmıştır. Yapımın çevresel etkisinin, malzeme ve enerji kaynaklarının azalması ile birlikte düşünüldüğünde, bu değişimler, akıllı ve kaynakların kullanımı açısından verimli tasarım çözümlerinin aciliyetini vurgulamaktadır. Buna paralel olarak, kültürel dönüşümler de çağdaş mimarlığın esneklik ve yeniden kullanılabilirliğe öncelik vermesine yol açmaktadır. Dolayısıyla, değişen zamanlar değişime yanıt verebilen değişken bir mimarlık gerektirmektedir.

Doğa olayları doğanın kendi dönüşümü içerisinde olağandır. Ancak, içinde bulunduğumuz yüzyıl, doğadaki değişim ve dönüşümlerin, mimarlığın doğaya uyumsuzluğuyla da tetiklenen, yıkıcı ve bozucu boyutlara eriştiği bir dönemdir. İklim değişikliğiyle birlikte artan aşırı hava olayları, sıcaklık değişiklikleri yapılı çevrenin bu değişken koşullara karşı uyumlu biçimde tasarlanmasını zorunlu kılmaktadır. Yaşanan yıkıcı depremler, yapı stokunun, yapma biçimlerimizin ve kentleşme anlayışının yetersizliklerini ortaya koymaktadır. Benzer biçimde, göç ve salgınlar da yaşam alanlarının birden çok işleve uyum sağlayacak biçimde dönüşebilmesi gereğini açıkça gözler önüne sermiştir. Enerji ve kaynak kıtlığı gibi çok yönlü küresel sorunlar, yapım tekniği ve malzeme kullanımında da yeniliklere ve yaratıcı çözümleri öne çıkarmaktadır.

Mimarlık, bu dönüşümde yeni bir değerler dizisi arayışı içindedir. Uyarlanabilir yapılar, artan ilgiye ve gerekliliğe karşın mimarlık pratiğinde henüz net biçimde tanımlanmamış ya da standartlaşmamıştır. Bu çalışmanın kapsamında, uzam-uyarlanabilir yapılar; bileşenlerinin yeniden birleştirilmesi ve yeniden biçimlendirilmesi yoluyla yeni niteliklere sahip uzamsal biçimlenişler üretebilen uyarlanabilir sistemler olarak tanımlanır. Bu yönleriyle diğer uyarlanabilir yapı tiplerinden farklılaşır ve özgün bir çalışma alanını temsil ederler.

Bu sistemler, yapısal mühendislik ile hesaplamalı tasarımın yanı sıra kinematik ve robotikten türeyen bilgiyle desteklenen disiplinler arası bir iş birliği gerektirir. Bu yöntemsel dönüşüm, tasarımın edimsel, devingen ve etkileşimli yönlerinin bu yapılarda giderek daha belirgin hale gelmesiyle, tasarımın ve tektoniğin yeniden ele alınmasını da gerekli kılar. Bu bağlamda, hesaplamalı tasarım yöntemleri ve sayısal ortamlar, karmaşık yapısal davranışların ve malzeme davranışlarının anlaşılması ve uyarlanabilir yapıların tasarlanabilmesi açısından önemli bir eşiği temsil eder.

Hesaplamalı tasarım uzam-uyarlanabilir yapıların karmaşık davranışlarını anlamada önemli bir kilometre taşını temsil eder ve bu yapıları tüm tasarım olasılıklarını içeren eşzamanlı bir bakış açısıyla tasarlamamızı sağlar. Tasarım olasılıkları sistemin dönüşebilirliğinden dolayı katlanarak artar. Bundan dolayı, tezin kapsamında bileşen-sistem ilişkileri aracılığıyla ayırt edici tasarım özellikleri; yeniden birleşim, yeniden biçimleniş ve duyarlılık olarak analiz edilmekte ve tanımlamaktadır. Uzam-uyarlanabilirlik, parçadan bütüne doğru birkaç temel özgün özellikten kaynaklanır. Bu sistemler, birden fazla kez takılıp sökülebilen, yeniden ayarlanabilen bileşenlerden oluşur. Bağlantı elemanları, çeşitli açılarda yapılandırmaya olanak verecek şekilde özel olarak tasarlanmıştır. Bileşenlerin bazıları ya da hepsi değiştirilebilir, yenilebilir ve tamir edilebilir. Tasarım başka konumlara taşınabilir ve farklı biçimlerde yine aynı bileşenlerle yapılabilir. Bu tasarım anlayışında, tasarım parçadan başlasa da bütün göz önünde bulundurularak yapılır. Tasarımın kendi üzerine kıvrılan tasarım çizgisinin ötesinde, bu tasarım düşüncesinde eş zamanlı bir düşünme gereklidir. Bu tasarım düşüncesi hesaplamalı, çok yönlü ve tasarım öğelerinin birbirine bağımlı olduğu bir dizge izler. Tasarım aracı ve tasarım ortamı da bu tasarım ilkelerine etkin bir şekilde yanıt verebilmelidir. Yeniden biçimlendirilebilen mekanizmalar yoluyla, değişen ihtiyaçlara yanıt verilmesi güçlendirilerek, tamamen söküm yapılmadan yeniden düzenlemeler yapılabilir. Böylece, uzam-uyarlanabilir yapılar içsel ve dışsal uyaranlara bir sistem olarak bileşenlerinin yeniden birleştirilmesi ve yeniden biçimlendirilmesi yoluyla yanıt verir.

Tasarımın bileşenleri arasındaki ilişkiler, tasarımın bütününü değiştirme yetisi verir. Bu şekilde, yapının tamamı ya da hiçbir bölümü sökülmeden yalnızca belirli mekanik dönüşümlerle değişen ihtiyaçlara daha etkin yanıt verilebilir. Bileşenlerin ve uyarlanabilir birleşim elemanlarının özgün tasarımı, tasarım ortamındaki geleceğe dönük biçim türevlerinin temsiliyle yapılabilir. İleri görüşlü ve özgür bir tasarım anlayışıyla, tasarım tek bir ana ya da tek bir biçime bağlı kalmadan bileşenlerin konumlarının ya da bileşenlerin biçimlenişlerinin farklılaşmasıyla üretken tasarımlar oluşturulabilir. Birleşim ölçeğinde ise bu sınırların belirlenmesi ya da tasarımcı tarafından hesaplanmasıyla bu farklı biçimlenişler olanaklı kılınmalıdır.

Tasarım, tasarımcının tasarladığı değişmez nesne değil, kullanım gereksinimleri, işlevsel değişiklikleri, çevresel etmenler ve etkilerle yeniden biçimlenebilir, esnek bir olanaklar dizgesidir. Bu olanaklılık, malzeme, bileşen ve sistem ölçeklerinde bütünsel bir tepkiselliğin ürünüdür. Malzeme odağında, malzemenin kendi iç yapısı, gömülü biçimsel davranışlar ve dış koşullara göre biçim değiştirme özelliği tasarımcının malzemeyi bu özelliklere göre kullanmasıyla ve konumlandırmasıyla yapısal bir davranışa dönüştürülebilir. Burada bileşenlerin bütün içerisindeki kurgusu ve bütünün davranışı önem taşımaktadır. Zamana bağlı benzetim ve malzeme tabanlı hesaplamalı yöntemleriyle bu fiziksel davranışlar ve şekil değiştirmeler öngörülebilir, hesaplanabilir.

Çalışma, araştırma yöntemi olarak, bu üç tasarım özelliğinin kural-temelli ve vakaya-özgü arkitektoniğini incelemek amacıyla, bu tez kapsamında tasarlanıp analiz edilen üç vaka çalışması üzerinden, tasarım-yoluyla-araştırma yaklaşımını benimsemektedir. Her bir vaka çalışması uzam-uyarlanabilir yapıların tanımlayıcı niteliklerini öne çıkaran hesaplamalı tasarım yöntemleri içermektedir. Bu araştırma, uzam-uyarlanabilir yapıların özgün özelliklerini ortaya koyan malzeme tabanlı, edimsel ve hesaplamalı tasarım yöntemleriyle tasarlanmıştır. Böylece, bu tasarımlar, uzam-uyarlanabilir yapılar bağlamında kuramsal çalışmalar değil, teknik ve mimari çözümlerle zenginleştirilmiş, çok yönlü örneklemler sunmaktadır.

Kural-temelli analiz, iki boyutlu kağıt düzleminde grafikler üzerinde sunulan kurallar aracılığıyla, vaka çalışmalarının temel geometrisine şekil hesaplama yöntemiyle odaklanır. Böylece, bileşenlerin konumlandırılması ve eşleştirilmesi, nesnelere veya geometrilere değil, farklı konumlandırılmalar ve farklı eşleştirmelerle farklı döngüler içinde yinelenen geometrik örnekler üzerine kurulu bir anlayış oluşturmak amacıyla tanımlanmaktadır. Bileşenlerin konumlandırılması ve eşleştirilmesi, bileşenler birlikte hareket ettiğinde ve birbirlerine karşı kısıtlandığında karmaşık bileşimler yaratır. Bileşimler bu kurallar aracılığıyla yeniden birleştirilebilirken, biçimlendirme ve yeniden biçimlendirme her bir bileşim ve yeniden birleştirme için tanımlanan kuralların belirlediği hareket aralığında gerçekleşir.

Vakaya-özgü analiz, kararlar (malzemeler, boyutlar, detaylandırmalar) ve faktörler (çevresel, yapısal, fonksiyonel) ile tanımlanan ve bu değişkenler aracılığıyla türetilen uzam-uyarlanabilir yapıların örneklerini araştırır. Vakalar hesaplamalı tasarlanmıştır ve tamamıyla tasarımdan üretime ve üretimden uyarlanabilirliğe doğru bir iş akışı sergilemektedir.

İlk tasarım, yeniden birleştirme özelliğine odaklanmaktadır. Bu tasarım, sökülebilir ve yeniden birleştirilebilir bileşenlerden oluşan bir yapısal sistem üretme ve oluşturma olasılıklarını araştırmaktadır. Yapısal birimleri, en basit geometrik biçim olan üçgenlerden oluşur. Bu geometrik biçimler aynı zamanda bir serbest biçimli bir topolojinin de geometrik çözümlenmesindeki yakınsamayı sağlayabilecek niteliktedir. Üç boyutlu bir düzlemde özgün birleşim elemanlarıyla bir araya gelebilen bu birimler, biçim etkin yapısal sistemler oluşturmaktadırlar. Yapısal birimler, bu geometrik birimlerdeki gerilim, kuvvet akışları ve malzeme iyileştirmesinden türetilmiştir.

İkinci tasarım, yeniden biçimlendirme özelliğine odaklanmaktadır. Bu tasarımda yeniden biçimlendirme, bileşenler arasındaki basit mekanizmalardan ortaya çıkmaktadır. Vakaya-özgü kararlar, yapının uzamsal ilişkisine, uzam içindeki konumuna ve farklı mekânsal koşullar arasındaki yerine dayalı olarak alınmıştır. Burada, düzlemler bir uzam tanımlama yetisiyle, kendi yükünü yere aktarabilecek, düşey ve yatay dengesini sağlayacak şekilde tasarlamıştır. Birleşim noktaları yapısal düzlemlerin birbirine görece şekil değiştirmesini ve bütünsel biçim değişimleriyle uzama uyum sağlamasını sağlar.

Üçüncü tasarım, tepkisellik yönüne ve afet-sonrası barınmaya odaklanmaktadır. Afet-sonrası barınma, uyarlanabilirliğin özellikle önemli ve gerekli olduğu bir alandır. Bir afetin ardından, çok kısa bir zaman diliminde barınakların toplu olarak taşınması ve konuşlandırılması gerekmektedir. Bu yüzden bu tasarım, taşınabilir ve aşamalı olarak eklemlenebilir bir anlayışa dayanır. Tasarım deprem bölgeleri için önceden hazırlanmıştır. Yapı, katlanarak paket haline getirilmesiyle kolay taşınma, ızgara kabuğa geri açılabilmesiyle ise hızlı kuruluma olanak tanıyan katlanabilir bir mekanizma barındırmaktadır.

Izgara kabuk yapı mantığında çalışan yapı, çizgisel yapısal birimlerin düğüm noktalarının dönüş serbestliği ve geometrinin rijitliği dolayısıyla yüklerin eksenel olarak aktarımına dayanır. Yapı, bileşenlerini en uygun duruma yeniden biçimlendirerek çevreye yanıt verebilecek şekilde tasarlanmıştır. Tasarım, hafif malzemeden oluşan dış cephe kaplamasının eklenmesiyle kademeli olarak geçici dönem barınağına dönüşür. Bu kademeli eklemlenme potansiyeli, düğüm noktalarının dikey eksendeki bağlantılarıyla sağlanmaktadır. Yapı, böylece uzun süreli barınma için kademeli olarak bir geçiş dönemi barınağına dönüştürülebilmektedir.

Sonuç olarak, uzam-uyarlanabilir yapılar, yalnızca malzeme, yapı ve yapım kaynaklı gereksinimlere yanıt veren sistemler olarak değil, aynı zamanda çağdaş mimarlık için farklı bir düşünsel çerçeve olarak ele alınmaktadır. Bu sistemler, barınma ihtiyacının acil olduğu durumlarda etkili çözümler sunmakta ve değişen çevresel koşullara, kullanıcı ihtiyaçlarına ve zamansal dinamiklere esnek biçimde uyum sağlayabilmektedir. Yapıların hem çevresel koşullara hem de işlevsel gereksinimlerine göre yeniden birleştirilebilen, yeniden biçimlendirilebilen ve yanıt verebilen şekilde tasarlanması, yeni bir dizi mimari değer ortaya koymaktadır. Bu değerler sisteminde, yapısal öğeler, malzeme davranışı, devinim ve performans önemli tasarım unsurları haline gelmektedir. Dolayısıyla, uzam-uyarlanabilir yapılar yalnızca malzeme, yapısal ve inşaat gerekliliklerine yanıt veren sistemler olmakla kalmayıp, aynı zamanda yeni bir kavramsal tasarım çerçevesini ve bir tektonik kültürü temsil etmektedir. Tez, mimari düşüncenin, tasarımın ve uygulamanın geleceğini şekillendirme yetisine sahip yeni uyarlanabilir, hesaplamalı ve edimsel tasarım yöntemleri sunmaktadır. Mimarlığın merkezinde yer alan uzam ile yapı arasındaki ilişki, bu yeni temel unsurlar ile uyarlanabilir biçimde yeniden tanımlanmaktadır.

1. INTRODUCTION

Global changes such as climate change, resource scarcity, and environmental instability show, architecture must transition toward alternative systems that are responsive, efficient, and resilient. Such systems capable of changing form or behavior in response to external stimuli offer significant potential in addressing these needs (Parlac, 2015b). As environmental and cultural conditions grow increasingly dynamic, architecture must evolve from static constructs to systems capable of responding to changes (Kolarevic, 2015). Adaptability offers a compelling path forward in redefining the practice and theory of architecture. Therefore, this research is driven by the conviction that to bring a dynamic thinking model and design workflow into architectural discourse (Kronenburg, 2015).

This study was motivated by the observations of adaptability in nature. Nature adapts various strategies to adapt to environmental changes through form optimization, behavior, or material redistribution (Menges, 2012a; Parlac, 2015a). Commonly found in mechanical systems and space structures, kinetic and reconfigurable structures introduce motion, transformation, and real-time responsiveness into the built environment (Akgun et al., 2013). These characteristics challenge conventional architectural norms and open new paths for innovation in form, material, and architectural discourse.

In the field of architecture, adaptive or adaptable architecture represents an emerging field with a strong historical background and variety ranging from environmental responsiveness to human interaction (Schmidt III & Austin, 2016; Schnädelbach, 2016). On the user side, digital technologies with advanced sensors and recognition increases the depth and quality of interaction (Chaturvedi et al., 2025). On the structural side, advancements in technologies such as smart materials, actuation and automation allow new strategies to be implemented in buildings for material efficiency (Abdullah & Al-Alwan, 2019; M. Maierhofer et al., 2025). However, efficacy of the structural systems does not solely depend on the active members but also the creativity in geometry, material understanding, and structural design (Forestiero et al., 2018).

In fact, a wide range of design strategies are not determined for these kinds of structures which may be caused by a lack of definition or a frame of specific field. Therefore, the research's first and foremost proposal is to adopt a new term that focuses on adaptability of structures i.e., space-adaptive structures. Under this term, it is possible to identify the frame, scope and design principles.

Space-adaptive structures, represents a complex system that exists in 4D spacetime that requires a design approach that is not stagnated by 2D representations. At the core of this inquiry is the transformative role of computational design (CD) (Lynn & Hoberman, 2016). CD is a design process combining computational methods and algorithmic thinking, in order to understand and fabricate complex systems (Caetano et al., 2020). Looking from a CD lens, it is deemed possible to achieve a full understanding by exploring all the possible configurations of space-adaptive structures. Although some CD approaches or tools were used in previous studies, a complete concept-to-fabrication workflow approach is uncommon.

The 21st century, especially, has been profoundly shaped by a series of global catastrophes, fundamentally altering environmental, social, and architectural paradigms (UNDRR, 2020). Natural disasters, such as devastating earthquakes, hurricanes, tsunamis, and wildfires, have become increasingly frequent and severe, often exacerbated by the effects of climate change. Climate volatility continues to redefine design criteria for architecture (Loonen et al., 2013). Structures must now contend with more extreme environmental conditions while remaining energy-efficient and resource-conscious (Dziadula & Fross, 2022).

Space-adaptive structures in the face of issues can be used to dynamically to answer these challenges and changes. In the case of post-disaster sheltering, deployable structures with transformable capabilities are designed and researched extensively (Cerrahoğlu & Maden, 2024). The researches in this area also focus on settlements and upgradability while the biggest challenge remains adaptivity to environmental context and mass-deployment (Abu-Aridah & Ligler, 2024). A holistic approach to design from-deployment-to-durable sheltering as well as a holistic approach for understanding behavior of structures and their components under the assumed load combinations is deemed necessary for a more capable, durable and sustainable post-disaster sheltering alternatives (Celik, 2019).

1.1 Aim & Scope

This study aims to establish space-adaptive structures as a viable architectural strategy for reducing energy consumption and material usage while enhancing spatial and functional performance. The research proposes that these structures are not just a part of new style or a category but a unique tectonic culture[1] with its own design principles, design workflows, construction methods and architectonic features (Oxman, 2012). Adaptability through its unique connections and open-endedness of its forms, presents a meaningful addition to the relationship of tectonic elements of the space-adaptive structures. Computational design of space-adaptive structures, involves the integration of computational design methods such as algorithmic modeling, generative algorithms, form-finding, structural analysis and solid-based physics simulations into architectural design processes for understanding and achieving higher adaptability (M. Maierhofer & Menges, 2019). As a design thinking model, it is proven as an effective way of designing with multiple parameters and multiple configurations suitable for a (Menges & Ahlquist, 2011)

In the scope of adaptive architecture, adaptive structures include but not limited to deployable, kinetic, active, responsive, reconfigurable, and modular structures. Though space-adaptive structures exclusively focus on the design of structures via form and geometry search. Equally important and defining criteria is the space created and transformed by the structure. This research specifically aims for the structures where space is the changing element, modified by the structure. Material and detailing—core parts of any structural systems—are also discussed as part of the case-based manner. Scope of this research is mainly architectural and structural design, however bridging disciplinary knowledge from engineering, material and computational fields with architecture aims to increase area of knowledge and interdisciplinary information. Following the establishment of foundation of space-adaptive structures, these structures are proposed for post-disaster sheltering. Post-disaster sheltering proves to be a difficult field considering swift transportation and massive construction demands. Research focuses on how can mass transportation, deployment and climate adaptation can be integrated into a space-adaptive shelter.

[1] Tectonics is term that describes combined interrelated roles of structure, construction and materials.

1.2 Outline & Methodology

The study comprises of two core parts. Similar to Isler's ice shells[2], which he created in his youth, this research started on exploration, observation, and understanding how structural systems work, as well as the relationship between material and form (Chilton, 2012). The thesis involves a critical review for basics of structures through forms, application, materials, geometry and structures. Nature-inspired, computational and adaptative design approaches introduces the space-adaptive structures. Aspects of space-adaptive structures are analyzed through establishment of theoretical frameworks and investigation of case-studies based on the methodology (Figure 1.1).

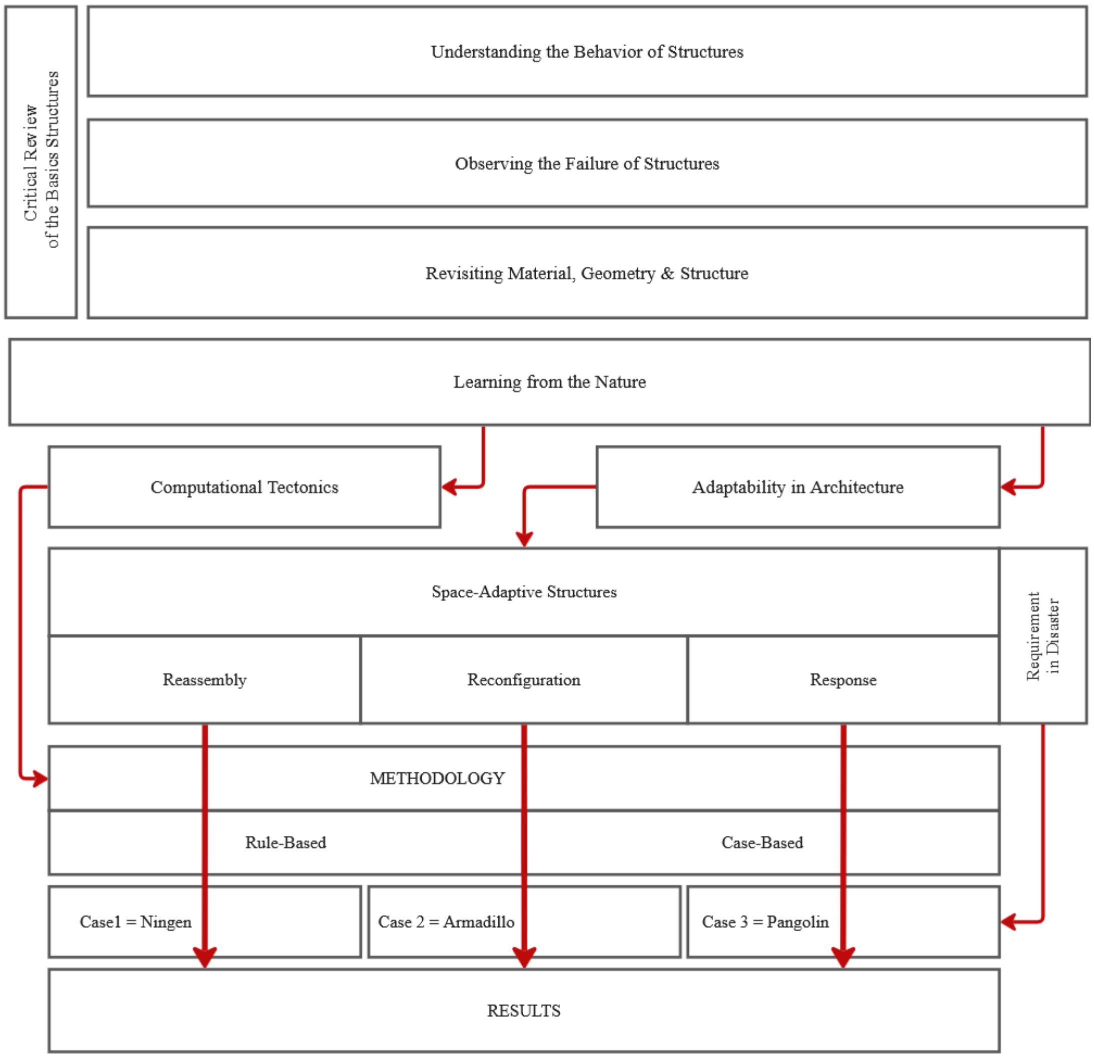

Figure 1.1 : Diagram showing the thesis outline (Cilesizoglu, 2025).

[2] Heinz Isler is known to be experimented with wet, draped textiles in winters in Switzerland. They were frozen, thus taking a form, a creative way to get shell structures (Chilton, 2012).

The thesis begins with Chapter 2, critical review of basics of structures, behavior and form-force relations stand out as a way of both understanding and designing structures. A reconnaissance after the February 6th 2023 Kahramanmaraş earthquake, assesses the current state of structures, including geotechnically and structurally induced failures, and provides empirical evidence on the structural performance. The relation between material, geometry, and structure is explored in the next section. This section is followed by a return to the basics of structures, examining nature as a source of inspiration. A section dedicated to learning from nature deepens the discourse on how natural systems work, and the discussions are expanded to the computational tectonics, computational methods used for interrelational parameters and structural elements.

Chapter 3 focuses on adaptive structures, and space-adaptive structures in particular. It begins with a description of the term “adaptiveness” and a brief examination of the historical and theoretical background of adaptive structures. It is followed by a section focusing on space-adaptive structures. Defining and separating them from other adaptive structures. This part continues with analysis of the core aspects of space-adaptive structures—reassembly, reconfiguration and response—and establishing them. An urgent need for space-adaptive shelters is defined with the minimum requirements.

The methodology of the study is explained in Chapter 4. Research-through-Design approach is explained with additional computational methods to understand the rules and design space-adaptive structures case-studies.

To deepen this understanding, the study conducted and analyzed in depth three case studies corresponding to each aspect. Chapter 5. The case studies are used to verify, expand and research the three aspects. For each case study, first, rules are presented using the methodology, second, case-specific design workflows are explained.

Finally, the research leads to results and discussions about space-adaptive structures and conclusions about the fundamental characteristics and design principles of adaptive structures, by combining and comparing the findings of the studies. An analytical evaluation is conducted with using the data for sheltering requirements and achieved sheltering qualities of the space adaptive shelter discussed in fifth chapter.

2. CRITICAL REVIEW

A critical review is deemed necessary due to this subject's reliance on a search for the new tectonics. As per the thesis, not only are the adaptive architecture terms are in investigation but also the basic terms found in architectural and structural design. The review section follows a simple logic.

First, a theoretical explanation of structural forms. Instead of individual elements or materials, research focuses on the relationship between force and form. This is especially important where the rest of the research does not focus on modern structural elements such as columns, bars or beams but rather on individual structural members.

The review does not rely on only theory but also on field study to both experience the effects of force—earthquake force—both also current use of materials—mostly reinforced concrete—and application—including the faulty applications— of the materials. This was especially important considering the role of application in construction.

Perhaps the most important part in the review is a revisit to the interrelated roles of the material, geometry and structure, as they affect each other in an important way that defines each element (Ashby, 1999). Mathematics as well as nature play a vital role in understanding organizations between parts and interscalar connections (Fratzl & Weinkamer, 2007).

Nature stands out as inspiration for optimization and organization of materials as well as structural compositions of heterogenous systems. Nature itself is built on the equilibrium and balance of hybrid and dynamic systems. Natural systems offer lessons on how the adaptation as a main strategy for material and structural efficacy.

Complexity of nature—though born of internal logics and balance of forces—cannot be understood or re-created without advanced thinking and computing methods. Computational design thinking plays a vital role in understanding and re-creating the complexity of nature. Design of adaptive structures are also increasingly complex due to their complexity. This is why computational design thinking is vital for the thesis.

2.1 Understanding the Behavior of Structures

Structures are systems of interconnected load-bearing and load-resisting members in equilibrium. They are designed in a way to transfer forces to a strong foundation without any plastic deformation. The most common way to define and analyze these structures is by the construction techniques and materials used. This study instead chooses to evaluate structures with their innate behavior under the loads. As Engel (Heino Engel, 2013) defined in his work, the form systems can be considered as form-active, vector-active, section-active, surface-active with a special system for extreme conditions and combined elements height-active and hybrid systems.

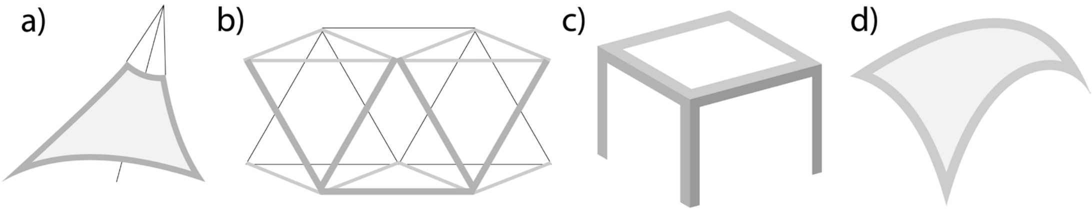

Figure 2.1 : Structural systems classified by Engel (a) form-active, (b) vector-active, (c) section-active, (d) surface-active (Cilesizoglu, 2025).

Form-active systems are the funicular structures that take the load in tension or compression only (Figure 2.1a). Tension-only non-rigid elements fixed to supports take form when under tension, when they are loaded or tensed, and transfer the loads through their form only in axial stress. Since the material itself is unable to bend or doesn’t take any bending moments, it doesn't exhibit a buckling effect. Compression-only structures, such as vaults or arches, as explained in Hooke’s Law, are the inverse of tension-only structures. These structures, through their meticulously calculated forms, eliminate bending moments and transfer loads in compression only.

Vector-active systems, just as funicular systems, transfer loads through their geometrically rigid configurations with hinged connections (Figure 2.1b). They utilize short members to articulate the transfer of loads between members. Since these members are short, they resist buckling and torsion. Elements don’t transfer bending moments. Since they only transfer axial loads, they are an efficient way of spanning long structures without any additional supports in between. Form is, once again, an essential part of these structures. Single and multi-layer systems can be used to increase the span to resist sagging. Single-layer, multi-layer grid shells, trusses, and space-frame structures utilize the use of standardized and basic elements.

Section active systems, resist loads by their cross-section (Figure 2.1c). They not only resist axial loads but are also able to resist bending moments and normal forces. This is extremely useful if we consider the fact that floors, one of the most functional structural members, are situated in Cartesian plane, since we build the floors in horizontal plane, stories in vertical axis[3]. The biggest risks associated with the type of structures involve buckling due to the element length and rigidity of frame structures that must be supported by moment-bracing details. The load transfers between horizontal and vertical elements occur through the joints. Section-active structures as well as surface-active structures are able to transfer unconcentrated loads, distributed and live loads without failing, through bending moments.

Engel (2013), considers surface-active structures to be especially efficient (Figure 2.1d). Surface-active structures, such as shell structures, resist and transfer the loads in various directions. They have the same principles considering the functionality of members as section-active structures. They are able to support distributed loads and able to resist moment. Structural capacity can be increased using folded or bent forms. Similar to principles in form-active structures.

Height-active structures, are subject to increased gravitational and lateral forces, requiring increased lateral stability. The height of the structure makes it important for the structure to transfer loads only along vertical axis. A balance between rigidity and flexibility is increasingly important as the structures are subject to vibration. These structures utilize other force systems to work efficiently. Hybrid structures are types of structures that combine different structures. Systems can work in parallel, while one system transfers the axial stresses the other system can resist the resulting moment. The systems can also work articulately in sequences, with one system resisting vertical loads with axial stresses and another system for spanning.

These are design behaviors but there are also failure modes, another kind of behavior with plastic deformations, decoupling and other undesired but still very real structural behaviors. The following section features global and local behavior and failures observed at the site after the earthquake.

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[3] Fuller argues that our way of building, as well as our perception of space and way of living, is shaped by the gravity.

2.2 Observing the Failure of Structures

On February 6th 2023, two major earthquakes struck southeastern Türkiye (Figure 2.2). The first, with a moment magnitude (M_w) of 7.8, occurred at 04:17 TRT near Pazarcık, Kahramanmaraş, and was followed by a second M_w 7.7 event at 13:24 TRT centered in Elbistan (Ding et al., 2023). A third significant event (M_w 6.4) occurred on February 20, centered in Antakya (Hatay). The M_w 7.8 earthquake was the strongest in Türkiye since the 1939 Erzincan earthquake and ranks as the joint second-largest in the nation's recorded history, after the 1668 North Anatolia earthquake. The damage spanned an area of approximately 350,000 square kilometers, impacting an estimated 14 million people about 16% of Türkiye's population. The confirmed death toll has reached 59,259, with 50,783 in Türkiye and 8,476 in Syria, making it the deadliest earthquake in the region's modern history. An estimated 1.5 million people were left homeless, with countless others displaced or traumatized (Celik et al., 2024).

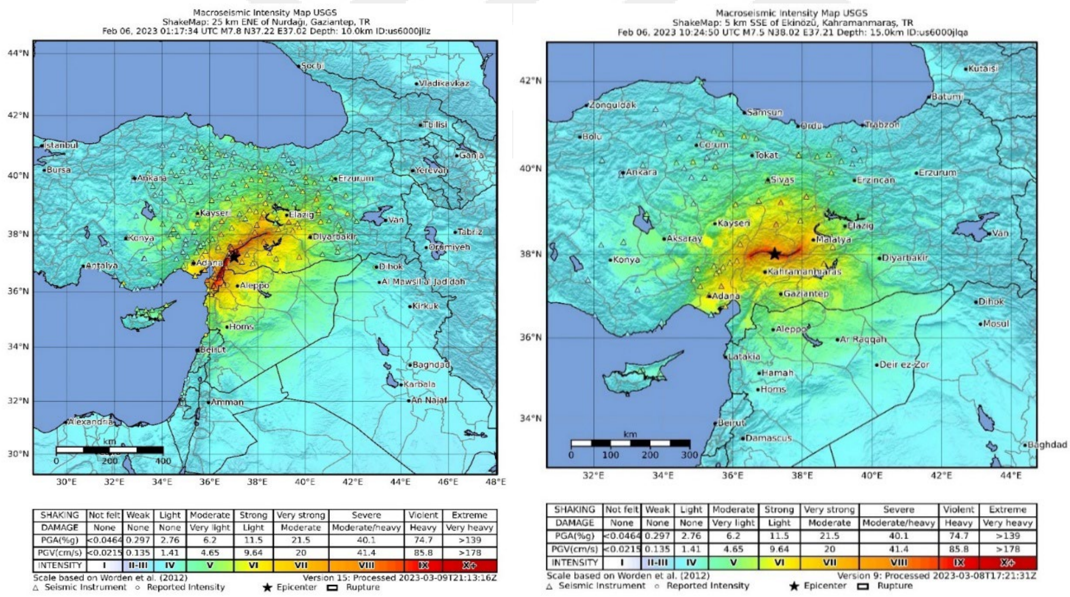

Figure 2.2 : First and second earthquakes (USGS, 2023).

Türkiye lies in a seismically active area and has a comprehensive earthquake code in place. Nevertheless, the events of 2023 highlighted the discrepancy between regulations and real-world construction practices. Numerous buildings collapsed as a result of failing to adhere to structural codes, substandard construction quality, and building on liquefaction-prone soils. This earthquake underscored the repercussions of disregarding seismic risk in design and urban planning.

Earthquakes present rare yet profound opportunities to study the actual behavior of structures under extreme conditions. Due to their magnitude and widespread impact, they provide deeper insights into failure modes, damage typologies, and the interaction between ground behavior and built form. The February 6th 2023 Kahramanmaraş earthquakes in Türkiye exemplify this, revealing critical structural vulnerabilities, the consequences of liquefaction-prone soils, and the importance of rigidity and shear wall implementation in building systems. Towns and villages of Şanlıurfa, Adıyaman, Besni and Gölbaşı districts were investigated for as part of a reconnaissance[4] study on the earthquake struck southeast Turkiye (Figure 2.3).

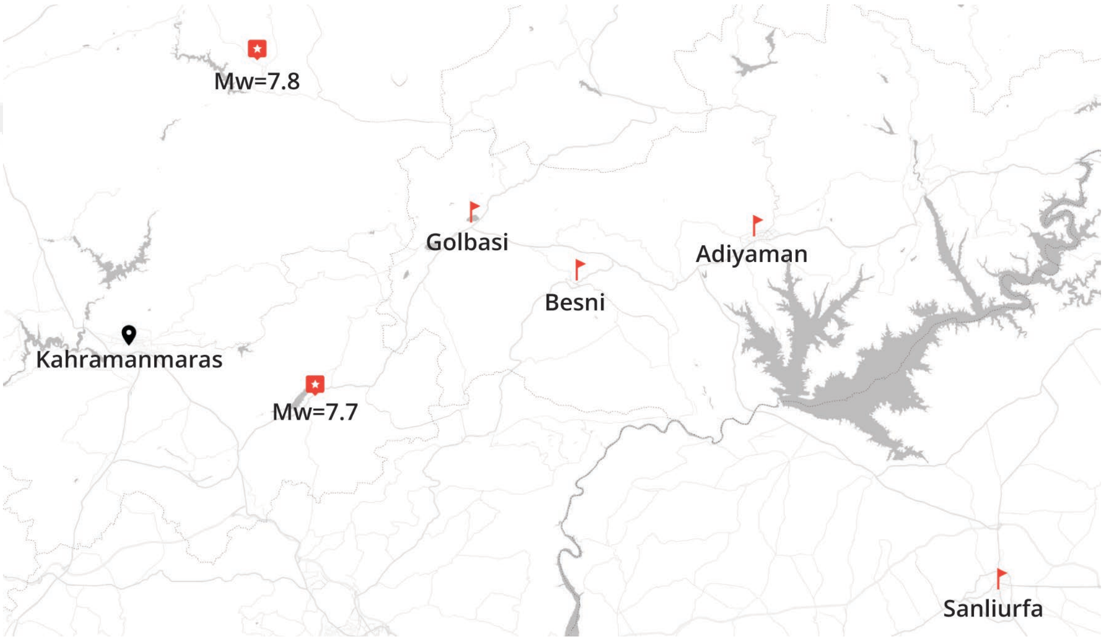

Figure 2.3 : Earthquake epicenters of the February 6th 2023 Kahramanmaraş and reconnaissance locations (Cilesizoglu, 2023).

These cities, which varied in the degree of seismic impact, revealed stark contrasts on damages types resulting from earthquakes, based on the distance to earthquake epicenters and geology of the site (Figure 2.2). Damage types and failure modes were assessed from architectural design perspective (decisions in plan, section and facades, detailing and material quality, structural and non-structural behavior) in five different building typologies: heritage buildings, low-rise buildings, mid-rise reinforced concrete (RC) buildings, pre-fabricated pre-cast RC buildings and steel buildings.

[4] Between May 6 and 7 2023, author take part on independent reconnaissance survey (Figure 2.3) led by Prof. Dr. Oğuz Cem Çelik from Istanbul Technical University.

The observations were made in still-standing heavily and/or moderately damaged buildings. Most of the heritage buildings in the area use stone masonry as construction technique. Masonry structures have inadequate strength—especially shear—and shows vulnerability against lateral forces (Table 2.1).

Table 2.1 : Damage Typologies in Heritage Buildings (Cilesizoglu, 2023).

	Form	Vulnerability to Lateral Forces due to Dome Form
	Design/ Application	Vulnerability to Lateral Forces
	Design/ Application	Vulnerability to Lateral Forces

Large span and heavy domes, form-active structures with adequate efficiency in dissipating loads in all directions, are especially vulnerable to seismic actions, as the dome deforms and loses the ability to resist forces with balance (Figure 2.4a). Masonry uses brittle material with low ductility, such buildings cannot resist to immense amount of shear loads and may collapse. Masonry (stone or brick or hybrid) materials are specifically vulnerable to earthquake effects due to many reasons; various modes of failure of the structure can be observed following an earthquake. Higher mode effects would dominate the behavior, leading to failures above balcony levels. Or, a total collapse of the impact is always possible to observe (Figure 2.4b).

Residential building stock is comprised of mid-rise RC buildings—most were heavily damaged—and low-rise buildings. The most common non-structural damage around the area was on facade elements and collapse of masonry infill walls (in-plane or out-of-plane failures). Most of structural damage can be summarized as inadequate workmanship, post-construction architectural modifications, and lack of code-compliance (Table 2.2). Lack of shear walls must be noted which increased the seismic demands and story drifts.

Figure 2.4 : (a) The most important mosque in Adıyaman, Adıyaman Grand Mosque, after the earthquake. (b) Base of the minaret, minaret is missing (Cilesizoglu, 2023).

Table 2.2 : Damage Typologies in RC Buildings (Cilesizoglu, 2023).

	Application	Corrosion
	Application	Bar buckling due to wrong stirrup application
	Design	Plastic hinge formation due to soft/weak floor
	Design/ Application	Shear wall failure due to poor concrete quality and over-loading
	Design/ Planning	Hammering due to lack of seismic gap and structural system height difference

In many buildings, failure occurred under shear. Quality of concrete was substandard, and the workmanship was inadequate (Figure 2.5a). Most of these structures lacked the necessary rigidity due to lack of any shear walls or structural bracing. Therefore, beam-column connections were subjected to increased moments (Figure 2.5b). Poor applications only exacerbated the amount of damage, there the failure at the joints.

Figure 2.5 : (a) Shear walls had low quality concrete and not designed for the immense amount of shear force. (b) Damage was concentrated at the connections (Cilesizoglu, 2023).

There was a significant issue with soft or weak stories and two-story height stories, as the ground floors were utilized for commercial purposes. In these buildings, infill walls and slabs in-between-floors were removed (Figure 2.6a). During the earthquakes, shearing focused on these floors with low rigidity and resulted in excessive displacement and failure at joints. In some cases, these resulted in total collapse of the first floor. (Figure 2.6b).

Figure 2.6 : (a) A case of two-story height floor. (b) A case of soft story, the ground floor completely collapsed (Cilesizoglu, 2023).

Buildings in Gölbaşı were adversely affected by soil liquefaction (Figure 2.7a). Most of the buildings were either tilted or sank into the ground, even if they did not take any structural damage (Figure 2.7b). These structures were constructed on weak soil vulnerable to liquefaction, and pointing to an interdisciplinary issue, lack of geotechnical investigation, soil study and urban planning. Large masses of loose soil contributed to the existing buildings becoming unusable and irreparable, necessitating their ultimate demolition.

Figure 2.7 : (a) As a result of liquefaction, buildings subsided and overturned, rendering them completely uninhabitable. (b) Subsided buildings (Cilesizoglu, 2023).

On the outskirts of the city, factories were also affected by the earthquake, especially prefabricated RC frame structures were mostly damaged. Prefabricated structures are prone to earthquake damage at connection points (Figure 2.8a). These prefabricated structures lack the required connections and during the earthquake can become loose and move from their places (Figure 2.8b).

Figure 2.8 : Heavily damaged/collapsed prefabricated factory buildings on the outskirts. Connection of concrete elements was not done according to code (Cilesizoglu, 2023).

The number of steel buildings was low in the area. Engineered steel buildings performed well while some others experienced damage levels from slight to heavy. This presents the fact that material's behavior, structural behavior and the application play significant roles in resisting the loads.

2.3 Revisiting Material, Geometry, and Structure

This research began with the foundational question of how atomic bonds form structural patterns eventually leading to architectural-scale systems. It asks: What is the relationship between structure and substructure? How does scale shape material behavior? And what role does form play in these interscalar relationships?

Galileo addressed the importance of scale through analogy. In his famous metaphor of bones, he argued that as an organism grows, the strength of its structure does not scale linearly. For a bone to support greater weight, its cross-section must increase disproportionately. This principle illustrates that scale is not simply a matter of geometric scaling, but rather a matter of behavioral transformation.

Engel (1997) notes that for understanding the structural mechanics of a particular system consideration of the absolute scale is not needed. The actions typical for the single system in order to attain states of equilibrium are basically not dependent on the scale. Otto also emphasizes use of models to understand behavior of the structure for his designs. Referencing the field of physics, Hendry (2021) notes that, quantum physics shows that material laws fundamentally shift at microscopic scales. Thus, scale should not be viewed as a continuum, but rather as discrete boundaries each with its own structural logic and behavior. In addition to what is stated by Otto and Engel, material behavior changes on extreme scales, micro, meso, and macro.

One of the most important lessons to be drawn from nature is the hierarchical and systemic organization of structures. Systems can be defined as the holistic and self-organized behavior of elements. Whether natural or artificial, all systems exhibit key principles such as resistance, balance, interdependence, and equilibrium (Von Bertalanffy, 1968). Large-scale formations create unique behaviors that emerge through the interactions of smaller components that behave coherently (Figure 2.9). This phenomenon, known as emergence in systems theory, reflects how small organizations give rise to unique global behaviors. These relational networks form the backbone of systemic behavior, governing everything from atomic structure to universal scale. In structural systems, such relationships can be described geometrically and in terms of force-form relationships. This study handles the relationship between form, material and structure in a holistic approach inspired by the emerging field of materiomics (S. W. Cranford et al., 2013).

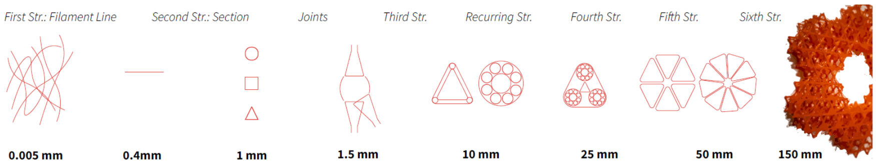

Figure 2.9 : Interscalar connections of a metamaterial (Cilesizoglu, 2025).

Biological studies reveal that nature often uses the same base material across multiple structural scales. Bone, silk, and shell are all composed of fibrous elements but vary dramatically in function due to their sub-structural organization. Materiomics represents a comprehensive approach to materials research (Naleway et al., 2015). Rather than viewing materials as static or isolated entities, this methodology considers the entire system of substructures, structures, and superstructures (S. Cranford & Buehler, 2010). These fibrous elements are organized in nested hierarchies, helical, layered, cellular, tubular, suture, or gradient-based, that recur across multiple scales. According to materiomics, structures are composed of components, each with distinct material properties and geometric configurations. These components exist within larger and smaller systems, forming what is known in materials science and biology as a hierarchical system. The field of materiomics investigates these relationships between subsystems, focusing not just on mechanical properties but on how materials function as interconnected systems at multiple scales.

Material, by itself, has no structural capacity unless shaped by geometry. Ashby (1999) emphasizes the relationship between form and material. Material not only possesses structural quality but also exhibits a unique behavior that emerges through its form. Form enables force flow and load distribution, which is also affected by the element's mechanical structure. Wood has an anisotropic internal structure consisting of fibers, which are tension-only elements. Yet wooden beams and posts not only carry tension loads but are also able to take compressive loads and bending moments due to their form. Other interesting ways wood is utilized include engineered wood materials, plywood, laminated, and cross-laminated timber. By changing the direction of the strand or fibers and combining them using a bonding agent, a complex structure is created that is optimized through its form. Steel, as opposed to wood, is an isotropic material that can be cold-formed or hot-formed. Load distribution can be further exemplified by an I-Beam, also used by Ashby, where steel is formed to take bending loads through its height, with compression and tension stresses concentrated on its flanges. Geometry, therefore, defines how a material performs.

On the structural scale, these components can be used create global forms. As an example, shell structures are three-dimensional, synclastic or anticlastic forms, that dissipate the load efficiently through axial stress. Shells can be made of different materials and components. Concrete, which is a moldable form-taking heterogeneous material, can be formed to act as a shell (Popescu et al., 2021). Another material, brick, which is a discrete element, can be ordered in a certain shape to act as a shell (Rippmann et al., 2016). Linear elements can also be used to create free-form or moment-free gridshell patterns utilizing steel elements Buckminster Fuller introduced the term geodesic to describe the shortest path between two points on a curved, developable surface, such as a dome or hyperboloid. This notion redefines the idea of a "straight line" in architecture, offering new ways to understand structural flow and material efficiency on non-planar surfaces. The geodesic principle not only optimizes structural form but also bridges geometry and force in structural behavior. Textile structures can also be considered a type of shell structure. Membrane elements are tensed in a specific way that any point has zero moment present. Single and multi-layered segmented or continuous wood elements can also be used to create gridshells, which employ patterns to achieve shell features (Adriaenssens et al., 2014). Another interesting example, using the same material, wood, demonstrates emergent structural behavior in bending-active shell structures made of plywood. Through deliberate manipulation of its anisotropic properties and its hygromorphic[5] inner structure, wood panels can be bent into forms that retain stored internal force. These forms redistribute bending energy as axial stress across the system, producing structurally efficient shells (Menges, 2012b) Here, form becomes the medium through which material behavior is enhanced and optimized. This phenomenon is a clear example of synergy, or emergence, where the behavior of the whole exceeds the sum of its parts (Fuller & Applewhite, 1975). In these cases, the inherent material properties are sometimes augmented, and even surpassed, by the structural logic of the global form. The inner structure and behavior of the material can be synthesized to produce composites, material combinations where each material compensates each other's disadvantages, or can be utilized engineer new materials for specific purposes and also design materials based on performance-based design approaches (Yazici, 2024).

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[5] Wood can be plastically deformed without damaging by increasing environmental precipitation or subjugating to steam. This feature wood natural inner structure that accommodates such feature.

2.4 Learning from Nature

Nature has always been one of the primary inspirations for art, architecture and engineering. This philosophy has long influenced architecture, traceable as far back as to the Renaissance, evident in Leonardo da Vinci's avian-inspired machines and Brunelleschi's dome of Santa Maria del Fiore, which emulates the efficiency of an eggshell. How and why this efficiency and optimization works, have been documented and scientifically researched by evolution and natural adaptivity (Darwin, 1859). Specifically, when we look at the natural structural systems, we can see there is an inherent material-based optimization in play.

Nature, broadly defined, refers to the material world and the interconnections of its elements. This concept encompasses everything from atomic behavior and organization to the formation and gravitational interaction of celestial bodies. Essentially, nature operates on a fundamental principle: minimal energy consumption. The arrangement of matter, be it at the atomic level or in complex organisms, stems from a continuous process of adaptation, refinement, and optimization aimed at achieving this energy-efficient state. Thus, in nature, form, material, and function are fundamentally linked; structural efficiency emerges as a result of evolutionary development. Until the 20th century, nature was primarily seen as an analogy for inspiration. However, today, nature-inspired design has become a recognized field in architecture. Designers increasingly utilize natural models not just for aesthetic purposes but also to drive functional and structural innovation (Dixit & Stefańska, 2023). A comprehensive perspective is essential, one that acknowledges the intricate relationships among material, geometry, scale, force, and behavior. Nature continues to provide a wealth of evolved strategies that inform more efficient, adaptive, and sustainable design solutions.

In the modern era, nature-inspired design has gained renewed attention through the work of Buckminster Fuller. In Synergetics, Fuller (1975) emphasized three key concepts: sustainability, ephemeralization, and tensegrity. Ephemeralization, a term he coined by Fuller, describes the principle of achieving more with less, mirroring nature's capacity for maximal performance using minimal material. This concept led to the development of lightweight, efficient, and structurally expressive systems.

As per the systems logic, a system is sum of its parts, and also different from its parts. System's possibly greatest advantage, as shown by the nature and emphasized by Fuller, natural systems combine different qualities. Nature provides numerous examples of hybrid systems. Bodies that combine rigid, compression elements, skeletons, and flexible, tension elements, muscles create a hybrid system that can withstand changing needs. Hybrid structural systems represent an innovative approach to architecture and engineering, integrating different structural frameworks or materials to achieve optimized performance. Unlike composite systems, where materials are bonded to function as a unified whole, hybrid systems maintain the distinct properties of each component, allowing them to work together while retaining their individual characteristics. Fuller identified tensegrity as a core structural logic in nature, a hybrid, kinetic system of discrete compression and continuous tension, yielding adaptive and materially efficient forms.

Nature has long served as a model of efficiency and resilience, demonstrating remarkable adaptability across various scales, from molecular structures to entire ecosystems. This ability to adapt is fundamental to survival, enabling organisms to respond to environmental changes through physical, behavioral, and structural modifications. Organisms adjust their form, density, and material properties in response to environmental stimuli, exhibiting capabilities such as self-healing, structural reconfiguration, and load redistribution. These mechanisms inspire architectural responses that aim to replicate such adaptive intelligence in the built environment. Charles Darwin's principle of natural selection illustrates how species gradually change in response to environmental pressures. Organisms evolve over generations, developing traits that enhance survival and reproduction. In essence, nature responds to a changing environment with dynamic and adaptive strategies.

Emergence, resistance, and equilibrium are fundamental properties observed in both biological and engineered systems, reinforcing nature's inherent efficiency. Understanding nature's adaptive strategies provides valuable insights for architecture and engineering, inspiring innovations in responsive and dynamic structures. By leveraging the principles of hybridization seen in nature, architects and engineers can develop more efficient, adaptable, and sustainable built environments, pushing the boundaries of structural performance and design.

Nature itself is full of imperfections and asymmetries. For instance, mycelium grows through irregular root networks, producing patterns that appear random but follow underlying biological logics. Emerging computational approaches, such as swarm intelligence, L-systems, and agent-based simulations, offer powerful frameworks to model such behaviors. These systems replicate growth, movement, and distribution patterns in both living and non-living materials.

The digital model becomes not only a representation but a material prototype; simulated, experimentally verified and digitally fabricated. This paradigm allows architects and designers to understand and engage with materials more profoundly. Rather than treating materials as passive inputs, structuring enables material-led design, where properties such as deformation, elasticity, porosity, and growth logic become active agents in the design process. Ultimately, this methodology supports more informed, efficient, and responsive ways of building, aligning architectural logic more closely with the behavior of natural and synthetic materials.

Recent advancements in materials science have proven pivotal in enhancing adaptability. Research on smart and responsive materials, such as shape-memory alloys, programmable matter, and adaptive composites, demonstrates their capacity to change geometry or stiffness in response to external input. These innovations lay the groundwork for emerging kinetic and morphing structures, presenting novel opportunities for architecture that can evolve over time or in reaction to utilization.

In structural design, geometry is fundamental. Components can be defined through geometric rules and fabricated accordingly. The abstraction of geometry and force flows not only helps us understand natural systems but also allows for the intentional design of efficient and optimized architectural structures. This principle, that materials can exhibit different behaviors depending on structure and scale, has led to the development of metamaterials. These engineered materials achieve extraordinary capabilities by structuring matter at the micro-scale.

One of the most well-known metamaterials is graphene, a carbon-based structure with exceptional strength, conductivity, and flexibility. Unlike traditional materials, whose properties are governed by chemistry, metamaterials derive their behavior from their geometry at a sub-material scale. They reflect a shift from imitating nature to feature engineering, where properties are designed rather than inherited.

2.5 Computational Tectonics

Nature has shown that forms are shaped and optimized by a wide variety of factors acting on the materials. In the field of architecture, interest on the relationship between form and material has been extensively researched through this form-finding works of Frei Otto, Heinz Isler and Antoni Gaudi (Schumacher, 2016; Xie et al., 2005). These studies expand the area structural design which was previously computed by geometrical equations and graphic statistics. These studies not only affected the structural design but it helped to explore and establish performative side of architecture, whereas forms are not designed but computed through a set of material-based methods. These works employed simulations made through physical models and design thinking that prioritize the design with material input and structural behavior (Chilton, 2020). Whereas resulting forms are complex in geometry can be only calculated through even more complex engineering calculations, the form-finding methods themselves offer a better understanding of forms distribute force through computational methods. Thus, making structural concept design available to an architect.

Computational methods and tools have been the catalyst for new design and thinking models, namely Computational design and Computational Design Thinking (Menges & Ahlquist, 2011). Computational design, in essence, is the understand and analyze a problem, create an abstract and repeatable logics to achieve to a design object/s. As a thinking model, it refers to the design of underlying framework that creates the design. The term computational design is widest term in and refers to a range of design models, including algorithmic, digital, generative, and parametric design approaches (Caetano et al., 2020). Although most of these terms denotes the use of digital tools or computers in the design process, its roots date back to a period preceding the emergence of regular computer use in architecture. This is evidenced by the use of physical model used by form-finding but also on the fact that computational design thinking is mental action that can be represented through other media not necessarily computers (Oxman, 2017). Ahlquist and Menges (2011) points out the difference of computed and computerized by showing how computational design differ from Computer-Aided Design (CAD). In CAD, information is represented through object-based instances, where these instances are organized through automated actions. Whereas in computational design, information is represented through abstractions—mainly algorithms.

Computational design thinking leverages the capacities of computation to enhance the interconnectivity and interrelationality of information that is simultaneously grounded in both the built environment and its broader context. Architectural representation, within this framework, evolves beyond guidelines, instead striving to define a liberated operational space wherein the architect develops relational principles responsive to increasingly complex informational inputs (Schumacher, 2016). This shift expands the performative space of the architect, particularly toward tackling the environmental and social issues that generative and evolutionary techniques were initially intended to address (Frazer, 2016). In doing so, it redefines the architect's role not as a form-giver bound to static geometries but as a strategic operator of information flows. Incorporation of algorithmic thinking and digital design tools including animation, simulation, form-finding tools, parametric modeling, scripting, and digital fabrication tools into the creative processes, extending the boundaries of design action beyond the static, object-based use of conventional representational techniques previously employed.

Oxman (2017) identifies a fundamental epistemological and formal shift in architectural geometry: from typology—which is based on static classification systems and predefined forms—to topology, which privileges continuous transformation, relational logic, and the capacity to adapt to contextual variation. This topological turn, rooted in Leibniz's logical calculus, becomes operative through the use of computational design tools that enable the modeling of fluid geometries, complex surfaces, and dynamic systems (Cache, 1995; Lynn, 1999). As architectural design integrates computational paradigms, motion and force are no longer external to form-making but are embedded within it—structuring geometry not as a fixed entity but as a process of becoming (Lynn & Hoberman, 2016). The interconnectedness of design elements exceeds the cognitive thresholds of traditional design thinking, which is historically grounded in sectional, planar, and perspectival reasoning as architectural culture itself remains largely constrained by Cartesian coordinates and fixed axes, (Lynn, 1999). CDT empowers designers to operate across a wide spatial spectrum, from minute structural connections to urban-scale interventions, via high-speed computational representation. This operative range destabilizes conventional architectural binaries, such as the transcendent subject and the finite object, as representational geometry gives way to a differentiated, topological understanding of form. Integrated digital analysis tools, such as structural solvers, load visualizations, and form-finding simulations, unveil latent connections between force and form, revealing structural and geometric relationships previously inaccessible to human perception, embedding structural logic within the very act of modeling.

This convergence of form generation and materialization defines a new frontier of architectural experimentation (Menges, 2016). Here, material and geometry do not merely guide form, they are embedded in digital tectonics, allowing for the formal expression of complexity without limiting the designer's imagination. As Oxman (2017) notes, tectonic orders are shifted in CDT. CDT design enables the creation of vast formal variations through digital simulations that integrate material behavior, geometrical conditions, and tectonic logic in iterative loops (Carpo, 2017). This is mainly linked to the advent of emergent simulation technologies and a deeper comprehension of materials and structural principles (Menges, 2015; Oxman, 2012). This radical shift in the fundamental priorities and elements that inform design, gives rise to the advent of a novel tectonic culture and requires a re-evaluation of the then-limited roles of structural design, fabrication, and construction in a design workflow and the integration of material, weight, behavior, forces, environmental factors, movement, and time into the design process (Fleischmann et al., 2012). Through the simulation of material behavior engaging how the material acts on the forces and responds to changes, makes it possible to create a performative design (N. Oxman, 2009). Thus, effectively creating a new understanding between designer and material, and present effective ways of efficiently using material to its fullest potential (Yazici & Tanacan, 2020). Material integration process is further enhanced with the deployment of digital fabrication tools whereby the fabrication process is integrated into the design workflow and informed by designers operated by digital tools (N. Oxman, 2007). Carpo (2016) points out its integration with mass production systems, providing the opportunity to mass-produce variations with digital fabrication logic. This results in removal of steps—rationalization—and people—manufacturer, builder—from the equation, thereby facilitating an uninterrupted data flow (Caetano & Leitão, 2024). Unlike conventional construction methods rooted in manual craftsmanship or industrial standardization, digital tectonics offers a pathway to re-engage with cultural traditions of building, not by imitation, but through reinterpretation using contemporary tools (Gramazio & Kohler, 2008). It presents an alternative to a building culture that has long been caught between the opposing poles of modernization and nostalgic revitalization. Computation does not merely assist design; it reshapes it, allowing for iterative feedback loops, real-time analysis, and direct material experimentation. This points out a new kind of knowledge-of-making, where digital tectonics replaces the conventional and building practices and cultures with the integration of computational tools (Oxman, 2010). The intrinsic qualities of computational design thinking make it an optimal choice for the creation of adaptable designs, given that the materials are inherently in a state of flux. A distinctive advantage of computational design is the use of an ever-present set of components. The design is synchronized across all instances, and the components can be observed in diverse real-time scenarios. Any modification to the details will result in an alteration to the overall configuration. The components are capable of interacting with one another, undergoing reversible transformations, and adapting to external forces. Materials may assume disparate forms contingent on the applied force, including constant-tension systems, bistable structures, or pneumatic systems wherein altering the position engenders an alternative equilibrium. By adopting a cradle-to-cradle approach and integrating future phases into the design itself, the functionality and efficiency of the design can be ensured throughout its life cycle. This is made possible by the design process provided by computational design thinking, which classifies data as not just representational geometry but also as informed and simulated geometry with embedded information. The algorithm in computational design functions as a system created by the designer that processes data through operations to generate a design set. The nature of these operations is that they are variational generators and optimizers, iteratively sifting through changing values (parameters) to achieve a goal that complies with all the conditions. Ultimately, the designer evaluates solutions or results to assess the system. Instead of reconfiguring the result, the designer tinkers with boundary conditions, parameters, optimization goals, and even the algorithm itself. The designer, who in this case designs the designer, instead of focusing on the object, focuses on the innate design principles. In the case of adaptive structures, it is essential to be able to both visualize and analyze all iterations and stages of a design object. It demonstrates versatility in navigating adaptive and modular design frameworks, thereby highlighting their adaptability and configurability in response to changing environmental and situational demands (Maierhofer & Menges, 2019).

3. ADAPTABILITY IN ARCHITECTURE

Space represents the most fundamental concept in the field of architecture. Space, as a phenomenon, can be defined only in terms of its intrinsic and extrinsic features, physical features, geometry, forms, light, and in relation to the perceptual features that are established in response to the spatial characteristics of the environment, boundaries, thresholds, the presence of obstacles, the availability of clearance, the quality and distribution of light, the use of color and materials, depth of view, and the pathfinding. The interaction and function of a given space are contingent upon a multitude of physical and perceptual factors, which can be better understood and evaluated with the aid of spatial perception and the principles of space syntax. The initial space-oriented designs were based on the fundamental concept of differentiating between structural and non-structural elements, thereby liberating architectural and spatial design from the constraints of traditional structural techniques. It can be proposed that the emergence of large-span construction was a direct consequence of the evolution of structural technology. This afforded architects a certain degree of autonomy in their design and planning strategies, enabling them to create space-oriented structures that were free of any other structural elements except those designated for the intended functional program. The function of a space is a significant determinant of its spatial characteristics, and the relationship between function and space is also largely contingent upon the spatial features, the infrastructure, and the quality of the space. As construction costs rise, land values increase, materials dwindle, and user profiles with socio-economic characteristics change rapidly, it becomes increasingly challenging to maintain the functionality of buildings. This presents a design issue that must be addressed in order to guarantee the building's continued functionality, either through alterations during the building's lifetime. This places an increased responsibility on the architect as a systems designer, requiring them to demonstrate long-term planning and management skills (Gosling et al., 2013).

A more profound examination of the relationship between users and spaces has led to the rejection of fixed functional assignments. This has led to a new understanding of the nature of space.

The activities and interactions that occur within these spaces can vary based on seasonal or daily requirements, they are no pre-determined. The concept of cross-programming and hybrid spaces represented a significant conceptual shift in planning and design, allowing for the integration of diverse functions within a single space (Van Rooyen, 2023).

The term "adaptiveness" refers to a system's ability to resist or evolve in response to changes. This is not merely a matter of adaptiveness in the structural sense; it is also a matter of functional, socio-economic, and historical changes (van Ellen et al., 2021). This is exemplified in architectural works where users, according to their financial capabilities, have the option to modify their housing or tenancy arrangements by reorganizing the layouts according to their needs, thereby facilitating adaptive reuse of abandoned buildings and restoration and renovation activities. From an architectural perspective, this inevitably raises several questions regarding space organization, the use of lightweight elements such as furniture, and the incorporation of heavier elements like stationary furniture and partition walls, among others. From a structural perspective, a multitude of modifications can be made, including the addition or removal of modules, movement, relocation, rotation of the modules, alterations, transformations, transfiguration, and reconfiguration of modules. The design of such spaces is contingent upon modularity, with the dimensions and composition of the modules themselves influencing the organization of the space (Mitsimponas & Symeonidou, 2024). Moreover, this is relevant concerning the life cycle of materials. It should be noted that additional examples of kinetic structures and pneumatic systems are employed in extreme cases and on a different economic scale, rather than being used on a daily basis. These practices warrant further consideration when evaluating the life cycle of materials and prioritizing cradle-to-cradle practices, design for disassembly and deconstruction (Rios et al., 2015) and emergency situations, (Heidrich et al., 2017), such as earthquakes, tornadoes, climate change (Loonen et al., 2013) and migrations. Schmidt III and Austine (2016) outlined eight conceptual approaches to adaptability, grouping them under three main categories: spatial strategies (such as loose fit and open plan design), physical components (including industrialization, kinetic systems, and unfinished architecture), and building configuration methods (like multi-level structures, layering, and systems-based design).

Adaptiveness is a fundamental attribute of any complex system. In the field of architecture, adaptability has been a pervasive characteristic. The idea of adaptability has its roots in prehistoric and pre-modern times. Urban fabric, and indeed people's lifestyles and manners of work, have always been in a state of constant change, due to inevitable changes in the socio-economic structure. From an architectural perspective, this can be traced back to the use of tents, which served as both a mode of living and a social construct, as well as a response to the surrounding environment. These were modular and repeatable structures shaped by local conditions and needs. Those primitive structures, such as huts and tents, consist of a single multi-use space that fulfills users' every need and adapts to any activity. In addition, primitive tents and huts exhibit an adaptive character through their use of lightweight materials, mobility, and responsiveness to seasonal and climatic changes. Whose reflections can be seen in the contemporary architecture as pneumatic and tensile systems (Kronenburg, 2008, 2013). Similar to early precedents, vernacular architecture often reflects an adaptive manner. Early societies utilized passive design strategies such as shading, natural ventilation, and thermal mass to create buildings that adapt to their environmental conditions. For instance, in traditional Japanese homes, flexible partitions called shōji screens alter interior spaces and respond to light or privacy needs. Furthermore, vernacular Korean Hanoak houses show a high level of adaptability with design solutions such as responsiveness to diverse climatic conditions, having a variety of functions within each space, having multivalent building components, and allowance of flexibility and adaptiveness through the life span of the house (Hugo, 2021). Likewise, European vernacular Renaissance architecture, with its generous scale, abundance, and well-proportioned spaces, unintentionally created a degree of spatial ambiguity that allowed for effective adaptation to various functions such as offices, apartments, or hotels (Schmidt III & Austin, 2016). Even though it was perceptible in the pre-modern era, the concept of adaptiveness did not become visible until the beginning of the twentieth century. The Industrial Revolution was the primary event that led to social change and the emergence of new building materials and construction techniques that provided spatial freedom to architects. It also increased demand for buildings prone to change. In the era of modern architecture, which emerged at the beginning of the twentieth century as a result of a rapidly evolving world, innovative materials such as concrete, steel, and glass gave architects unprecedented design flexibility.

In the modern era, adaptability has also manifested in the form of space-function relationships, made possible by advancements in construction technology. The criterion of adaptability developed through the years owing to the designs of leading modernist architects such as Ludwig Mies van der Rohe, Le Corbusier, Alvar Aalto and Frank Lloyd Wright. With Le Corbusier's early 20th-century Dom-Ino house and concept of open plan, a flexible arrangement of interior spaces becomes feasible by eliminating most load-bearing walls. It is proposed in the modern architecture that the separation of different systems in building (façade, roof, structural system, ground) can be isolated to create the freedom of plan (Le Corbusier., 1986; Van Rooyen, 2023). Becoming a foundational principle for prominent modernists, the free plan concept has been advanced by Mies van der Rohe with the Universal Space notion, which is a seamless interior space characterized by evenly apportioned service spaces and minimum structural elements (Schmidt III & Austin, 2016). Moreover, Louis Kahn's Loose Fit approach emphasizes the idea of designing spaces with flexibility and openness that allow for various usage scenarios, rather than strictly adhering to a single predefined function. Modernism aimed to accelerate and improve construction processes by embracing industrialized and modular building techniques.

The advancement of enhanced structural technologies has further facilitated the spanning of expansive spaces, shell structures, and space frames, thereby reinforcing the notion that spatial constraints are not absolute. Multi-functional halls, convention centers, exhibition spaces, and concert halls exemplify this concept of uninhibited spatial freedom (Tang, 2015). From early examples such as Paxton's Crystal Palace to contemporary designs, this afforded architects a greater degree of freedom in their design and planning strategies, allowing them to create spaces that were free of any structural elements. Offering fast construction, mobility, and multifunctionality, industrialized architecture demonstrated modern technology while providing flexibility with demountable building components. Movable-demountable building parts were a strong influence in prominent designs such as Fuller's geodesic dome structures and Prouvé's Maison du Peuple de Clichy. Furthermore, the High-tech movement adopted open-ended design strategies, allowing buildings to expand or contract over time, exemplified by the Centre Pompidou, where upper-level terraces were intentionally left adaptable for potential future enclosure (Schmidt III & Austin, 2016).

Both industrialized architecture and the High-tech movement prioritized flexibility of use for the user and the architect, and this notion was emphasized by subsequent movements and approaches such as kinetic architecture, megastructures and Archigram's works.

Modernism's principle of "form follows function" led to buildings with single-purpose, overly defined spaces. This, in turn, contributed to the rapid obsolescence of buildings and a decline in their adaptability. Moreover, Modernist design tended to neglect context and sought to offer "universal" solutions while overlooking the needs of users. In the mid-20th century, structuralism emerged as a prominent counter-movement to modernism's monumentalist and function-oriented design approach. Dutch structuralist architects like van Eyck, Hertzberger, and the metabolists, such as Kurokawa, supported open-endedness and indecisiveness in the architecture. Reflections of this movement to architecture and adaptive design can be seen in the Hertzberger's structure-infill model. Embracing the interactive, active public spaces, and designed for endless possibilities, and open to interventions.

Works of contemporary architects Koolhaas and Tschumi have been influential in reflecting the dynamic and evolving nature of the built environment, fluid spaces that are cross-programmed, always in motion and welcoming unexpected (Koolhaas, 1987; Tschumi, 1996). Contemporary public architecture is shaped by these principles of spatial flexibility and indeterminacy, allowing for spontaneous and diverse uses rather than predetermined functions. These spaces are designed to provide infrastructural support for a variety of activities, encouraging users to appropriate them according to situational needs. A similar design ethos is present in commercial architecture, which prioritizes adaptability to accommodate the evolving dynamics of work culture and the real estate sector with minimal physical intervention.

In contrast, residential architecture has exhibited greater resistance to change due to its association with traditional living. To achieve long-term sustainability and applicability, residential architecture must integrate flexibility and transformability as fundamental design strategies (Stojanović, 2024). However, the concept of incremental housing, commonly associated with Aravena, offers new and adaptive solutions to housing. This model involves providing a complete structural framework and roof, but constructing only half of the dwelling, while leaving the remaining portion for future self-construction by the homeowner (Carrasco & O'Brien, 2022).

This approach not only offers a cost-effective path to homeownership but also engages with deeper issues of individuality, cultural identity, and social equity in the built environment. By enabling user-driven completion and customization, incremental housing repositions residents as active participants in shaping their own living environments, fostering a sense of agency and belonging.

The scarcity of materials and urban space has prompted the development of innovative strategies and the utilization of alternative resources, including the repurposing of underused urban spaces due to socio-economic factors. In other respects, the existence of unoccupied space has the potential to exert a detrimental effect on the overall value of the urban environment (Conejos, 2013; Pintossi et al., 2021). The process of adaptive reuse involves the restoration, renovation, and reuse of existing spaces, as well as the incorporation of new programs, additions and extensions (Aigwi et al., 2023). The application of material studies and engineering knowledge has resulted in the development of more efficient structural designs and the utilization of materials in a more effective manner.

The advancement of technology, such as pre-cast and modular industrial production, has facilitated the rapid growth of the modular construction industry. The use of lightweight structures, where lightness is a crucial factor in both design and resulting in more versatile applications, has been instrumental in developments in modular structures. Furthermore, multidisciplinary information and innovations in kinematics and mechatronics have led to the development of actuator and kinetic façade technologies, where structures are in an actively adaptive state, based on daily or seasonal bases (Loonen et al., 2013).

In the 21st century, shaped by technological advancement, societal transformation, and environmental imperatives, adaptability has emerged as a critical architectural paradigm, underscoring the necessity for buildings flexible enough to evolving demographic and climatic conditions (Onishchuk, 2025). The adaptability in the 21st century rises alongside urban density, declining resources, economic conditions, the decline of craftsmanship, the shrinking availability of urban spaces, and the costs and environmental impact of construction. The use of adaptable structures represents an optimal choice for efficiency, sustainability, and effectiveness in the utilization of both materials and space.

3.1 Space-Adaptive Structures

Adaptivity is a term that changes its meaning over time in the literature. Meaning shifted from open, flexible, prefabricated, modular, design for disassembly (DfD) to design for assembly (DfA) (Mlote et al., 2024). Adaptiveness can be provided through skin via climate-adaptive systems (CABS) or interior adjustments. The scale of adaptive architecture also varies, as with furniture, cladding elements or partition elements. Therefore, a name that better defines the scope is deemed necessary. Nomenclature similar to CABS, the term "space-adaptive structure" is used to define the spatially transformative features and self-standing nature of these structures (Figure 3.1). In that regard, space-adaptive structures are concerned exclusively on the structural part of a building or the corresponding part. (Figure 3.2).

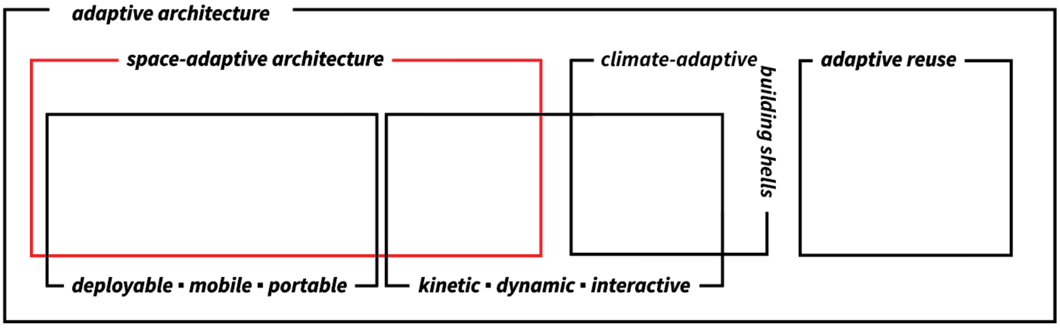

Figure 3.1 : Comparison of adaptive terms (Cilesizoglu, 2025).

Figure 3.2 : Layers of a building (Brand, 1994; Schmidt III & Austin, 2016; Cilesizoglu, 2025)

In the context of this thesis, space-adaptive structures are not classified or categorized but rather identified and analyzed based on their unique design aspects. These aspects, in order from parts-to-whole, are identified as reassembly, reconfiguration, and response (Figure 3.3).

Reassembly refers to transportability, interchangeability and reassembly of discrete parts (Figure 3.3a). This involves reorganization of the modular parts with the innate capability of multi-connection.

Reconfiguration refers to the shape-shifting capability of the configuration due to innate joints that allow rotations and/or translations (Figure 3.3b). Structure can be reconfigurable without the need for reassembly.

Response refers to the behavior of the structure as a whole to environmental and internal changes (Figure 3.3c). It is provided by a number of factors, including reconfigurable parts that can respond to the environment through sensors or actuators, smart or responsive materials.

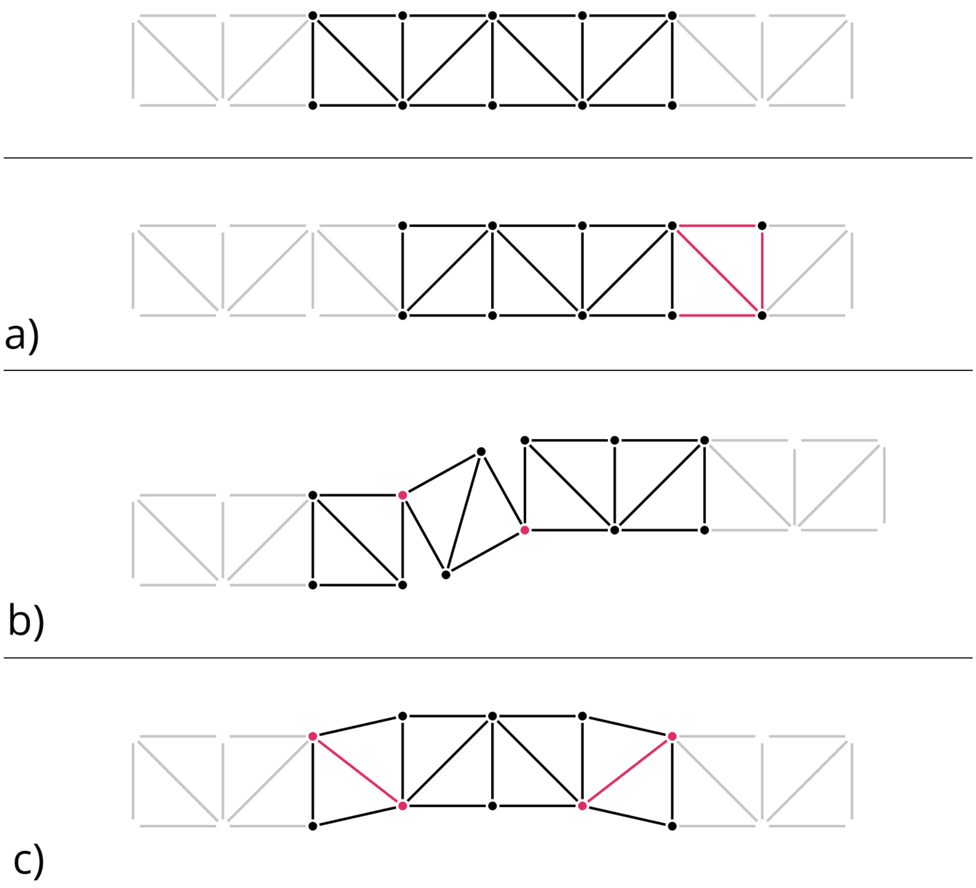

Figure 3.3 : Design aspects of space-adaptive structures are identified as (a) reassembly, (b) reconfiguration, and (c) response (Cilesizoglu, 2025).

3.1.1 Reassembly

Traditionally, assembly comes from mobile architecture practice. Tents have been a historical precedent for this type of shelter. It includes pieces that can be disassembled and reassembled without harming the structures. They utilize tensile strength-gaining structural forms, as membranes have the greatest strength per material weight. In modern application, assembly is used for constructions with pre-fab elements and modular structures. Modularity is an approach to design that emphasizes the use of standardized, interchangeable components to create flexible, scalable, and efficient structures or products. These systems are widely used in architecture, engineering, product design, and industrial manufacturing, allowing for streamlined production, ease of assembly, and adaptability to different needs. In architecture, modularity offers numerous advantages, including reduced construction time, cost efficiency, and the potential for reconfigurability. Prefabrication, a key aspect of modular architecture, enables components to be manufactured off-site under controlled conditions and then assembled on-site. This method streamlines the workflows, enhances and ensures quality and speed of both production and construction with integrated quality control mechanisms. From a sustainability perspective, modularity minimizes material waste by allowing the reuse of molds and scaffolds. Modules are not only designed for assembly but also for disassembly. It is possible to partially disassemble, reassemble using existing pieces, or manufacture and transport only the required pieces without replacing the structure. This aids in adapting to new functions or expanding, receding, or making repairs and replacements.

The main challenge in modular structures is detailing and defining the module size. As an early design problem, module size and detailing are connected to global form, potential configurations. Here, computational design plays a crucial role, utilizing digital models and prototypes to simulate various configurations, test structural integrity, and evaluate performance before fabrication. This approach ensures the maximization of the number of configurations, freedom, precision, and efficiency, while fostering creativity in modular architecture. As such, modularity is not actually a problem of scale but also a problem in 3D configuration. Joints can be designed to transfer loads, exhibit rigidity, and have sufficient load transfer capacity, while also allowing for flexibility in various angles.

In 3D, in order to achieve stability and transfer loads, the global form needs to have a stable form-active or surface-active form (a quadric surface). In that regard, only shapes derived from solid geometries have ideal shapes that can be made of modules while having continuous closed edge loops. This, in fact limits the range of forms that can be created and requires further research and work on tessellation. Simplest examples can be seen on regular polyhedra, Platonic solids and their derivatives Archimedean and their Catalan solids. In order to achieve free-from surfaces other strategies should be employed. These are modeling or form-finding methods that rely on NURBS or mesh—though it is also based on triangulation—geometry, which expands the geometry beyond the Euclidean solids.

Alternatively, a base shape made of modules can be used which is identical to the final form and then the system can be optimized and rearranged with the same modules—this method was used in the thesis. Even then, when working with discrete elements, the parts-to-whole approach must be optimized according to the whole. Form finding algorithms like dynamic relaxation can be used to optimize the placements of these triangles. In physical world this can be prototyped by materials with high expansion coefficient. The system can be setup with varied expanded parts and when they retract to their old forms, they would be creating the system with the same length materials. Here, physical world and computational design environment share a common feature. Lengths of the materials will not be equal to desired to ideal length but they will approximate by balancing the whole structure. This number, when in a controlled tolerance, in structural model can be compensated by specially built joints. In computational design a structural model can be transferred directly to fabrication information. Therefore, the system can be reliable built.

Assembly therefore depends on two basic facts. First, the whole must be buildable, rationalized through discrete elements. Second, the modules should able to connect each other in varied orientations in 3D. The focus on joint points out also to the second characteristic, reconfiguration.

Reassembly also appears as a key characteristic in the action of a progressive or developable structure. As established in the previous chapter, spaces in these field of area tend to change and transform according to requirements. The assembly provides the necessary connections for additional building elements.

3.1.2 Reconfiguration

Mobility requires reconfigurability as a construction method for the efficiency and speed. Reconfigurability can be defined as embedded transformational capability through mechanical parts or actuators. Space architecture has been one of the fields that pioneered, or rather popularized, this construction technique as a research area. There are two important constraints in reconfigurable space structures. The first factor is the transportable volume of the structure, which is limited by the spacecraft's cargo volume. Structure’s volume must be minimized by folding, telescopic, or scissor-like mechanisms. The second one is the lack of material and working conditions in an extraterrestrial environment. Therefore, these structures must already be built on Earth and easily reconfigured to create the volume.

In the field the architecture, these kinds of structures are commonly called deployable or portable structures. They are used for speedy, traveling or ephemeral[6] construction projects like pavilion or fair structures. They are made of lightweight materials, steel, wood, textile or membrane to provide ease of transportation or erection.

For steel and wooden reconfigurable structures, linear elements with flexible joints, ranging from simple hinge and pivot mechanisms, are used in the forms of auxetic[7] patterns, folding patterns or bi-stable configurations. Design issues in the area of reconfigurable structures are stiffness in joints and rigidity in the structures. Engineering aspect of the reconfigurable structures carries a great importance as these structures comes with unique joint non-regular structural configurations. Stiffness must be controllable to allow transformation and post-transformation it must be stiff enough to act as structural joints transfer loads. This required an engineered joint solution with mechanical analysis. The rigidity is another point caused by hinged joints and non-rigid geometry (mostly) of the global form. Form must be stabilized by stiffening the joint or using additional elements enhance the rigidity of geometry. This phenomenon is also observed in gridshell structures with continuous elements. After erection of the gridshell structures, the form’s rigidity is provided by additional structural elements.

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[6] Ephemeral, a word coined by Fuller, meaning temporary. The term highlights the lightweightness of structure.

[7] Auxetics structures, have negative Poisson’s ratio. Axial elongations under load causes transversal elongations.

Tensile structures are also capable of deployment as displayed in the modern tent structures. There have been faster construction methods researched in the area of foldable structures. These structures lean on self-standing of self-tensing aspect of tensegrity structures. Tensegrity[8] structures employ compressive elements to structure the tensile members. Pneumatic structures like tensile and tensegrity structures weigh less and take up minimal space during transportation. These structures use air pressure get tense and load-transferring capabilities, instead compressive elements which reduces the overall weight and overall detail and workmanship. The more materials work together the more complicated it gets from structural detailing perspective. Structure should not be thought a something static. Reconfigurability follows a similar logic to reassembly. Same parts are used for different configuration. However, there is a key difference. Reconfigurable structures have multi-stages for the configuration. In the design phase all stages must be tested both statically and spatially. Modeling of the joints is also important in that regard. Computational design proves itself highly efficient and useful in this area. In addition to creating different variations (configurations), computational design is also capable of creating a range of variations based on parameters (stages). Mechanism must be checked for inner collisions either by modeling the full range of motions and full range of stages or using a mechanical or physics-based modeling tool. Extremes of this range of stages must be selected with parameters like functionality and performance. These extremes must be subjected to structural analysis and other required analysis individually. Optimization of use of materials should suffice both stages. Though this futuristic way of building is efficient in building it is only stagnated by limiting the architectural freedom with structural and mechanical elements, size, material and requirement of complex modeling and advanced engineering. Therefore, a more suitable place for these structures can be where there is housing crisis. Deployable structures are also considered for post-disaster shelter requirement due to their light transportation and fast construction advantages. Their design for disassembly or in other words design for deconfiguration makes possible to build mass housing sites without irreversible effecting nature. Reusability of this material, like in reassemble section, makes it possible for materials to complete their lifecycles.

[8] Tensegrity means, tensile integrity.

3.1.3 Response

In reconfigurable systems, active systems or kinetic systems, incorporate mechanical components with movable joints that enable structures to change their configuration in response to environmental or user needs. Kinetic systems are particularly relevant in responsive architecture, where buildings or structures modify their form, function, or performance based on changing conditions such as climate, user preferences, or structural demands. These systems can be manually adjusted or actuated through mechanical, hydraulic, or digital controls, allowing for dynamic adaptability in architecture, engineering, and industrial design. However, in the field of architecture movable parts are not common. Interestingly, active structures have been a part of architecture since antiquity. Windmills with rotating caps and adjustable windshafts, are both reconfigurable and responsive (Medioli et al., 1977). In the contemporary era, in the form of tuned mass dampers we can see how to respond to seismicity with form of counter-movement and vibration control. (Yang et al., 2022)

Advances in robotics, material science, and mechatronics have significantly expanded the possibilities for kinetic architecture. A key advantage of kinetic systems is their ability to optimize performance in real-time. Dynamic facades that adjust to optimize shading and ventilation, retractable roofs for adaptive shading systems, and reduce energy consumption produced by climatization systems. Passive climatization has roots in vernacular architecture. These systems enhance comfort, energy efficiency, and spatial flexibility while offering dynamic architecture. In addition to mechanisms and complex motorized actuators controlled by sensors and automation systems, smart materials, such as shape-memory alloys or bi-stable materials and living materials, such as hydromorphic materials can be used for the creation of passive responsive systems. These systems use temperature or, precipitation to produce different expansion and shrinking effects to create movement. Computational design with physics-based algorithms offers an advanced simulation and complex modeling framework. Inside this framework moving parts are mechanically modeled as solid parts and their relationships are governed by algorithms. Structure works as system and it requires holistic approach to simulate or understand the behavior of the structure. Additionally, functional prototyping plays a critical role in the development of such systems. Prototypes serve not only as physical proof-of-concept models but also as testing grounds for mechanical, material, and spatial behaviors.

3.2 Requirement for Post-Disaster Sheltering

Post-disaster sheltering is a practical area where space-adaptive structures are especially suitable. Sheltering requires a before-hand planning, mass and swift deployment. Transformable and portable structures, in particular, are recent research topic enhancing the sheltering requirements (Cerrahoğlu & Maden, 2024; Oliveira & Campos, 2019; Rezoug, 2013). However, not every problem can be solved by a transportable structure. Sheltering is not just a structural design problem but also a process design problem. Emergency reactions must be followed by a series of phases spanning up to 10 years.

Quarantelli (1995) divides post-disaster housing to four categories. Emergency shelter is the first response in the immediate aftermath of a disaster, this can be any covered space in the vicinity or tents. Temporary shelter, a short-term solution for a housing, this is usually a tent or container. Temporary housing which is a long-term housing solution until the last stage, permanent housing. There are various widely recognized post-disaster shelter types offering solutions to different sheltering issues such as emergency, upgradability, durability or comfort. Transitional, temporary, progressive, and core housing terms can be used interchangeably (IFRC/RCS, 2013). Transitional, temporary, or T-Shelters are intermediate shelters types that are designed to bridge the gap between emergency and durable options. They are designed provide better service faster. Core and progressive shelter have durable parts, and incremental additions to upgrade the shelter to a more permanent housing type.

While current solutions suffice the requirements for each stage, their temporary nature and immense numbers creates an abundance of material waste, energy waste and occupied plots (Rios et al., 2015). Materials, time, energy, and costs used for temporary shelters, as the shelters are deserted or demolished while phasing to the next step, are completely wasted. Ongoing studies aim to bridge the gap between stages; however, an all-encompassing solution is not available due to unique properties of each stage (Abu-Aridah & Ligler, 2024; Shahkar, 2022).

A good shelter design, is also not about one instance of structure. It is all about integration, progression, and interaction of the design with the user and their needs. In that regard, a good shelter design must employ a full-scale adaptation. Starting from swift transportation, to swift deployment to adapting user comfort and needs. Design should able the necessary skin and service additions.

UN Sphere Handbook (2018), provides the basis for the spatial needs of an earthquake area (Table 3.1). These spatial needs depend on climate, effect of climate to space and spatial organization. For hot climates, open spaces can be utilized in the sheltering scenarios. WASH[9] and cooking spaces can be planned on the outside. Covered spaces must have an internal height of 2.6 meters for adequate ventilation. For cold climates, WASH and cooking spaces must be included inside the covered space. Internal height must be minimum of 2 meters, to preserve heat.

Table 3.1 : Minimum Spatial Standards and Ratios (Sphere Association, 2018)

	Living Space	WASH and Cooking Spaces	Household Plot Size	Settlement Area	Communal Area
Area	3.5 m2	1~2 m2	7~14 m2	30 m2	15 m2
Ratio	1:1	1:0.5	1:2	1:8	1:4

In order to review applicability and feasibility of the case study; spatial, material and construction standards, have been established through analysis of universally accepted guidelines (Sphere Association, 2018) , local regulations (TS498, 2021; TBEC, 2018) and 53 well-documented works built in the 21st Century (IFRC/RCS, 2011, 2013; UNHCR, 2016, 2021).

A list of requirements, standards, average values and ranges are identified through comparing the dataset. Table 3.2 established for each sheltering stage by Cilesizoglu & Celik (2025) for the purpose of creating a benchmark to test and guide multi-staged space-adaptive shelter structures. In the table, values present a data that is acceptable for a shelter in the specific state.

The material and construction techniques vary considerably. It needs to be considered that these applications are real-life applications but not necessarily engineered and designed considerably. Most of these studies utilize local materials and building techniques for reducing the costs and increase accessibility. Shigeru Ban is well-known architect for his disaster relief projects across the globe particularly in Japan, Türkiye, Haiti etc. His work on disaster struck regions focus on using inexpensive non-engineered structural materials like beer crates, paper logs and paper for accessibility of shelters to everyone (Shamloo et al., 2024).

[9] WASH stands for water, sanitation and hygiene.

Table 3.2 : Required values for three sheltering stages (Cilesizoglu & Celik, 2025)

	Immediate Stage	Interim Stage	Intermediate Stage
Lifespan	1 Year	5 Years	10 Years
Construction Time	1 Day	7 Days	10 Days
Cost	€500	€2000	€2500
Covered Living Area	12 m2~18 m2	12 m2~24 m2	16 m2~24 m2
Cargo Weight	5000 kg	10000 kg	50000 kg
Cargo Volume	5 m3	10 m3	40 m3
CO2 Footprint	1000 kg	5000 kg	10000 kg
Cost/ Lifespan	€500/ year	€400/ year	€250/ year
Cost/ Lifespan/ Area	€40/ year/ m2	€20/ year/ m2	€5/ year/ m2
Cargo Weight/ Area	300 kg/ m2	500 kg/ m2	2000 kg/ m2
Cargo Volume/ Area	0.3 m3/ m2	0.4 m3/ m2	1.6 m3/ m2
CO2/ Lifespan/ Area	50 kg/ year/ m2	40 kg/ year/ m2	30 kg/ year/ m2
Construction	Pre-fabricated	In-situ	In-situ
EQ Resistance	Lightweight Structure/ Adequate Rigidity		
Wind Resistance	Deep Foundation		
Flood Resistance	Elevated Floor		
MEP Services	Not Mandatory	Mandatory	Mandatory
Lifespan	1 Year	5 Years	10 Years
Construction Time	1 Day	7 Days	10 Days
Cost	€500	€2000	€2500
Covered Living Area	12 m2~18 m2	12 m2~24 m2	16 m2~24 m2
Cargo Weight	5000 kg	10000 kg	50000 kg
Cargo Volume	5 m3	10 m3	40 m3

4. METHODOLOGY

This study utilizes a research-through-design (RtD) approach to explore adaptive structures in architecture (Frayling, 1993). Designing is at the heart of architectural education, professional practice, and research within the field of architectural design. Architecture fundamentally embodies ideas, placing a strong emphasis on materiality and construction practices. These elements deeply influence architectural concepts, thought processes, and language (Roggema, 2016). This method uses the architectural design process to gain new insights, knowledge, practices, or products. The evolution of architectural practice, driven by new digital tools, reflects a continuous interaction between materiality and the act of making (Hauberg, 2011). The RtD approach focuses on iterative design exploration through case studies, each representing a specific type of adaptability and acting as a testing ground for theoretical and practical issues. These studies produce empirical insights and identify situational challenges that lead to further design improvements.

Following establishment of the aspects of adaptive structures, the research is structured around three space-adaptive case projects developed within the framework of the thesis. Based on the design aspects of space-adaptive structures—reassembly, reconfiguration and response—three projects that present each characteristic were chosen.

These projects are designed performatively, utilizing three distinct materials, unique concepts, custom-designed details, forms and algorithmic schemas. The research employs computational design tools, encompassing form-finding and digital manufacturing, to thoroughly realize these structures. The design process itself, unveils the complexities associated with these structures. The research concludes with an analytical examination of the data, comparing the processes, differences, focal points, and unique attributes surrounding the adaptive design framework, as well as the simultaneous design and simulation of multi-phase processes, reassembly of modular components, reconfiguration of elements, and response of the structures.

Each case was computationally designed[10] individually using the same workflow with case-based differences (Figure 4.1). Methodology consists of two parts, first part is based on the underlying relational logic of the elements, second part is case-based design and the adaptation into final assembly/configuration/response. The study employs computational methods and tool for a complete—concept-to-fabrication-to-adaptation—performative design workflow.

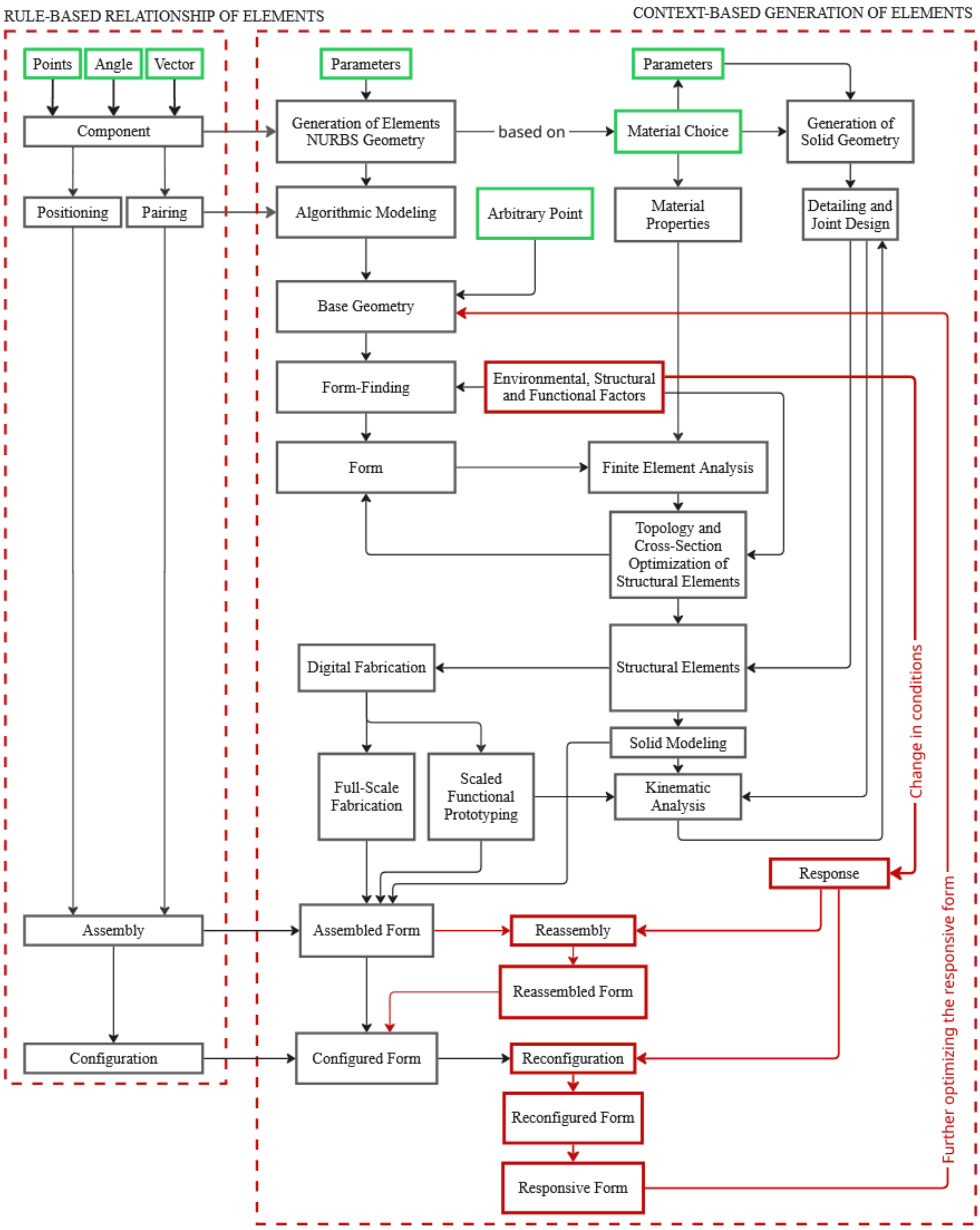

Figure 4.1 : Outline of the methodology presented in thesis (Cilesizoglu, 2025).

[10] Conceptualization and creation of the design workflow is not in the scope of this thesis.

Since the relationship between elements constantly change, CD offers a design workflow based on the relationality of the components. The first part of the methodology, which is presented here is partially based on graph theory and shape computing, and borrows some terms from the field of kinematics. Systems and connections in the case studies are expressed through graphs and components—structural members—are expressed through shapes. Shape computing offers a computation method that computes with shapes and rule-based transformations, similar to Monge's descriptive geometry (Stiny, 2006). Kinematics, specifically focuses on position, movement and loops in a system, as well as the pairs and constraints, and how elements move together or limit each other inside the system.

The reason for following such approach is the interrelated loops in space-adaptive structures. In systems like the cases presented in the research, components are repeatedly employed, in different orientations, in pairs. The same component can be repeated in the different loops and paired in multiple ways, which hinders a linear understanding. That's why shapes and graphs increase our understanding of such systems since we can see all parings and positionings of the components simultaneously.

Components are generated through points and geometrical equations. The same components are repeated in the systems; however, they are in different orientations. Though they are the same components and oriented through Euclidean transformations (rigid body transformations) relative positionings of components are important inside a kinematic system. They could be facing each other or opposite directions to create structural connections and movement. Positionings come together in a matter of ways, with different connections allowing movements. Every positioning as a part of system connects in each other multiple pairings.

Pairings are rules that simplify the understanding of component connections. Instead of using shapes, pairings define operations. How each component positions itself in relation to the other and how they move in relation to each other. Pairings are fixed or movable connections with certain degrees of freedom (DoF) and constraints. Pairing of positionings create assemblies, whereas configurations and reconfigurations are the variations of the same assembly or reassembly created through moving connections.

Following the establishment of rules, second part of the case studies is commenced in the digital environment using a non-uniform rational basis spline-based (NURBS) CAD modeling program[11] and integrated visual algorithm tool[12] used to for computational design. NUBRS geometry allows mathematically-defined generation of complex structures with precision and scalability in design. It provides an optimal workflow into digital manufacturing without any loss of data due to meshing or line segmentation. Visual algorithm tool is used to create rule-based algorithmic schemas that create, transform or modify the NURBS geometry synchronously, real-time and iteratively, allowing for swift exploration of design options based on the parameters. Structural parts are 3D NURBS geometry, generated through case-based parameters.

Form-finding is used for every configuration—fixed form—in every case study for increasing the structural efficiency and also for choosing a configuration based on the objective goals, such as generating a smaller shelter for cold climates, with a steep roof and increased structural resistance snow loads. An interactive physics solver[13] integrated into the same digital design environment is used for form-finding (Piker, 2013). Solver operates through energy minimization, treating various design objectives, such as maintaining lengths, enforcing angles as goals. Each goal defines an energy function that is minimized when a specific geometric or physical condition is achieved. Unlike classical Dynamic Relaxation (DR), a method where forces are iteratively balanced by calculating resultant accelerations and applying damping, solver adopts a more efficient approach inspired by Projective Dynamics (Piker, 2019). Instead of summing and integrating accelerations, the solver projects point positions directly onto the target configurations defined by each goal, iteratively combining these projections to find a compromise that reduces the total system energy.

In performance-driven architecture, incorporating fast-responding finite element analysis (FEA) into the design process—and preferably integrated to design tools—and is increasingly essential for increasing the understanding of structure-form-material relations, pre-dimensioning and optimization (Frogner & Møkkelgård, 2022; Holzer et al., 2007; Preisinger et al., 2018).

[11] Rhinoceros3D is NURBS-based CAD tool.
[12] Grasshopper is an algorithmic modeling and visual scripting tool integrated to Rhinoceros3D.
[13] Kangaroo is a physics solver integrated to Grasshopper.

Supports, loads, materials, and cross-sections (assumed), are defined in the design environment for evaluation of deformation, stress distribution, utilization per case (Figure 4.2). The analysis necessitates a degree of abstraction for computing resource efficiency; therefore, various combinations of lines—present in base geometry—and shells are employed to conduct the analysis in the case studies.

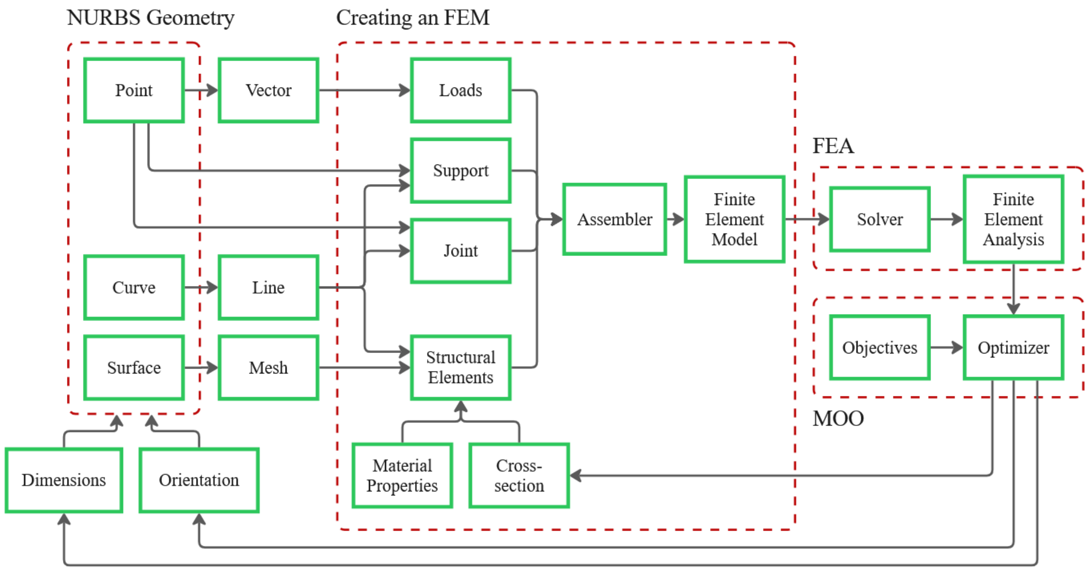

Figure 4.2 : Diagram showing FEA and MOO process (Cilesizoglu, 2025).

Lines are utilized to formulate beam elements, while meshes are utilized to generate shell elements. Supports and joints with varying rotational and translational stiffness (fixed or hinge) may be defined at the end points. Loads can be designated, including gravitational, dead/live loads, as well as point or distributed loads (constant or varied) using vectors. The assembled models were conducted using linear analysis (first order theory) and buckling. The solver is utilized in parallel with cross-section, dimensioning and form-finding tools.

In the thesis, in the context of beams, FEA solver[14] employs a power series approach to compute the element stiffness and states at arbitrary points along the elements. This method, grounded in the research conducted by Helmut Rubin, encompasses second-order theory and incorporates the Timoshenko-Ehrenfest beam theory, which takes shear deformations into account. The triangular shell elements utilized in FEA solver are derived from the TRIC element developed by Argyris.

[14] Karamba3D is a FEA solver integrated to Grasshopper, designed specifically for architects.

These elements adhere to the Euler-Bernoulli approach, signifying that, lines which are initially perpendicular to the middle plane remain perpendicular in the deformed configuration. The buckling calculations performed by FEA solver are based on the resolution of the generalized Eigenvalue problem, which entails the elastic and geometric stiffness matrices of the system (Preisinger, 2024).

Based on the form's function, fabrication possibility and structural requirement a suitable material is defined per form. Assemblies and/or configurations are subjected to form-finding methods with FEA to optimize the configuration and dimensioning of forms for structural efficiency –or any other optimization goal per case study. Final dimensioning achieved through optimization. Integration with other tools design tools allows iterative design assessments, facilitating immediate feedback loops between form creation and performance evaluation.

Since all elements are constrained, structural behavior or movement is to be thought as a whole. In these analyses, full range of motion, and constrains and relations of elements are evaluated for structure. For reassembly, this is not done for kinetic members but evaluating range of connections. Reconfiguration capacity of the structure is displayed and analyzed through both solid-based physics simulation[15] and scaled functional prototyping. Digital fabrication method 3D Printing is used for directly fabricating from the digitally designed parts.

Scaled functional prototypes are built using Fused Deposition Modeling (FDM) 3D Printing. FDM is one of the most widely used additive manufacturing technologies for its viability as a method for manufacturing complex components, especially for prototyping and cost-effective production. The Fused Deposition Modeling (FDM) technique is widely esteemed for its accessibility, material versatility, and cost-effectiveness, thus establishing itself as a preferred tool in the design research and iterative prototyping (Tümer & Erbil, 2021).

This process follows G-code instructions generated from the same 3D model generated in the digital design environment, specifying and optimizing the print path, extrusion rate, infill materials—homogenous infill was used—support positions and temperature settings.

[15] Solidworks is physics-based parametric solid modelling, simulation and analysis tool.

In the context of this thesis, materials were printed using a biodegradable thermoplastic filament Polylactic Acid (PLA) to prototype and validate designs (Joseph et al., 2023; Tümer & Erbil, 2021). PLA is heated to its melting point and then extruded layer by layer to create a three-dimensional object based on a digital geometric model and the G-Code.

Components for the full-scale model—only one case—are also digitally fabricated using substrative manufacturing processes. In the case of Armadillo, computer numerical control (CNC) cutting machines are used for the fabrication of the parts. Similar to the 3DP, a G-Code including the path data is generated from a digital drawing. Automated machinery in this case utilized to minimize the potential for human error—by reducing or completely eliminating the manual labor—and enhance the efficiency and precision of the manufacturing processes by allowing design-to-fabrication workflow (Aguilera et al., 2000; Hanincová et al., 2024).

Cases in this study were assembled by hand and tools using standard steel connection members –bolts and nuts. Reconfiguration is also done by hand. Theoretically both assembly and configuration can be done via robots and actuators—but was not further discovered in the scope of thesis.

In design phase, during the design exploration, any of parameters can be changed freely in order to experiment. Alternatively, parameters can be used in MOO process to further optimize the system for desired objectives. Both in design and physical model, structure is open to change and can be changed interactively. Methodology displays that, adaptations –reassembly and reconfiguration—occurs as a response to environmental, structural and functional conditions. The analysis and optimization stages can be repeated for the possible reassemblies and reconfigurations –in order to optimize the responses. As such, for all the cases, reassembled, reconfigured and respond forms and the comprising modules were optimized for the scenario.

5. CASE STUDIES

Case studies in the scope of thesis were done in the field of space-adaptive architecture. Each of these projects display both or some these aspects in their designs. First two designs are preliminary projects for the development of the third project, space-adaptive shelter, Pangolin.

Ningen[16] is a reassemble structure with identical pseudo-triangular fiber-reinforced lightweight concrete structural components. Components can be reassemblable to create a free-from single layer shell structure. Main challenge of these project was to create a global form with identical modules which requires topology optimization with physics-based simulations.

Armadillo[17] is a reconfigurable self-standing shell structure with plywood arc elements varying in height. Components can be reconfigurable to enhance the space use and provide alternative forms. Main challenge in this project was to design a joint that both accommodates rotational movement and compensating change in height. Vertical and lateral stability was to provide by the structure itself therefore through arcs, joints connecting arcs and the global form.

Pangolin[18] is responsive deployable multi-stage space-adaptive shell structure made of tubular steel elements. System can be easily transportable and deployed on site with a folding mechanism. Form can be self-optimized on field based on the structural or spatial requirement. Main challenge was the creation of a folding mechanisms with interrelated elements, thus unique joint design. These joints, allow movements, connections for modular cladding elements. Modular components can be used to increase stability of the structure, offer climate and comfort solutions.

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[16] Name is inspired by the Japanese letter “人” meaning human or humanity. The original concept was designed for a competition by the author, Furkan Berke Cilesizoglu, Yeliz Kaya, Ilayda Omer and was supervised by Assist. Prof. Kurtulus Atasever,

[17] Armadillo is shape-changing animal with segmented conical shell pieces. The original concept was designed for a workshop by the author, Furkan Berke Cilesizoglu, Bariscan Avci, M. Ali Vural, Sinem Sezek and was supervised by Assist. Prof. Kurtulus Atasever,

[18] Pangolin is shape-changing animal with tessellated shell pieces.

5.1 Ningen: Reassemblable Modules

The case study, entitled "Ningen," was developed illustrate innovative use of concrete that challenges its negative associations. Concrete is a widely utilized and versatile construction material, ranking among the most consumed materials on Earth and holding a dominant position in the construction industry. Concrete has a long history of utilization, spanning from the Roman era to the present and has demonstrated significant potential in both architectural aesthetics and construction technology. This is exemplified by the works of notable architects such as Nervi, Candela, and Isler (Tang, 2015) However, in recent times, there has been a negative perception of concrete among the general public, largely due to its association with dense urbanization and significant environmental impact.

In the context of this project, "junkspaces" are targeted. There are the residual spaces that result from the development of large-scale construction projects that disrupt the existing urban fabric, such as the erection of new viaducts or motorways (Koolhaas, 2002). These emerging residual spaces lack the essential spatial qualities, land value, user profile, and management structures required to function, creating land that is unused and wasted. As a result, the urban fabric is left with voids that are mostly inhabited by illicit activities. In order to address this situation these junkspaces were repurposed into functioning public areas that can be used by communities.

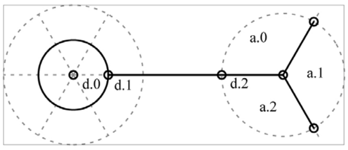
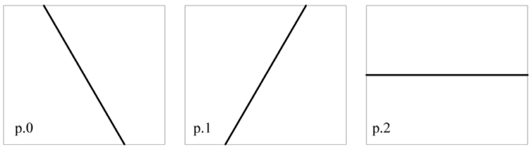
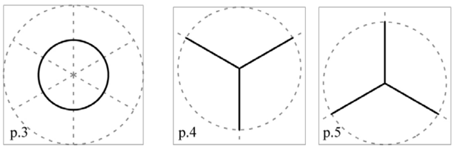
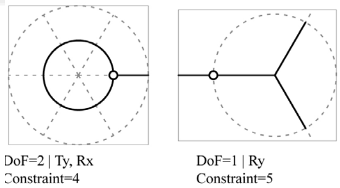
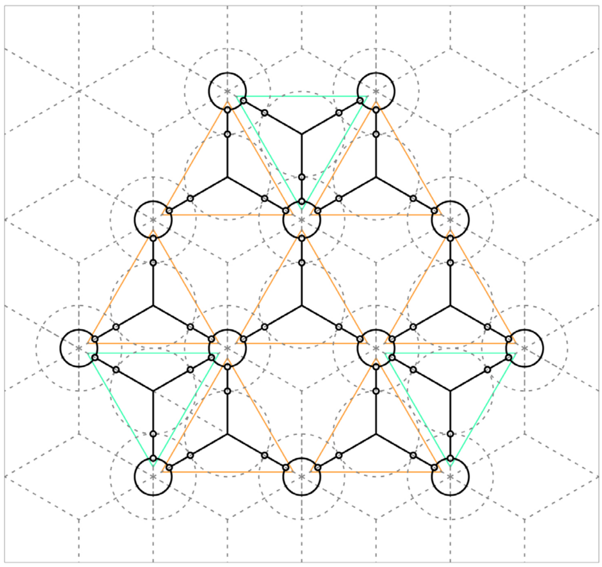
This was done through the use of architectural interventions that are temporary structures, which could transform the perception of space and bring attention to these areas. A considerable number of urban centers will inevitably encounter similar scenarios, and the phenomenon of junk spaces is likely to persist, given its universal prevalence.

The focus was not on a specific site, but rather on understanding the underlying causes of the problem and creating a generic schema that could generate unique solutions tailored to each and every context, with the same identical materials. A modular system was proposed that would utilize identical pre-cast fiber-reinforced lightweight concrete (FRLC) modules named "Ningens" capable of being deployed in a way that creates self-supporting structures, and can be assembled, disassembled, transported, and reused for new applications.

5.1.1 Rule

Rule is generated based on the discrete assembly possibilities of the same-sized equilateral triangles surfaces (Table 5.1). Pseudo-triangles generated from these triangle surfaces' vertices. Joints are generated as the geometric doubles[19] of connection point of each 6 triangles. Due to use of equilateral triangles rotational DoF of 2 allows all the possible configurations probabilities, whereas translational DoF accommodates non-Euclidean surface arrangements.

Table 5.1 : Rule of Ningen (Cilesizoglu, 2025)

Generation of Components (XY Plane)	
Positioning of Components (XY Plane)	 
Pairing of Components (XY Plane)	
Assembly of Components (XY Plane)	

[19] Geometric double is the replacement of any edge with corner, and any corner with edge.

5.1.2 Design

To gain further insight into the adaptability and applicability of Ningen in response to site-specific conditions and to visualize the design, the Ningen was proposed for a site comprising a section of the historical neighborhood that was demolished during the construction of a metro bridge project (Figure 5.1). The site is circumscribed by neighboring blind walls of remaining buildings, and clearance is constrained by the bridge. The area was simply modeled to ensure an accurate representation of the spatial features of the digital environment regarding the design process.

Figure 5.1 : Project area, underside of Haliç Metro Bridge intersecting with historical walls and urban fabric of Azapkapı (Cilesizoglu, 2023).

The design adheres strictly to a performative design approach, generating from a single point, controlled by a set of clearly established rules, parameters and boundary conditions (Figure 5.2). It was conducted exclusively using algorithms created with a visual scripting (Grasshopper) using non-uniform rational B-spline (NURBS) geometry (Rhinoceros). NURBS geometry accurately creates the geometry with precision, can be scalable and can be transferable to digital fabrication tools without decrease in precision.

An arbitrary point on the ground plane is defined as a starting point (Figure 5.3a). As the next points are generated from the initial point, the relationship between two points is determined with a length parameter. As a result, the relationship between each three points creates an equilateral triangle and a reference plane, which is used for creation of guide vectors.

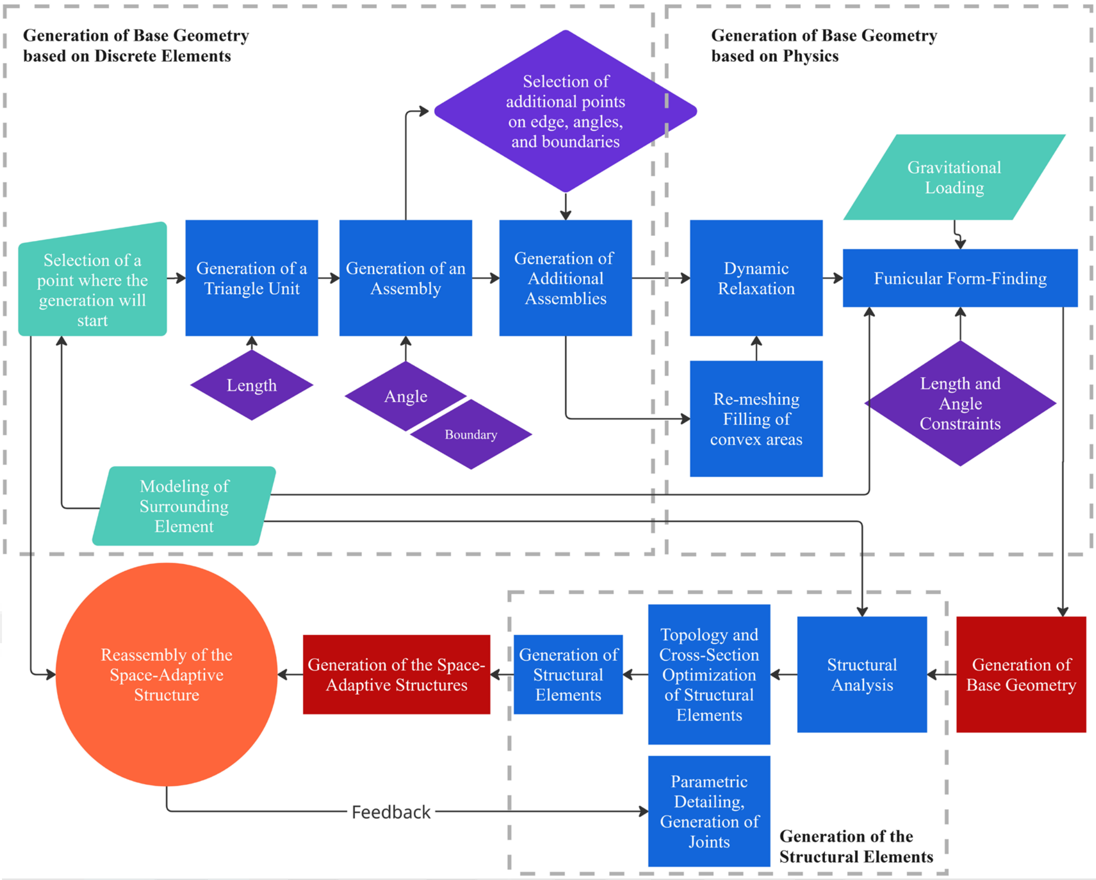


Figure 5.2 : Algorithm, showing the operations that occur synchronously in Grasshopper to generate the structural system (Cilesizoglu, 2025).

These rules pertain to the angle located on the corresponding symmetry plane. A discrete aggregation model (Rossi & Tessmann, 2019) is employed to generate points continuously within specified boundary planes (Figure 5.3b).

Algorithm runs until the all-possible points are generated (Figure 5.3c). Additional connection points can be assigned to one of the naked vertices, with a new set of boundary conditions, to expand the structure further. After multiple connected structures are generated together, the points on the entire geometry are analyzed and necessary connections are made based on distances within the range of tolerances (Figure 5.4).

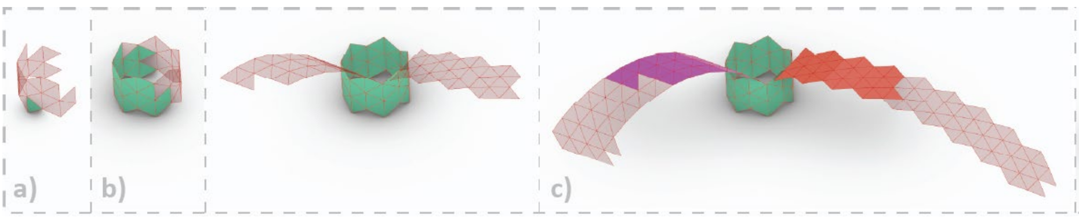


Figure 5.3 : Discrete aggregation model, articulating step-by-step according to geometrical rule (Cilesizoglu et al., 2025).

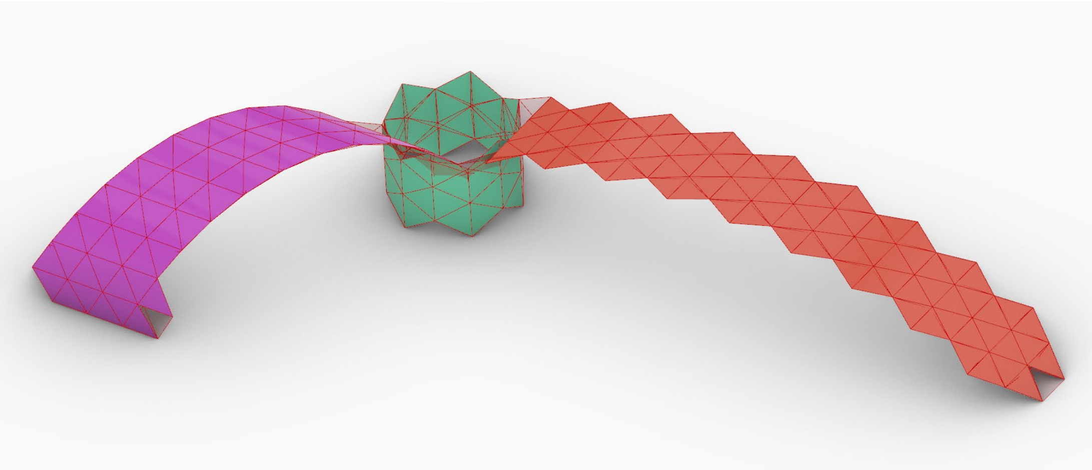


Figure 5.4 : The points are analyzed and necessary connections are added (Cilesizoglu et al., 2025).

Entire geometry with is then reorganized to the principle of dynamic relaxation with reverse gravitational force (beneficial for compression-only system), fixed length and angle condition (Figure 5.5). This method is an iterative approach that simulates dynamic processes, it runs until each vertex reaches the equilibrium position of the system (Chen et al., 2024).

This creates an optimized force flow while preserving the point relations, updating their locations with harmoniously differentiated values in the topology. The versatility of the triangle as a geometric shape allows for the creation of a multitude of surfaces with varying Gaussian curve values through the use of these aggregations. Geometries are generated through the algorithm, inside the defined boundary conditions and parameters, in a differentiated manner.

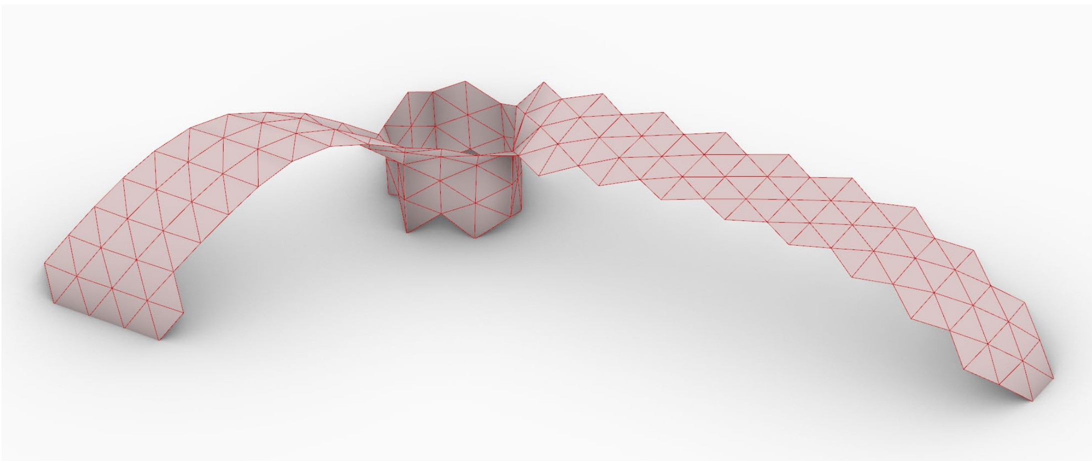


Figure 5.5 : Discrete geometries generated through rules, differentiated geometry generated through DR and form-finding (Cilesizoglu et al., 2025).

Geometry of structural modules were computed using the same three points. Three vertical circles, where the connection to the joints will eventually occur, facing the center of mass are used to construct a soap bubble model.

Based on these circles, a subdivided triangular bipyramid volume is generated with equally spaced closed loop segments. The volume is then optimized with a physics-based component simulating a soap bubble and shrinking the surface area and minimizing the volume (Figure 5.6).

Figure 5.6 : A soap bubble film simulation was used for topology optimization of the structural element (Cilesizoglu et al., 2025).

Points are designated as joints and hexagons are extruded perpendicular to the plane connecting center of masses of adjacent planes of the structural modules. Connections to the joint are generated between each element using the reference planes of elements and joint (Figure 5.7).

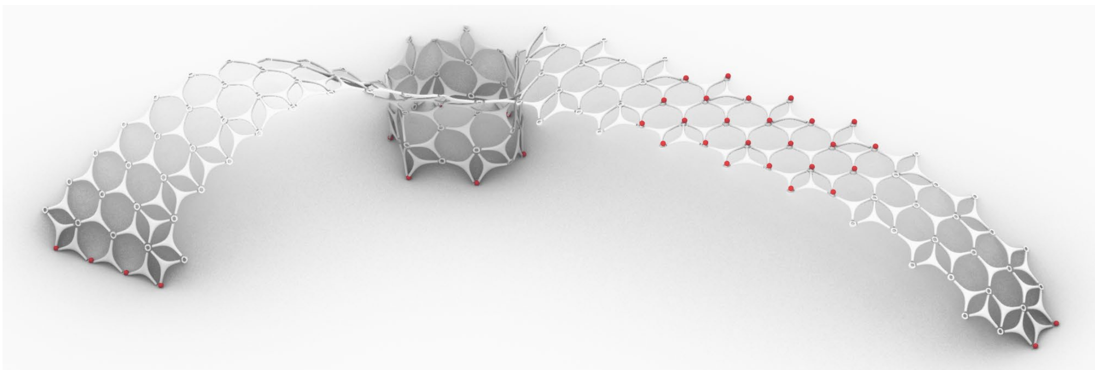


Figure 5.7 : Generation of structural elements according to reference planes and orientation (Cilesizoglu et al., 2025).

Differentiation in the early design phase provides valuable information to the designer as the decision maker, as each change in the parameters, effect the structure and create slightly new variations. Algorithm creates a diverse array of results is elicited by inputs such as ground and enclosing surfaces, steep angle, and parameters like the size of the elements and material properties. Optimization goals are assigned to parameters to increase structural stability.

Every element, structural modules and joints can be individually identified inside the system and related information are embedded on them. Meaning that modules can be traced from data to fabrication. Modules can be readily analyzed, can be modified or replaced with other modules according to new input, such as a result of a cross-section optimization.

The size and weight of the components would also affect the fabrication and construction methods. It is aimed for these structures to be built without heavy machinery, in narrow spaces, and with a minimal number of people. During fabrication, the goal was to reduce waste material and use fewer molds. Arguably, larger sizes would affect the feasibility and application of molding. Therefore, an optimum size that best reflects the initial curvature and shape of the surfaces is chosen. Additionally, modules can be reused in new configurations. Design process follows a material-based approach with a strong emphasis on the fabrication and construction. Geometry has served as a fundamental basis for establishing the basic relationships between elements.

Furthermore, physics-based models were employed to comprehend and optimize structural behavior. Materials were selected based on their intrinsic properties and the fabrication processes employed. For the main structural elements, fiber-reinforced lightweight concrete was employed due to the ease of fabrication of molds for the amorph geometry. The main structural joints are made of steel due to the necessity for higher strength in joints. The structural connections are generated using the geometric relationships between elements, as the angles are varied for each connection. For the case, a complete structure for site is generated with structural elements, joints and details (Figure 5.8). Based on the pre-dimensioning, in relation to form-finding, module of a Ningen has a circumradius of 70 cm (Figure 5.9a).

In FEA[20], steel joints are considered semi-rigid connections and calculated with rotational stiffness. (Figure 5.9b) Since Ningen is temporary structure, structural design algorithm in elastic conditions is implemented under specific boundary conditions. The support points are fixed on the ground and under the surface of bridge, and the structure is subjected to its self-weight along with an additional live load of 1 kN/m.

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[20] FEA and cross-section optimization has been conducted in Karamba3D (Preisinger, 2013).

The generated system uses a fiber reinforced lightweight concrete (CEN, 2021) as the structural material which is engineered specifically for high tensile strength (Deng et al., 2023). Material properties are assumed as Young's Modulus (E) of 25 GPa, density (ρ) of 1900 kg/m³, tensile Strength (f_{ctm}) of 6 MPa, compressive Strength (f_{ck}) of 30 MPa.

Feasibility and the material optimization of design are assessed through the evaluation of stress/strength ratio (smaller than %100) and maximum displacements (smaller than $L/250$) (Figure 5.10a). Optimized cross-sections vary from 12 cm to 24 cm in diameter (Figure 5.10b). Based on the assumptions and numerical results obtained, it is deemed that the proposed configuration is structurally reliable (Figure 5.10c).

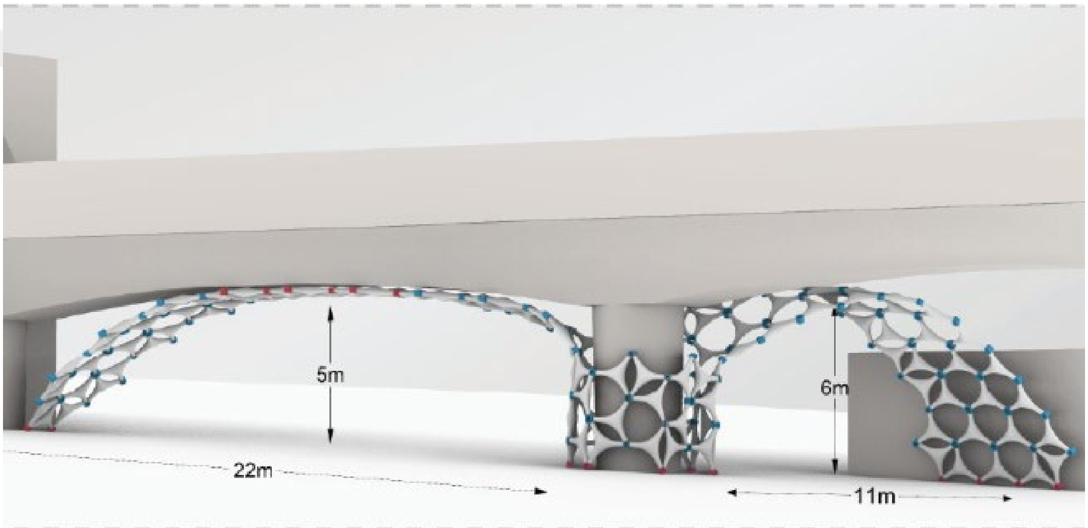


Figure 5.8 : Generated structural elements, joints (blue), supports (red) and detailing according to geometric relations and environmental boundaries (Cilesizoglu et al., 2025).

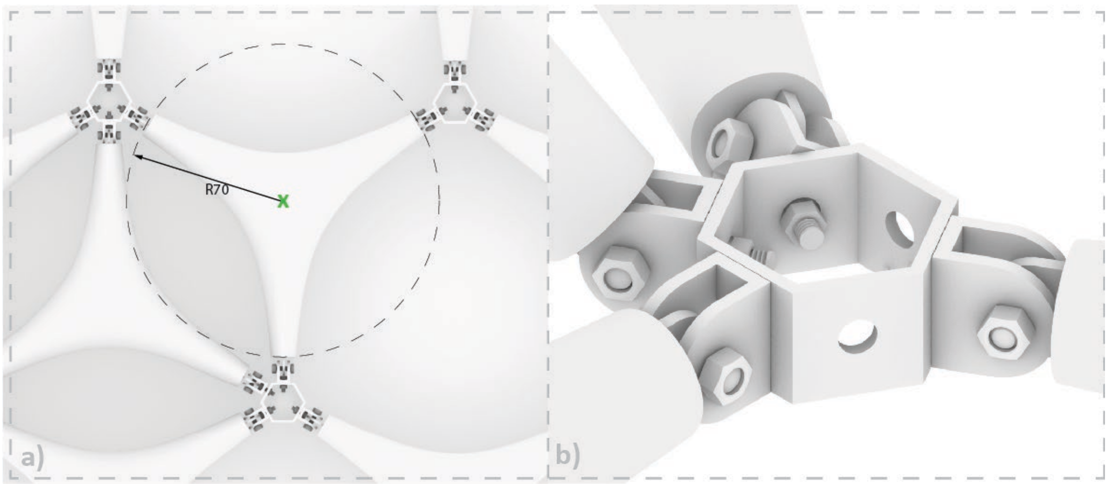


Figure 5.9 : (a) Structural element, (b) steel joint member (Cilesizoglu et al., 2025).

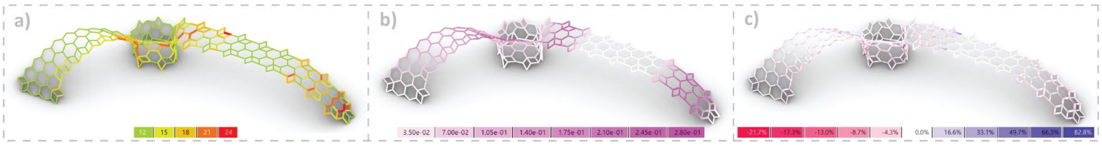


Figure 5.10 : (a) Optimized material distribution based on analysis data, (b) displacement analysis, (c) stress/ strength ratio analysis (Cilesizoglu et al., 2025).

Established modules were prototyped with scaled elements and details using 3D printing (Figure 5.11). The components were printed individually and subsequently affixed to one another. The structure and its structural behavior were subjected to testing, and the design was found to be viable under its own weight. The structural system was deemed to be reliable and joints to be functional, rigid and allowing configurations.

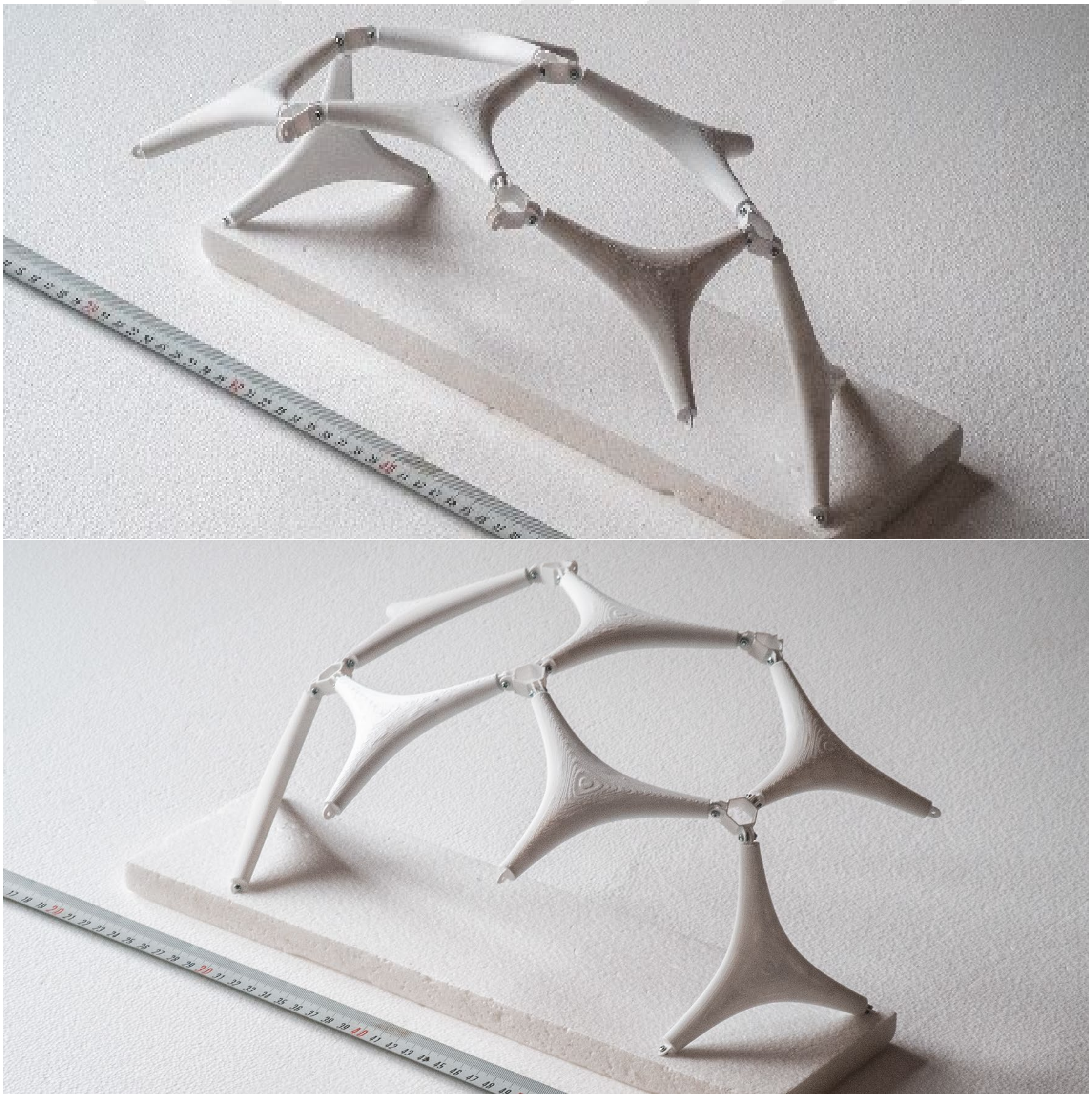


Figure 5.11 : Functional prototype of structural system, scale 1:10 (Cilesizoglu et al., 2025).

5.2 Armadillo: Reconfigurable Space-Adaptive Structure

In a traditional sense, architectural design is dependent upon spatial context, movement and usage patterns, program, environment, orientation, and other factors. Designing for a situation with no context, location, or program meant that the design proposal had to be conveniently transportable and self-supporting without any ground connections. The design must be adaptable to accommodate reconfiguration for use in different spatial contexts. It should be capable of creating a variety of spaces through manipulation of obstacles, pathways, and the creation of subspaces. Additionally, the design should be able to introduce new functionalities and enhance the existing spatial configuration.

In the context of a building's lifespan, the role of an organizational or governing body in decision-making processes pertaining to construction, maintenance, relocation, and demolition is of paramount importance. In terms of adaptability and applicability, the project asserted that, due to the straightforward assembly process, the lightweight nature of the material, and the portability of the materials, it could be constructed, maintained, relocated, and demolished by its users. The initial assembly was conducted by individuals without specialized training who were provided with instructions on the fundamental logic of the structure in accordance with the project specifications.

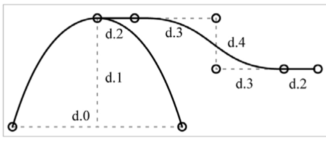
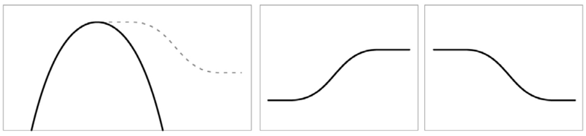
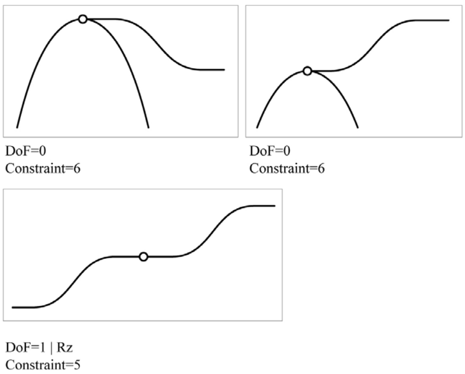
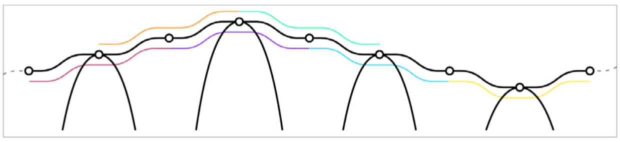
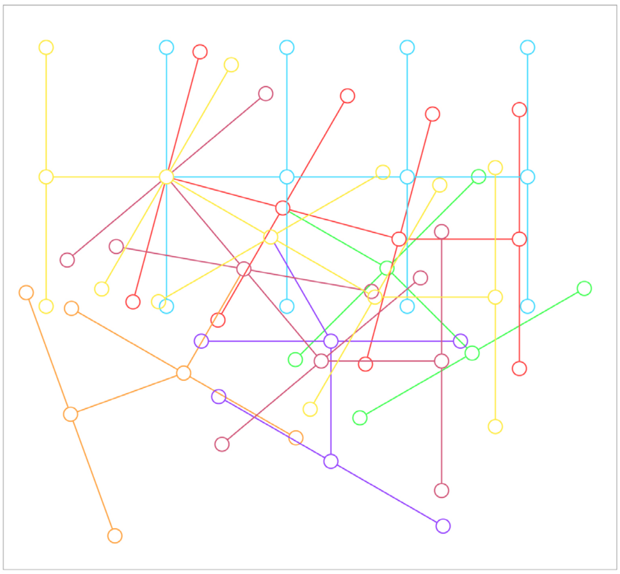
The assembly process commenced with the integration of the fixed components. The spines were then fixed to the corresponding ribs, utilizing a modified double mortise and tenon joint with two loose tenons, beginning from the lowest rib. The ribs were coupled with one another via pivot joints at the juncture of the spines. The bolts were fastened with a loose grip to prevent rotation of the components and ensure the stability of the system. This process was repeated until all ribs were connected to each other. The completed system was found to be stable, yet capable of facilitating rotations, movement, and relocation.

Additionally, the space usage implications of the proposed relocation were evaluated using agent-based movement analysis tools. Following the relocation of the system he bolts were fastened in order to secure the system and ensure its rigidity. It was dissembled as fast as it was built and transported another location to be reassembled. Due to flexible detailing, no material was harmed.

5.2.1 Rule

The design process depends the most basic forms generated through mathematical equations (Table 5.2). Main components are catenary arches—an arch shaped by gravity between two points—and Bezier curves—geometrical definition of a curve formed by control points—generated between and through extremis points of these catenary arches. System is reconfigurable in XY planes.

Table 5.2 : Rule of Armadillo (Cilesizoglu, 2025).

Generation of Components (XZ Plane)	
Positioning of Components (XZ Plane)	
Pairing of Components (XZ Plane)	
Assembly of Components (XZ Plane)	
Configuration of Components (XY Plane)	

5.2.2 Design

The design adheres strictly to a performative design approach, generating from a single point, controlled by a set of clearly established rules, parameters and boundary conditions (Figure 5.12).

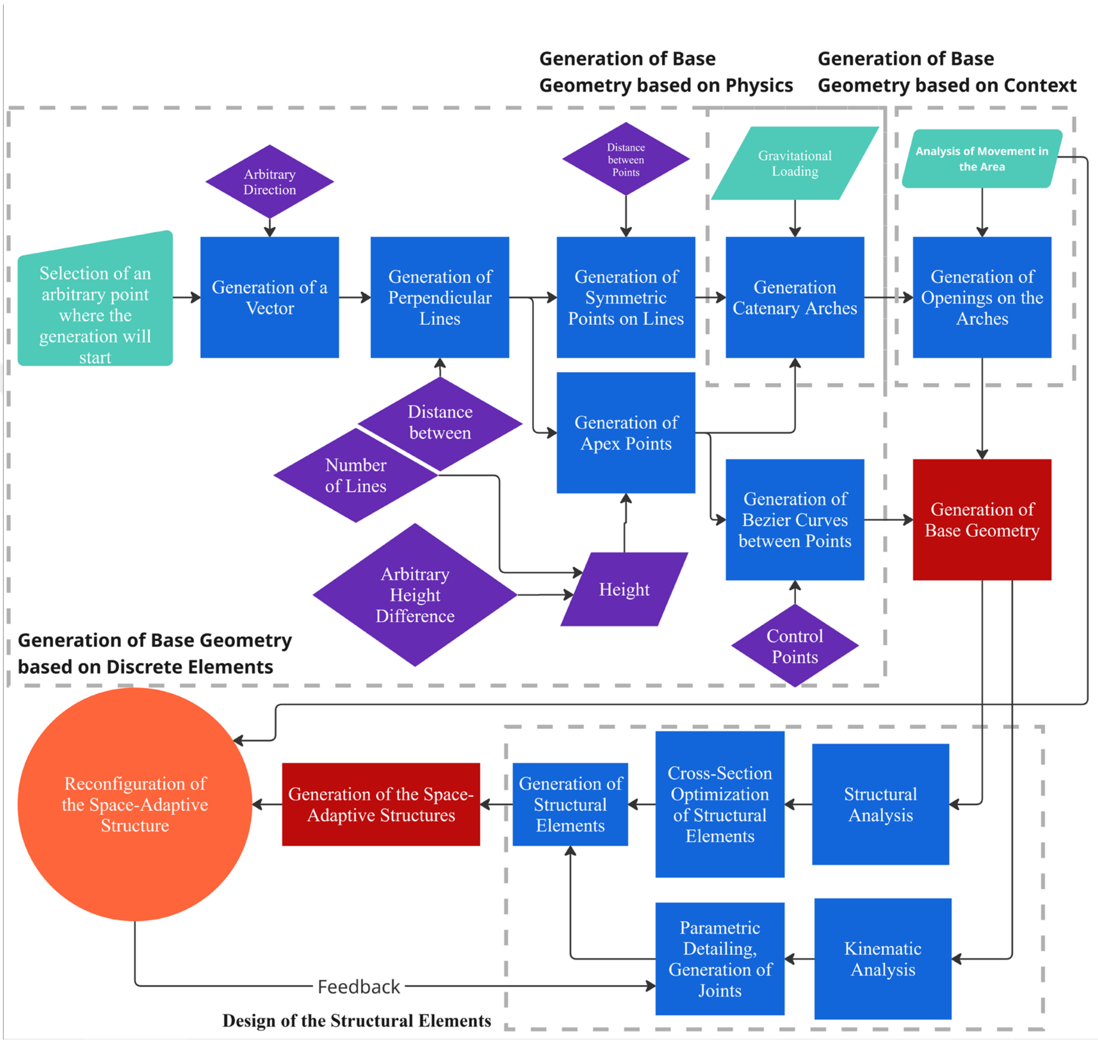


Figure 5.12 : Algorithm, showing the operations that occur synchronously in Grasshopper to generate the structural system (Cilesizoglu, 2025).

The design process commenced with the drafting of a base guide curve and guide sections of the structure at pivotal points, including the lowest and highest points, entrances and exits, widest parts, and endpoints (Figure 5.13). This was done to ensure the functional dimensions of the structure. The higher sections were designated as openings for the pavilion, thereby facilitating uninterrupted movement within and through it. In contrast, the lower sections were designed to create obstacles. Therefore, design response the environmental stimuli through design decisions.

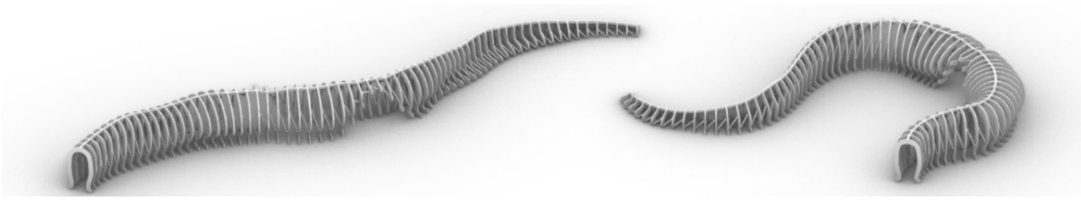


Figure 5.13 : Different configurations of Armadillo (Cilesizoglu, 2024).

The sections were lofted and re-sliced based on the frequency parameter and were arrayed on the guide curve (Figure 5.14). The optimal distance value for the distance between ribs was selected to limit passage between sections while maintaining visual permeability. The generated sections are then transformed into structural elements through the extrusion of profile sections. The dimensions of these sections are influenced by the type of strength and the material to be used. As the final product takes shape throughout this iterative process, adjustments can be made to the distance and dimensions of these profiles to achieve the desired spatial or aesthetic effects.

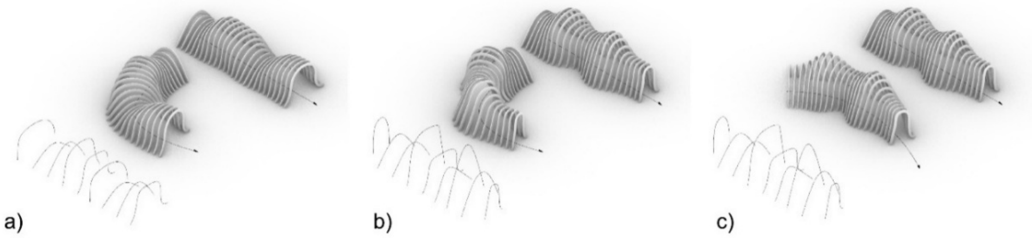


Figure 5.14 : Variations generated through guide curves (Cilesizoglu, 2024).

The design is composed of two fundamental elements: spines and ribs. The ribs are a series of arc-shaped sheets positioned perpendicular to the main line on which they are arrayed (Figure 5.15). They establish a permeable boundary between the interior and exterior spaces.

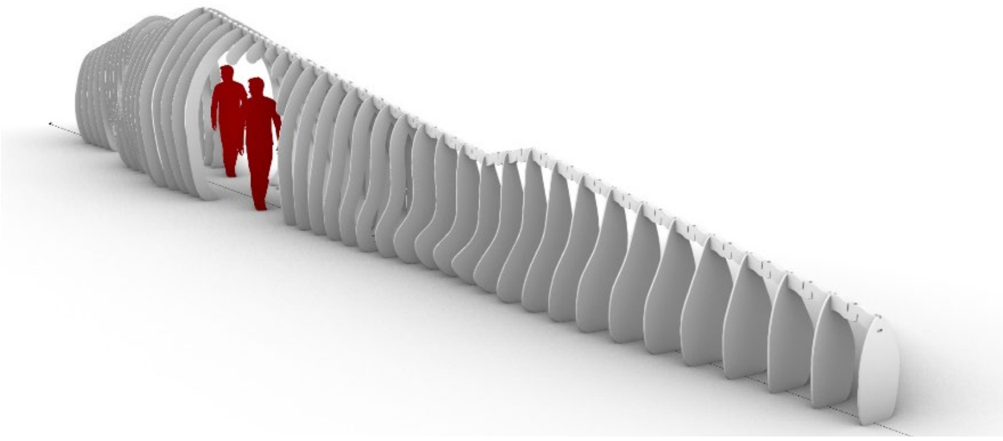


Figure 5.15 : Perspective of digital model of the Armadillo (Cilesizoglu, 2024).

Spines are a series of horizontal structural elements affixed to the ribs at their uppermost point (Figure 5.16). Pivot joints are situated between each spine and are held in place by fastened bolts. These joints are designed in a unique manner with locking mechanisms, which serve to hold the system together and provide a degree of rotational movement, thus facilitating reconfiguration. The objective was to achieve portability. The selection of materials in sheet form ensures that, during transportation, the components can be stacked without risk of breakage and can be readily reconfigured.

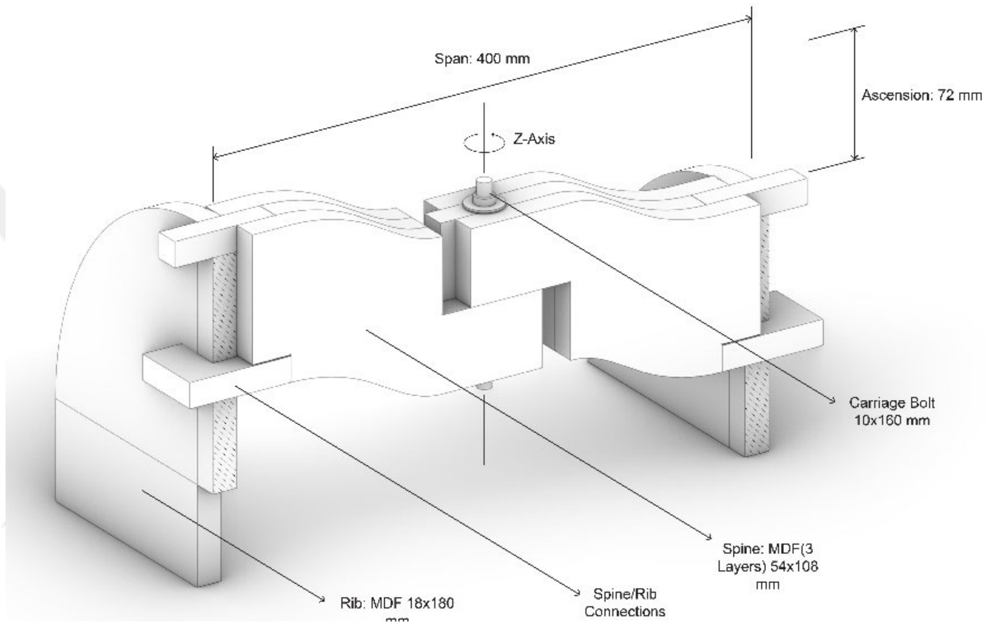


Figure 5.16 : Axonometric perspective of a spine elements, dimensions in mm (Cilesizoglu, 2024).

The primary structural characteristic of this structure is its self-supporting nature, independent of any external connections. In regard to the vertical axis, the load is transferred through the feet to the ground. The computation of each curve is carried out in accordance with the principles of chain curves, with the objective of optimizing the material strength. Each section is susceptible to failure in its cross-axis, yet is connected to the spine of the adjacent section. Each rib was connected to the adjacent ribs by joints situated at the uppermost point of each section. The aforementioned joints served the function of structural members, providing the necessary support to hold all the ribs together. The joints were designed to permit a certain degree of rotation between the ribs and to allow for a fixed amount of height increase. This ensured that the positions and heights of the ribs remained interconnected and regulated.

The spine/rib connection detail has been developed to accommodate height changes and to enable limited rotation along the Z-axis while effectively resisting moments in the perpendicular axis. The structure's placement makes use of curves, including S-shaped and Bézier curves, which feature both convex and concave curves. As the orientation of each rib varies, the probability of toppling decreases. Such an arrangement guarantees the diversification of forces acting upon the structure. The fixed structure functions to establish a new equilibrium as it is constructed.

Structural analysis algorithm is conducted using the Isogeometric Analysis (IGA) method (Längst et al., 2017). IGA utilizes Non-Uniform Rational B-Splines (NURBS) as basis functions for Finite Elements, eliminating the need for meshing during analysis. It should be noted that the structure employs the use of pinned and hinged supports. The structure is subjected to its own-weight along with an additional live load of 1 kN/m. Timber is used as the structural material, with a design strength of 24 MPa (This is corresponding to a timber grade of C24. The modulus of elasticity (E) for timber material is considered to be 11 GPa. (European Committee for Standardization, 2016) The design's feasibility is determined by evaluating peak (i.e., axial) stresses (Figure 5.17). Analysis shows the stresses are at their peak, around the area where there is a passage in the structure.

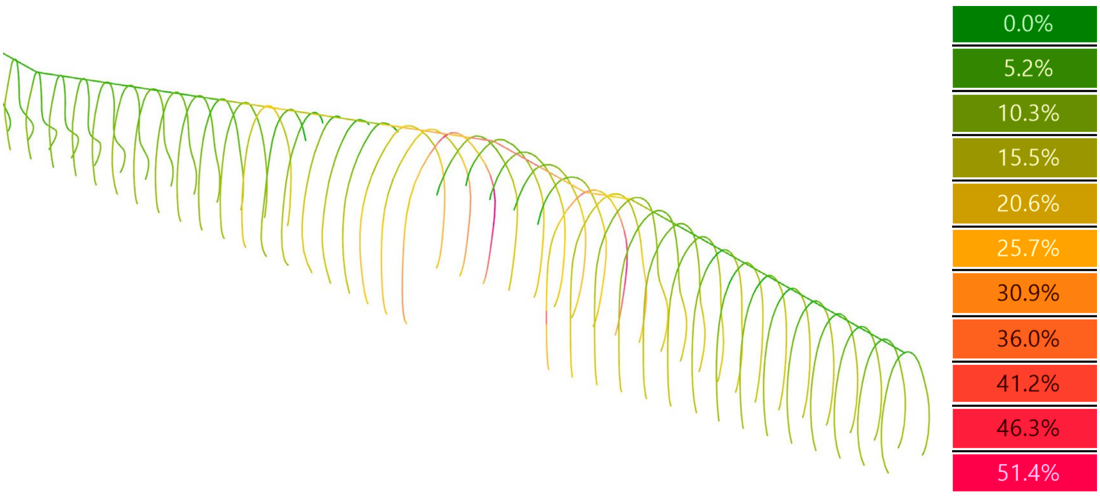


Figure 5.17 : Structural Analysis using IGA (Cilesizoglu, 2025).

This study was also selected to be built in two scales 1: 4 and 1:1. For 1:1 scale, MDF was selected for its homogeneous properties and cost-efficiency. For 1:4 scale, a homogeneous material and cross-section was selected as the infill material, with the objective of providing a uniform inner structure comparable to that of MDF.

A 1:4 scaled physical prototype was constructed to model the structural behavior and movement of the pavilion. The scaled model was produced using 3D printing with PLA, and it was created to feature all of the identical functional details, connections, and joints. This approach may be regarded as a form of performative research by design and design by building, offering an evaluation of both the design and the design process. The scale provides valuable insight into exploring the form and possibilities, transcending the constraints of digital point-and-curve-based designs to embrace a touch-based, intuitive, and analogous approach.

MDF with a thickness of 18mm was selected for its accessibility and cost-effectiveness, as well as its ease of use with CNC. Medium-density fiberboards (MDF) or dry process fiberboards represent a class of engineered wood-based panels. These are manufactured from wood fibers bonded together with an adhesive on the base of a synthetic resin. MDF panels possess a homogeneous structure and exhibit a higher degree of isotropy, which provides uniform bending strength in all directions. The aforementioned homogeneity permits the cutting of MDF panels in the desired direction of the panel, eliminating the need to consider the direction of the span of the loaded panel. This is a crucial aspect for optimizing the utilization of the sheets. (Jakimovska Popovska et al., 2016)

A single layer was utilized for each rib, while three layers were adhesively bonded together by means of a structural adhesive to form the spines. Given the considerable stresses induced by lateral loads and resulting flexural moments at the joints, the use of thicker dimensions for the spines was deemed necessary.

Cutting schemes were generated as CAD data, derived directly from the model, through the utilization of computational design tools. The aforementioned CAD data and embedded data, was nested within sheets with dimensions of 2100x2800 mm. Placement was optimized through the utilization of packing algorithms, with the objective of minimizing waste material (Figure 5.18). The cutting schemes were prepared in accordance with the specifications of the CNC mill, including the blade radius and tolerance. The G-Code was generated using the provided CAD data.

A total of 50 sheets of unique ribs were produced. For the 98 spines, three layers were manufactured for each element, comprising 62 middle layers and 124 edge layers for the ascending and 36 middle layers and 72 for the descending (Figure 5.19).

The spine layers were bonded to each other using an industrial wood bonding agent. Holes for the bolts were drilled into the spines. Additional wooden parts were cut from the untouched parts of the same sheets.

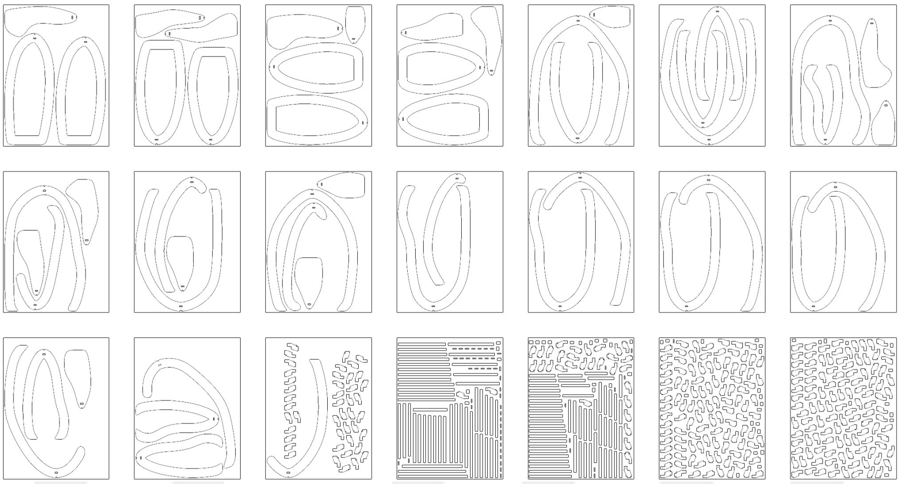


Figure 5.18 : Fabrication schemes packed on the MDF sheets (Cilesizoglu, 2024).

Figure 5.19 : CNC cut MDF panels (Cilesizoglu, 2024)

Armadillo was assembled and reconfigured by hand. Each reconfiguration introduced a new function and effected the movement pattern of the users in the courtyard (Figure 5.20). Assembled and reconfigured structures was deemed rigid enough to be considered a moving structure (Figure 5.21).

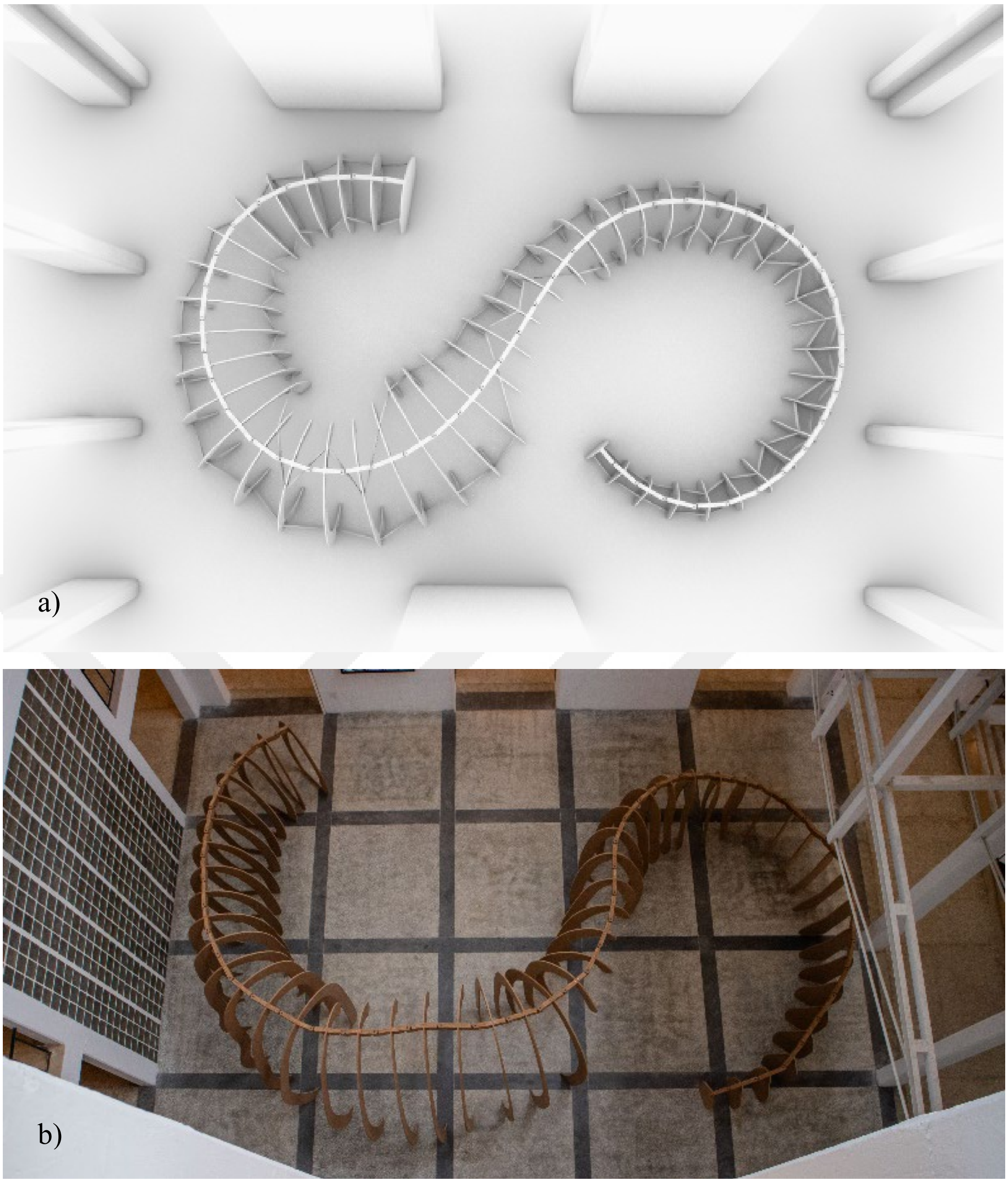


Figure 5.20 : (a) Digital and (b) Assembled structure inside the courtyard of MSGSU (Cilesizoglu, 2024)

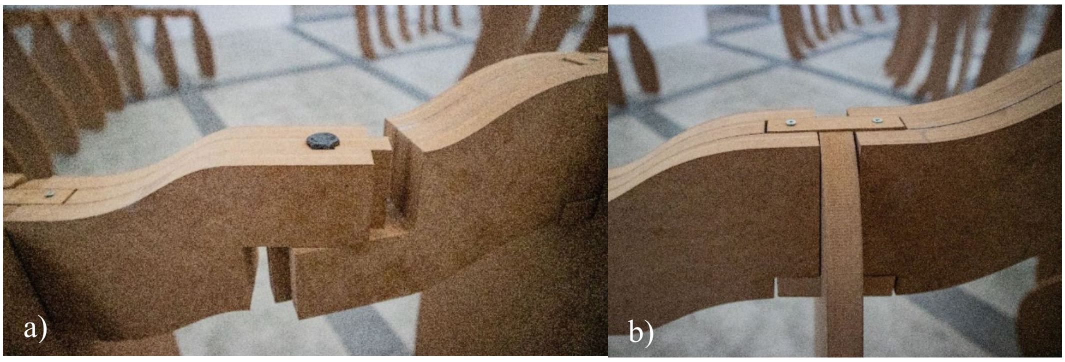


Figure 5.21 : (a) Spine/spine connection, rotated, fastened by bolt, (b) Interlocking spine/rib connection, fixed with screw (Cilesizoglu, 2024)

5.3 Pangolin: Multi-Stage Space-Adaptive Shelter

The February 6th earthquake doublet of M_w=7.8 Pazarcık and M_w=7.6 Elbistan/Ekinözü (Ding et al., 2023) have devastated the southeast Türkiye by damaging the existing building stock and urban infrastructure, affecting nearly 13.5 million people living in the region (Celik et al., 2024). A comprehensive reconnaissance study was taken place on the aftermath of the earthquakes to assess the damage and disaster-relief sheltering situation. Tents and containers were the main sheltering solutions in the region (Figure 5.22). Immediate need of shelters in abundance, caused a strain on manufacturing, construction and design. After 2 years, official documents show that 650.000 people still live in 395 container sites in the region (Presidency of Strategy and Budget, 2025).

Figure 5.22 : (a) Tent sites, (b) Container cities in Adiyaman (Cilesizoglu, 2023).

In the context of this research, sheltering three important and distinct stages based on both core and recent literature are identified (Figure 5.23). An immediate stage that answers the emergency need for sheltering, deployed quickly and intended to be habitable for a short time. An interim stage that answers basic requirements and partial comfort until next stage. Finally, an intermediate stage offering temporary housing with adequate comfort conditions. Based on space-adaptive structures that progressively answer the aforementioned three stages, workflow of disaster-relief sheltering is improved by offering an alternative sheltering solution.

The case study is designed for Burunçayır Village in Adıyaman. Village of Burunçayır was seriously affected by the earthquake (Figure 5.24a). All buildings were damaged, most masonry buildings were collapsed. People were living under their stilted foundations, inside containers and tents supplied by the emergency services (Figure 5.24b). The following case-study is designed for Burunçayır Village.

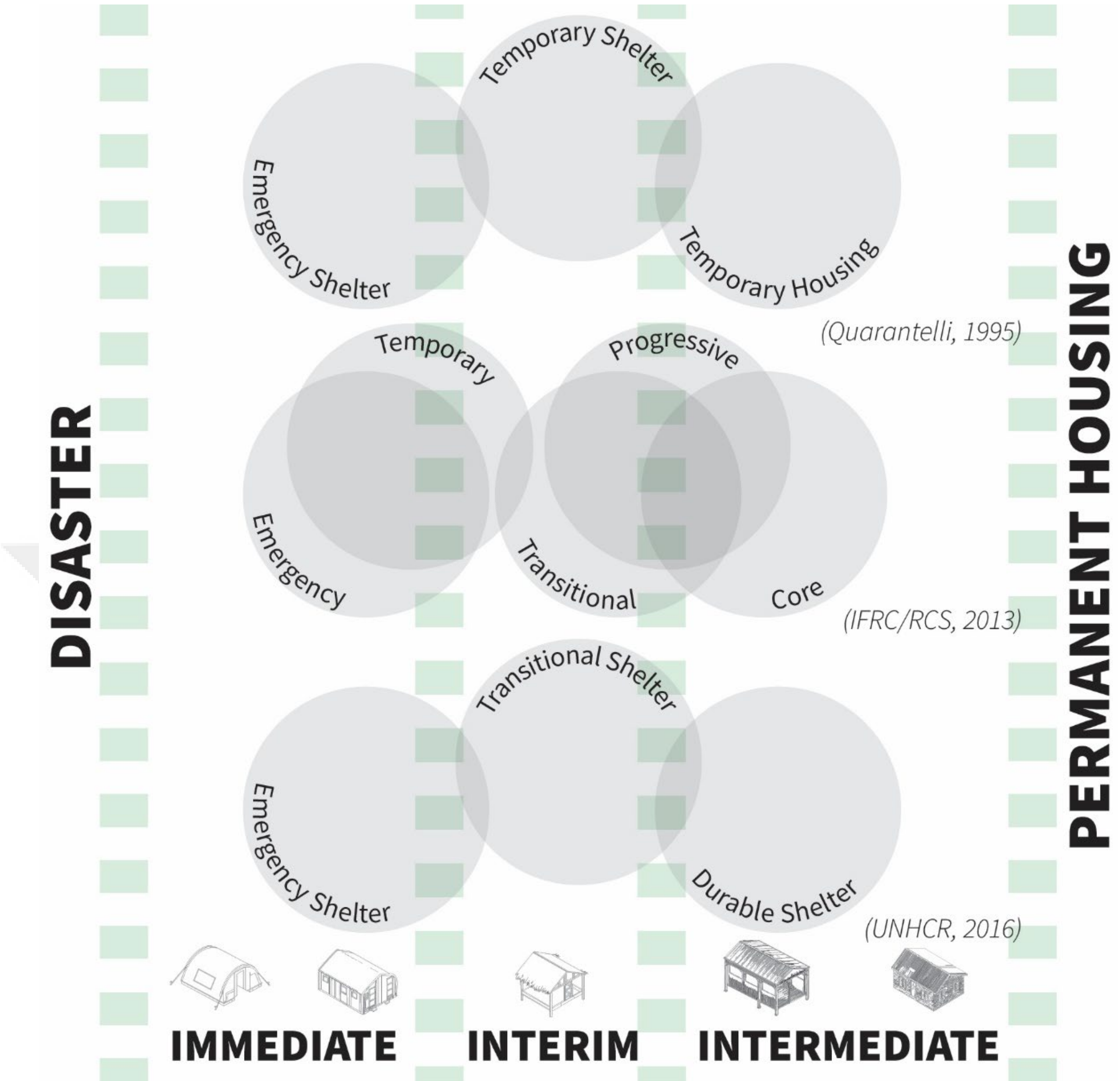


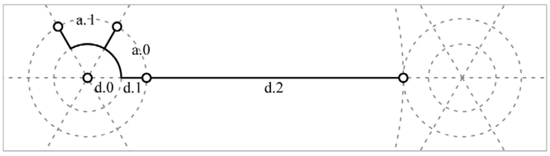
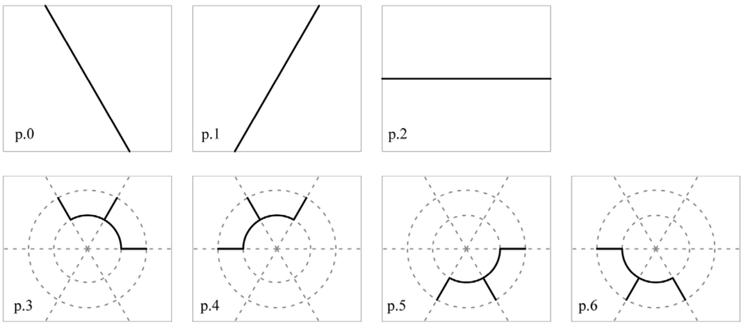
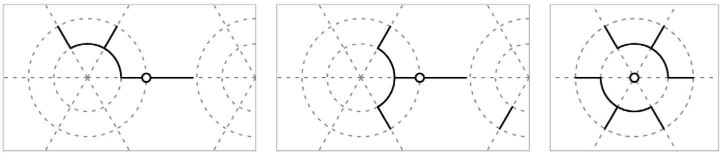
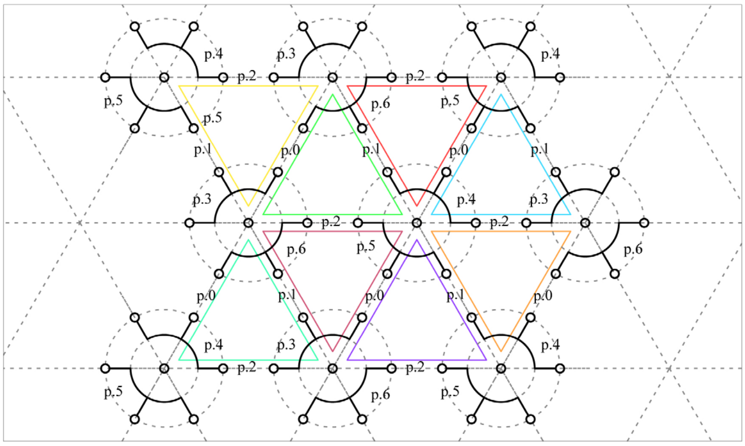
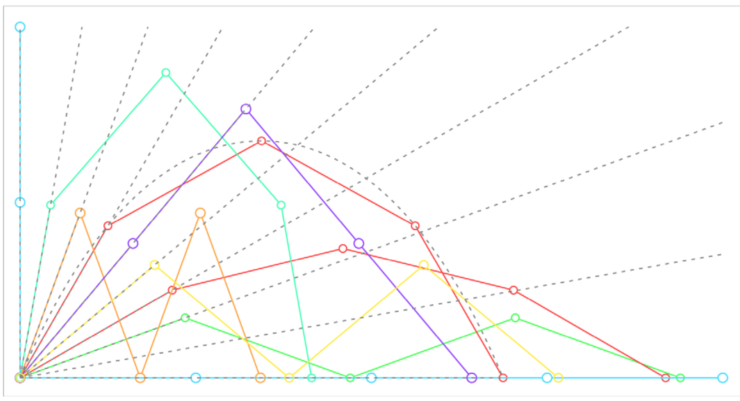
Figure 5.23 : Graphics shows the comparison of sheltering types (Cilesizoglu & Celik, 2025; Geneva: International Federation of Red Cross and Red Crescent Societies., 2013; Quarantelli, 1995; UNHCR, 2016).

Figure 5.24 : (a) Village of Burunçayır was heavily damaged during February 6th earthquakes(b) adapting to disaster (Cilesizoglu, 2023).

5.3.1 Rule

Rule is based on the triangular arrangement of tubular members with hinge-action defined at joints to allow for the folding movement (Table 5.3).

Table 5.3 : Rule of Pangolin (Cilesizoglu, 2025).

Generation of Components (XY Plane)	
Positioning of Components (XY Plane)	
Pairing of Components (XY Plane)	 DoF=1 | Ry Constraint=5 DoF=1 | Ry Constraint=5 DoF=1 | Tx Constraint=5
Assembly of Components (XY Plane)	
Configuration of Components (YZ Plane)	

5.3.2 Design

Pangolin[21], is a multi-staged space-adaptive shelter (MSSAS) with deployable progressive structure supported by modular elements and reconfigurable parts. MSSAS are structures that can respond to the changing needs and environmental effects whose spatial qualities can be altered through their structural parts, deployment or replacement. MSSAS and their inherent adaptive attribute were employed to answer different needs and challenges of these stages using computational methods. A combination of durable high-tech materials and local low-tech materials were proposed for the flooring, roofing and facade (Antonini et al., 2020). Similar to other case studies, the design starts with an arbitrary point and employs the rules in the previous sections (Figure 5.25).

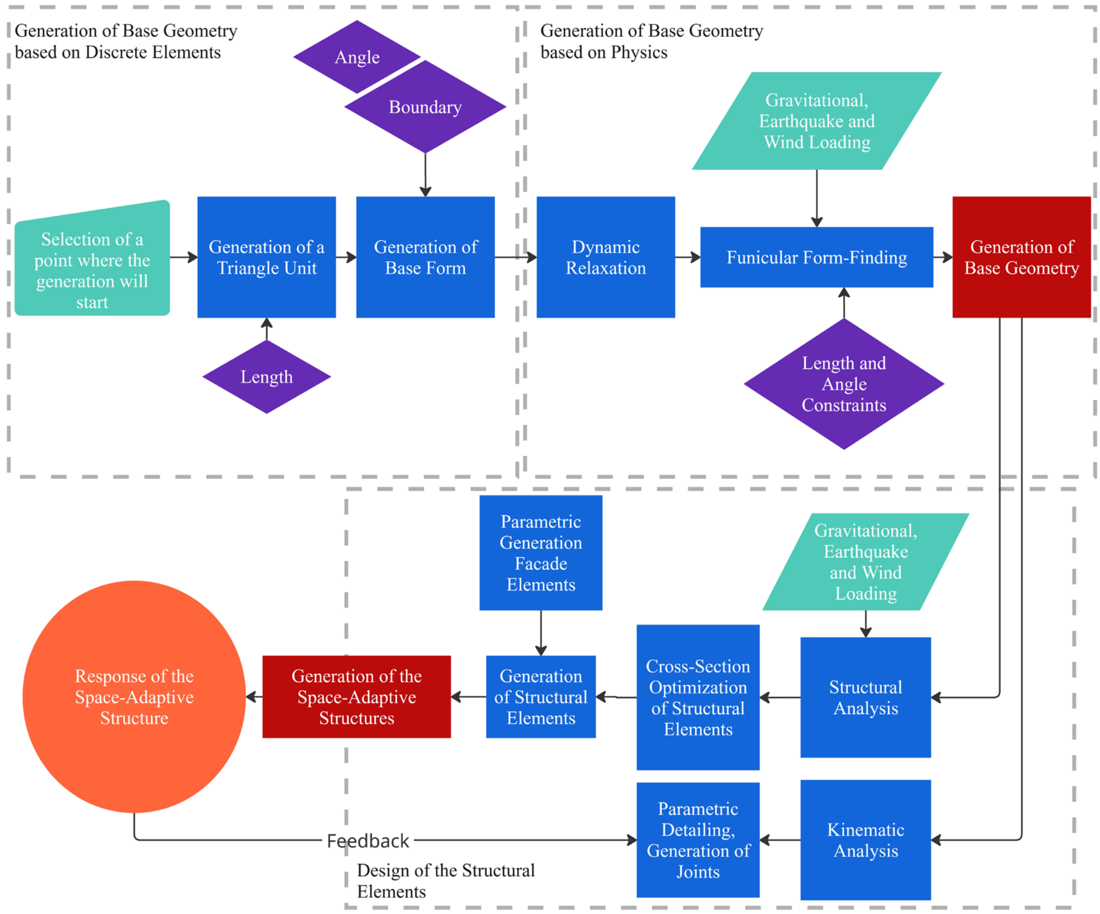


Figure 5.25 : Algorithm, showing the operations that occur synchronously in Grasshopper to generate the structural system (Cilesizoglu, 2025).

[21] Pangolin is an armored mammal with scales that can curl up.

MSSAS is unfolded/deployed to create a self-supporting single-layer shell structure. Form finding algorithm based on hanging chain model were computed using multi-objective optimization algorithm with minimum weight, minimum displacement (in relation to minimum stresses), maximum living area goals. It must be noted that the elements are parametrically generated through their geometric relationship and the dimensions can be freely changed, according to site-specific need. Due to its modularity and transformable form, different size shelters for different functions can be built by the same elements (Figure 5.26). While a shelter for a climate with harsher winter requires a more usable indoor area with lower roof height and increased strength against the live loads, a climate with harsher summer requires the opposite.

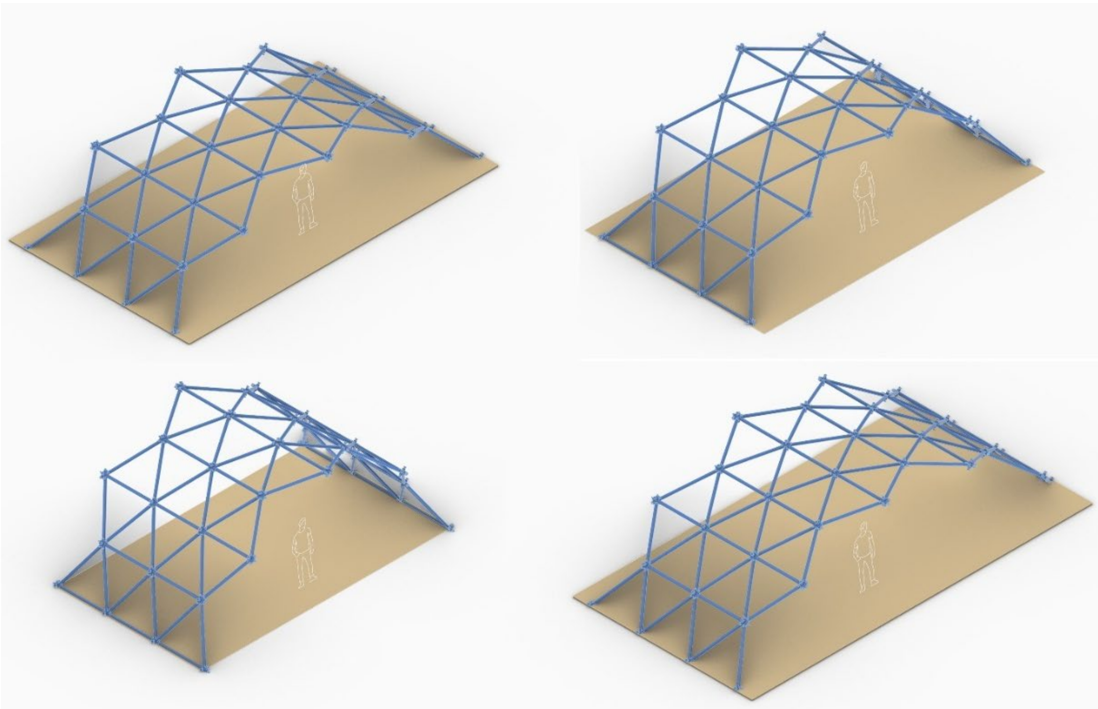


Figure 5.26 : Axonometric diagrams showing different dimensions and forms (Cilesizoglu & Celik, 2025)

A functional prototype using the FDM 3D printed materials were built (Figure 5.27). Prototype was both used as a proof-of-concept but also as a way of understanding structural and mechanical parts. Especially in this project, understanding the motion and interrelationships were important. Prototypes has shown that in fact some parts of the structures were working in unison and orientation of parts of the joints were affecting this movement. Structure has shown that even by not stiffening the joint the structure was able to stand in some configurations. These forms coincided with catenary shapes that was achieved in computational environment.

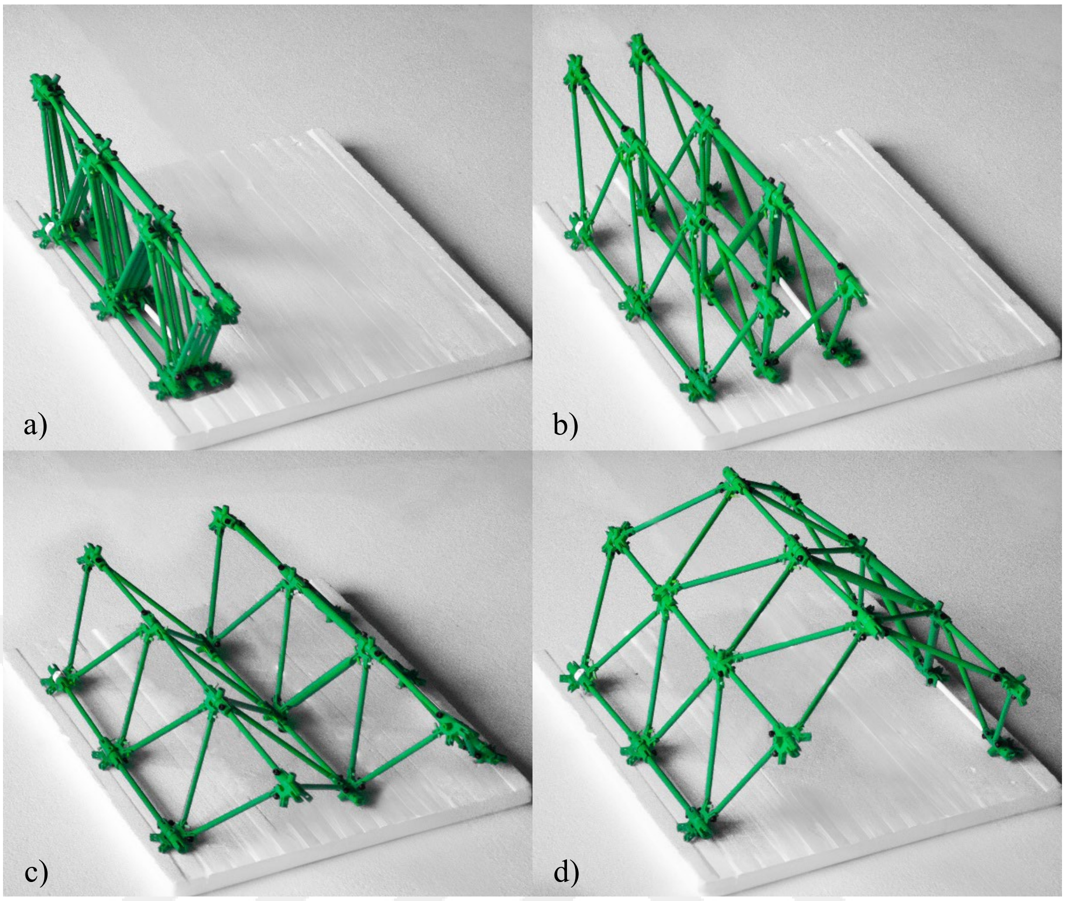


Figure 5.27 : 3D printed functional prototype, scale 1:15. Unfolding of structure: (a) folded, (b) semi-unfolded, (c) completely unfolded, (d) deployment of gridshell (Cilesizoglu & Celik, 2025).

Z axis allows direct connection to cladding material, effectively transferring the loads directly to the joints (Figure 5.28). These authentic details were inspired by assemblage of patented MERO connections. Joint is made three parts. 2 of these parts connect to structural steel elements and another part is used for aforementioned cladding. Hinge movement is constrained by the stiffening of joint with tightening of nuts on the sides.

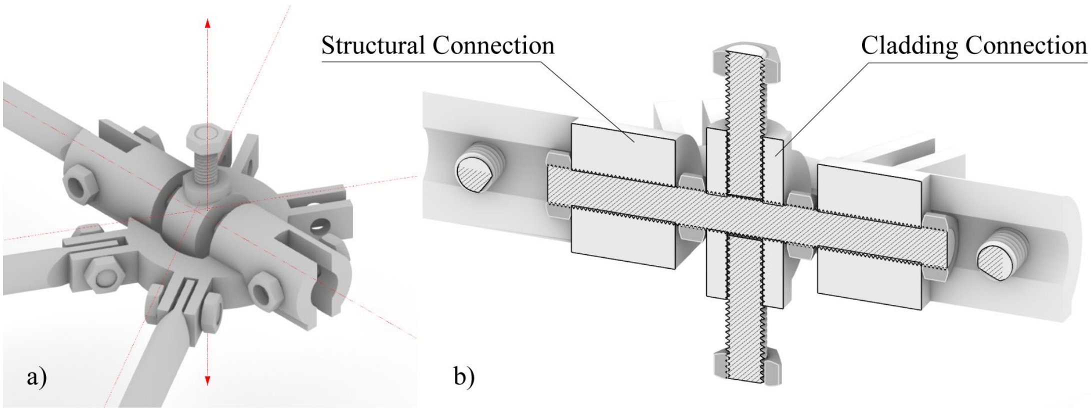


Figure 5.28 : (a) Hinged connection detail, (b) section of the connection detail (Cilesizoglu & Celik, 2025).

Deployment mechanism of the structure quickens the construction with the advantage of quality-controlled detailing and construction, which helps with avoiding the most of problems that comes with poor workmanship. Immediate stage, consists of a foldable deployable shell with a very lightweight cover, like fabric, textile or tarp, a basic stilted foundation and simple floor (Figure 5.29a). Interim stage of the structure is the next stage, and designed to be built as soon as possible, up until resources are available to upgrade into next stage (Figure 5.29b). This stage, utilizes simple or low-tech materials to upgrade the structure and improve living conditions. Thatching can be used for roof, while plywood, bamboo and straw mats can be used for both flooring and cladding. Intermediate stage is the heaviest and ultimate stage of this shelter (Figure 5.29c). Bracings are added increase stability of the structure. Double-layered cladding and roofing with insulation in between is used to enhance climate conditions for the shell. A second shell can be added to increase footprint to further create rooms, and kitchen and bathroom areas. Additionally, MEP systems are added to supply electricity and water to bring living conditions close to a temporary housing standard.

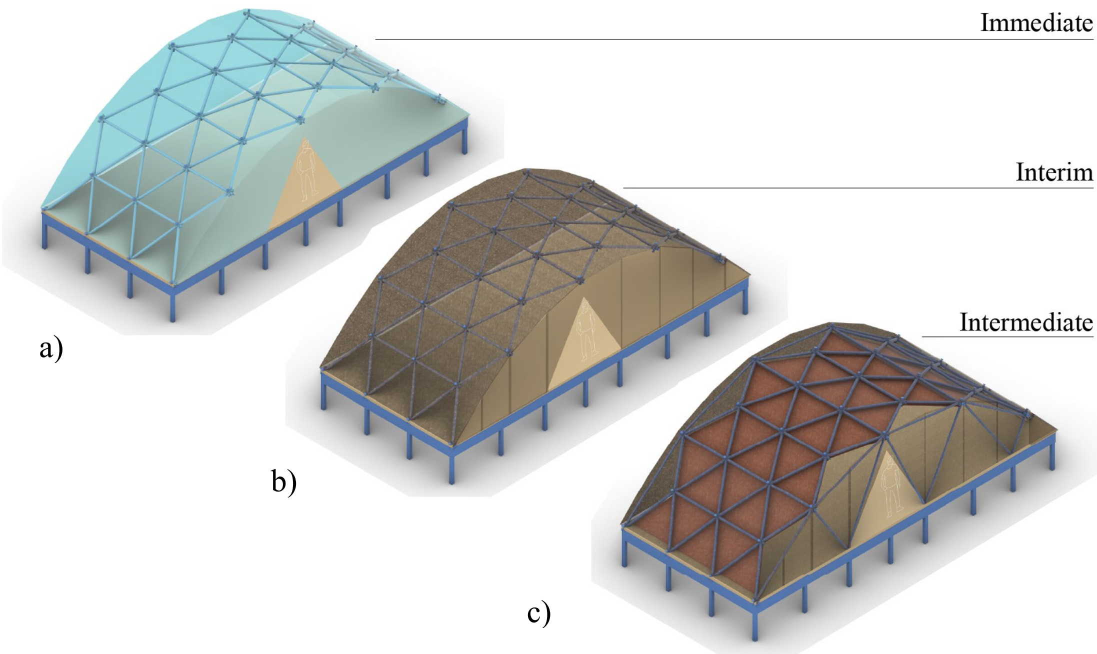


Figure 5.29 : (a) Immediate stage, (b) Interim stage (c) Intermediate stages (Cilesizoglu & Celik, 2025).

Settlement is another important subject and briefly touched in the scope of this project. Just like the structural customization to environmental factors. Settlement morphology shall be also adapted to different climate conditions. Planning should consider expansion of these modules and how they interact with each other (Figure 5.30).

Additional modules can be added in order to increase living area in intermediate stage or long-term stage. In hot climates, open area usage is preferred to closed spaces. Therefore, placement shall be done considering those open areas in front of the shelters.

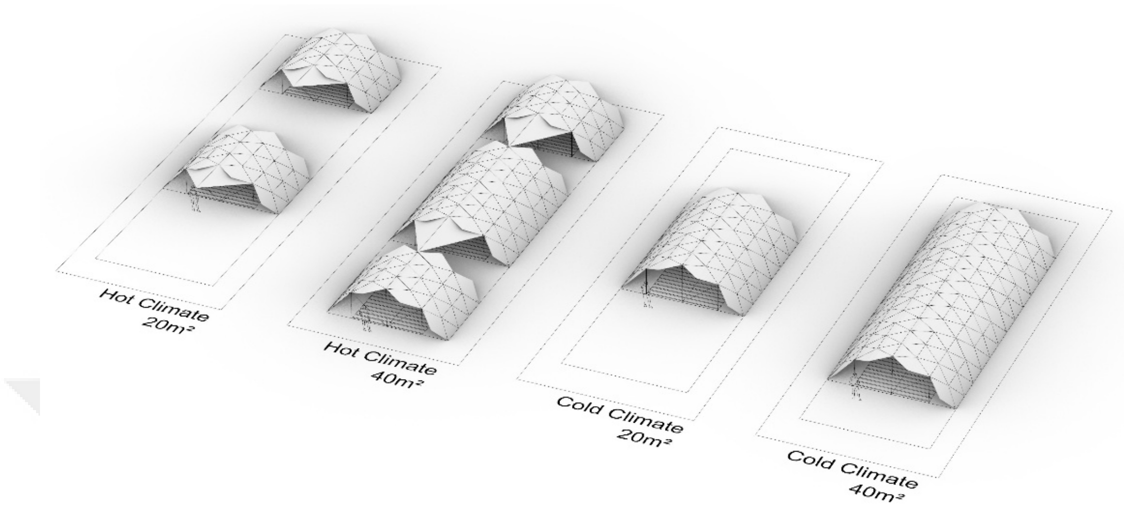


Figure 5.30 : Overview of settlement variations (Cilesizoglu & Celik, 2025).

For this variation, Gridshell's elements are circular hollow profiles with 5cm diameter and 0.5cm wall thickness. NPI220 and NPI180 beams are used for floor beams. Gridshell spans 8 meters and it's 6 meters wide. Structure has 26 m^2 living area with additional 16 m^2 covered areas reserved for storage and installation (Figure 5.31).

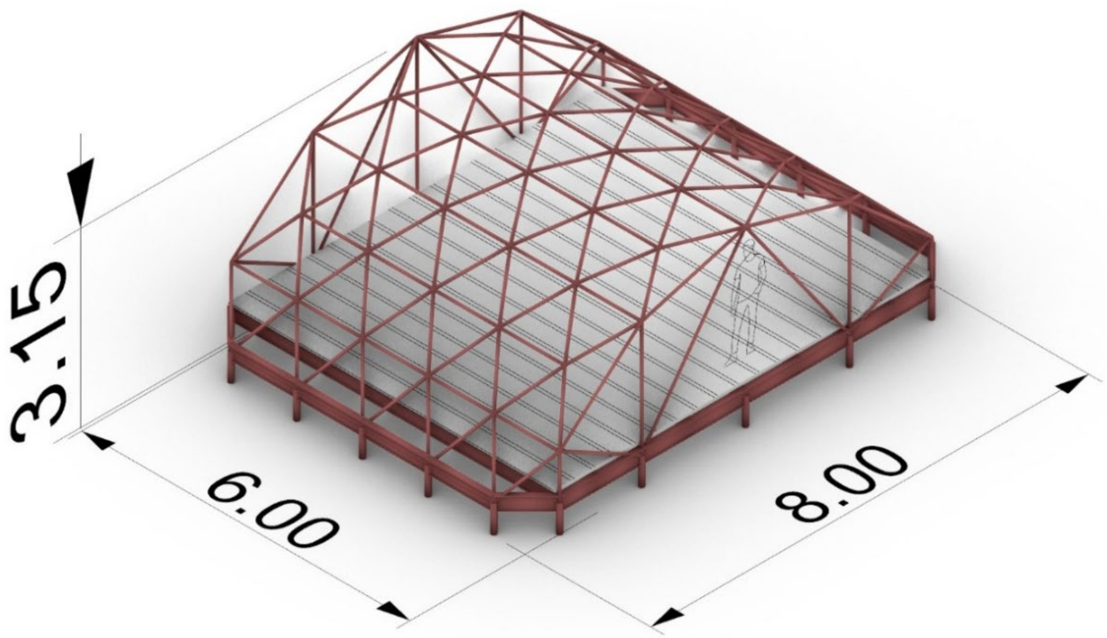


Figure 5.31 : Case study for Buruncayir Village, dimensions in meters (Cilesizoglu & Celik, 2025).

Dead loads (self-weight of the structure), live loads (for residential, 2 kN/m^2), snow loads (for zone 2, 930m elevation, 1 kN/m^2) and wind loads (28 m/s wind speed) were calculated according to TS498 (2021). EQ loads were calculated per design code TBEC (2018) (soil condition ZD, building importance coefficient BKS=3, building height value BYS=8) and values for DD-2 received from AFAD Seismic Map (SS = 1.028 S1 = 0.278 SDS = 1.119 SD1 = 0.568 PGA = 0.431 PGV = 27.270). Structural analysis (FEA) was conducted within the design tool with the aforementioned loads, S235 steel material (σ=23,5 [kN/cm²], E=21000[kN/cm²], and checked for displacement ($\delta < L/250$), axial stress and buckling (Figure 5.32).

The foundation can be built using anchors or micro-pile on compacted earth. The floor must be elevated using adjustable steel footing to level living area and protect flood protection. Crawl space can be used for MEP installation at later stages. The floor can be constructed using steel frame with plywood/ bamboo mat. In order to increase rigidity against EQ and wind uplift, additional bracing can be implemented. SAS can be covered by plastic sheeting, plywood or local lightweight cladding solution like thatch or bamboos. A durable cladding material and MEP installation can be installed in intermediate stage.

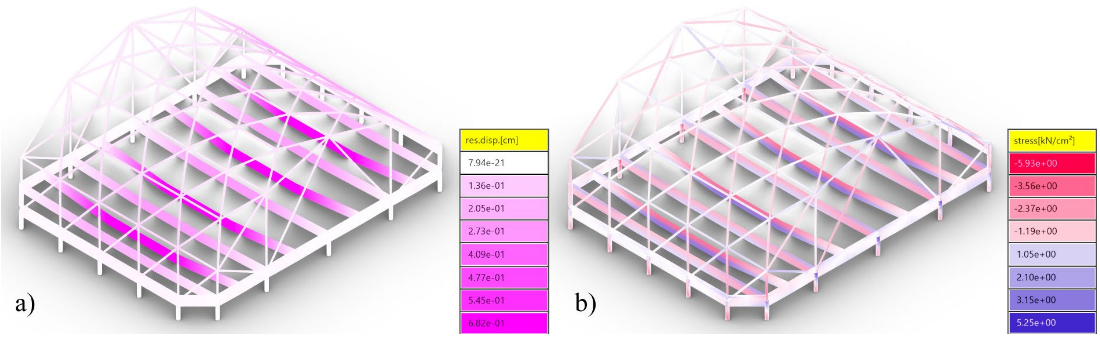


Figure 5.32 : (a) Deflections, (b) axial stress (Cilesizoglu & Celik, 2025).

6. RESULTS AND DISCUSSION

The concept of reassembly, reconfiguration and response was—when compared—manifested itself in every project in some capacity. Most of these factors are emerging from the assembly techniques that were used in the projects. All characteristics are therefore interconnected and can be considered vital and recurring parts of space-adaptive structures.

In theory, every case can be reassembled, due to these reversible (non-damaging) connections. Ningen can be reassembled completely to create any variety of forms allowed by the orientation of elements and DoF of joints. In Armadillo and Pangolin, components are assembled with a reversible technique, but they are not intended to be reassembled. Armadillo can be disassembled during transportation and reassembled in a new location. Pangolin is transported as a whole, and even in transportation components are not expected to be reassembled. Though it may be considered that the structure is reassembled or reconfigured to be transported and deployed. Reassembly in the context of Pangolin has a key role in the progression and adaptation of the system. Through reassembly, new elements are added to the system.

Assembly technique, if not fixed to the ground or any other elements or global form, does not depend on the rigidity of the structure like in Ningen and Pangolin, design allows reconfigurability. In the case of Ningen, the system can be reconfigured during the assembly to ease the assembly process. In the case of Armadillo, the system is totally reconfigurable within the bounds of the range of motion, which is limited only by collisions. In the case of Pangolin, reconfigurability plays a key role in the deployment process. Reconfigurability increases the range of forms that can be achieved through a single structural form.

Response, depends on embedded forms and can be provided through the elements' joints or other responsive elements. Respond is the holistic behavior of a system to change. Through a combination of reassembly and reconfiguration, responsiveness is achieved in Pangolin. Pangolin is deployed to a pre-designed embedded form.

Table 6.1 summarizes and compares how these characteristics appeared directly and indirectly in the case studies.

Table 6.1 : Comparison of characteristics of space-adaptive structures (Cilesizoglu, 2025)

Case	Reassembly	Reconfiguration	Response
Ningen	Structural elements of Ningen can be easily reassembled.	Configuration is possible due to DoF of connections.	Limited to environmental and context-based decisions by designer.
	Each and every element can be replaced with one another.	Limited to assembly stage configuration.	Possible through reassembly.
Armadillo	Can be assembled part by part.	Through its mechanical connections Armadillo can change its shape without reassembly.	Limited to environmental and context-based decisions by designer.
	Parts are not interchangeable.		Possible through reconfiguration.
Pangolin	It is not preferred to be reassembled part by part, rather it is intended to be deployed together as a system.	Cannot be reconfigurable easily. Partially during deployment.	Pangolin is deployed create a responsive embedded form according to requirements.
	Additional elements can be added, therefore reassembled gradually.	Limited to deployment stage configuration.	The structure can be upgraded, therefore respond to changes in time.

Space-adaptive structures in all cases, create new spatial possibilities. However, they are mostly pavilion-like structures, and their effect on the environment or the users cannot be explained through quantifiable methods. They create and transform the space, with transforming the most stagnant layer of the building. Since function is deemed to most important objective of a building, these structures bridge the gap between two opposite (dynamic-static) parts of the building.

Therefore, they provide multiple structural variations for multiple functions for the entirety of the structure's lifetime. In other words, they are efficient through their multiple reassemblies, reconfigurations and responses.

Not every design has to be justified quantitatively as stated. However, in order to display and prove the efficiency of space-adaptive structures, case of Pangolin was used. Pangolin is both a proposal for a real-life problem and can be compared and evaluated against other real-life solutions (Table 6.2). Emergency package, with lightweight cladding elements, takes 9 m^3 (6x1,5x1) of space and weighs ~3000 kg. Intermediate shelter with heavier and durable cladding, and MEP installation weighs an additional ~1000 kg and needs to be transported to area. Cost of a Pangolin is estimated to be 4000 euros in 2025. In total, Pangolin's estimated per year carbon footprint per year is 600 CO_2.

Though initial cost, transportation volume, mass and material usage for Pangolin are higher than regular emergency shelters, design itself accommodates multiple stages (immediate, intermediate and moderate) addresses multiple settlement situations (climate, location etc.) and multiple social parameters (sizes of families, budget) in one single modifiable structure.

Table 6.2 : Evaluation of Pangolin to other Shelters (Cilesizoglu & Celik, 2025).

	Pangolin (Initial)	Pangolin (Total)	Three Shelters (Total)
Lifespan	1 Year	15 Years	15 Years
Construction Time	1 Day	7 Days	15 Days
Cost	€2000	€4000	€5000
Covered Living Area	26 m^2	26 m^2	24 m^2
Cargo Weight	3000 kg	4000 kg	50000 kg
Cargo Volume	9 m^3	15 m3	50 m3
CO_2 Footprint	5000 kg	9000 kg	15000 kg
Cost/ Lifespan		€ 260/ year	€ 350/ year
Cost/ Lifespan/ Area		€ 10/ year/ m^2	€ 15/ year/ m^2
Cargo Weight/ Area		200 kg/ m^2	2000 kg/ m^2
Cargo Volume/ Area		0.6 m^3/ m^2	2 m^3/ m^2
CO_2/ Lifespan/ Area		25 kg/ year/ m^2	40 kg/ year/ m^2

Overall, when compared to all three shelters combined, which normally have to be built for each stage from scratch, it is estimated that Pangolin decreases costs, transported volume, transported mass, and carbon footprint by a considerable amount. Though available materials and costs can change based on location, site and case, SAS is a design principle that should be evaluated and further developed based on its attributes as a disaster-relief solution.

In conclusion, while the implementation of Pangolin considering initial cost would not be desirable, ease of transportation, use and promotion of local low-tech materials, engineered structural and climate performance, sustainability and durability makes it a more, ecologically, socially and, most important of all, psychologically sensitive alternative to current shelters. This result is mostly because of adaptability. Applicability and intelligent form can also be attributed. However, they are also a part of adaptability workflow. Earthquake zone has taught us that application is a considerable attribute for structural quality. Adaptability/deployment assist with the transportation of already built detailing. Therefore, what we transport is not only a shelter, but also structural knowledge. Structural knowledge is carried through reassembly, reconfiguration and response.

7. CONCLUSIONS

The concept of adaptability in design is becoming a prominent topic of discussion in the fields of architecture in response to the impact of global environmental and social changes, crises, migrations, emergencies, and major situations. It is becoming increasingly evident that space is a valuable commodity in today's context. The need for space is on the rise, driven by a number of factors, including urban density, population growth, limited resources, economic conditions, a decline in craftsmanship, shrinking urban areas, construction costs, and environmental concerns related to construction. Adaptable structures are an optimal choice for efficiency and effectiveness in the use of both materials and space. The inherent flexibility of such structures allows them to be adapted to suit a variety of users and purposes, making them a highly versatile solution. The adaptability of a space effectively contributes to its sustainability and dynamism.

The study expands on the idea of space-adaptive structures as an integral part of a new structural and tectonic culture, establishing core design principles that distinguish them from other conventional typologies. Space-adaptive structures are authentic in the way that they function, the way they are built and, the most of all, the way they are designed. Study points out a design workflow that works with computational design thinking, digital and physical modeling, testing and optimization methods. Research focuses on the nuances that differentiate adaptive structures from other architectural approaches, highlighting the unique workflows and decision-making processes that define this emerging field. Rather than following static methodologies, these adaptive systems challenge traditional design paradigms by introducing flexible, interactive, and evolving processes fundamentally altering the relationship between structure and spatial configuration. The ability to assemble, transform and respond, places these structures in a category of their own and defines its own research field. This research field requires an expansion beyond architectural design, and emphasizes evolutionary biology, material sciences, mechanics, robotics and an integrated structural design.

In the scope of this thesis, three are different case studies, each with its own unique design problem and solution. During the research-through-design, key characteristics emerged in defining the design approach for space-adaptive structural systems. Each project demonstrated unique aspects in its design practice due to material and contextual differences. Characteristics are in order of component-to-systems: reassembly, reconfiguration and response. These characteristics became essential in understanding an adaptable framework that could be used to identify or apply to new studies in this field.

In reassemblable structures, every new state, requires re-using and re-organizing of modules, which presents a complex but efficient approach to generating new structural configurations. It significantly reduces material consumption, contributing to a more sustainable and resource-efficient design process. Modularity is already widely employed to streamline the manufacturing-to-construction cycle, with standardized components facilitating the assembly of lightweight structures that can be disassembled and re-used. However, in the context of adaptive structures, modularity becomes more intricate, involving highly specific and specialized components, joints that allow multiple configurations in 3D space. This increased complexity for the joints allows for the creation of more advanced structural systems capable of accommodating possible transformations and complex geometries. By integrating computational design and parametric modeling techniques, designers can optimize these modular systems, ensuring structural efficiency while maintaining adaptability across various configurations.

One of most important part of any adaptive structure is joints. Joints based on their type and their design create the required inner boundary conditions. It allows a degree of movement, either along an axis or around an axis. This part is physical counterpart of geometrical composition of the elements, allowing physical compositions. Joints, are designed according to the principle of connecting at the specific angles in 3D space, allowing uninterrupted transfer of force, while withstanding secondary moments acting on the joints. Joints are the key to reconfigurable structures. Joints, should have the flexibility to be easily configurable, translated or rotating while constructing new stage of the same configuration. This increasingly enhances the transformative capabilities of a structure.

An adaptive system's ability to adjust to contextual changes and boundary conditions is crucial for its functionality and efficiency. Whether during or after deployment, the system must be capable of accommodating and withstanding these changes to maintain structural stability and performance. Reactive adaptability is primarily achieved through the inherent movement capacity of mechanical or actuated parts, which enable the system to reconfigure in response to environmental or operational demands. By re-organizing itself, the structure can control environmental condition or forces or even redistribute forces to maintain equilibrium.

As much as this research focuses on structural design, the processes of manufacturing and construction play an equally significant role in the practical implementation of adaptive structures. The adaptability of such systems extends beyond their initial design to include their assembly, transformation, and potential disassembly for reuse or modification. Unlike traditional architectural approaches that emphasize the static representation of a structure, designing an adaptive system requires a comprehensive methodology, one that considers not only the final form but also the entire process of material selection, fabrication, deployment, and long-term adaptability. This shift in focus necessitates the use of computational tools, parametric modeling, and digital fabrication techniques to optimize both the structure and its capacity for change. The system must be designed with an awareness of its full life cycle, ensuring that adaptability is embedded not just in its form but in its function and interaction with environmental and operational conditions. By integrating adaptability into the design process, itself, architects and engineers can create structures that are more efficient, sustainable, and responsive to evolving spatial and functional requirements.

Computational design is a valuable approach for developing adaptive frameworks. This approach aligns with the concept of creating systems that can evolve and adapt to different scenarios and contexts. CD addresses numerous aspects and facilitates the design of structural systems. Case studies in this thesis were created entirely through the use of computational design tools, with digital prototyping and fabrication employed throughout the process. The designs were validated through structural analysis, prototyping and the construction. As observed in design processes, designers utilized the characteristics of CDT to adopt a holistic approach to design, from conception to construction, effectively transforming digital models into built reality.

Computational design tools were extensively employed to construct and calculate complex relations throughout the process in order to create a variety of solution sets adapting to evolving needs and environments, demonstrating the flexibility and adaptability of this design approach. The geometric transformations and detailing were verified through the utilization of algorithms, which demonstrated the extremis positions and the multitude of states situated between them. This served to affirm that the angles and the range of motion were valid, that there were no instances of collisions, and that the structures were structurally stable. The interconnectivity and malleability of structures and the transformation of space.

While analysis of CDT and its characteristics shed light on design process, it definitively highlights the transformative potential of computational design thinking and computational design tools in shaping the built environment responsively and responsibly. This is one of the most fundamental characteristics of space-adaptive structures. The design must be applicable to different types of configurations, both structurally and logically. During the design phase, this adaptability provides a significant advantage, allowing for design without fixed dimensions and enabling the re-editing of dimensions based on the final designs. It completely changes how the design workflow goes, instead of going from top to bottom or from bottom to the top, it proposes an omnipresent design workflow. Which is not possible without any traditional method, whether it's drafting or modeling. Thus, within this research-through-design framework, these case studies not only serve as explorations of space-adaptive structures but also contribute to a broader understanding of computational methodologies in architectural design. Through iterative prototyping and computational tools, they present insights into material behaviors, structural adaptability, and the challenges inherent in responsive architectural systems.

In conclusion, space-adaptive structure can be considered unique and authentic from the perspective of architecture, tectonics, engineering and construction. These structures display unique features for DfD and for the life-cycle of materials. Space-adaptive structures offers alternatives to changing environmental and socio-spatial conditions. Computational design of these structures introduces creative and dynamic approaches to the area of design with performance-based applications to reduce material and energy waste. By defining and designing a construction and building management workflow, they ensure longevity and sustainability for the structures.

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